How long does it take to learn trimanual coordination?

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***Abstract*— Supernumerary robotic limbs can act as intelligent prostheses or augment the motion of healthy people to achieve actions which are not possible with only two natural hands. However, as trimanual control is not typical in everyday activities, it is still unknown how different training could influence its acquisition. We conducted an experimental study to evaluate the impact of different forms of trimanual action on training. Two groups of twelve subjects were each trained in virtual reality for five weeks using either a three independent goals task or one dependent goal task. The success of their training was then evaluated by comparing their task performance and motion characteristics between sessions. The results show that subjects dramatically improved their trimanual task performance as a result of training. However, while they showed improved motion efficiency and reduced workload for tasks with multiple independent goals with practice, no such improvement was observed when they trained with the one coordinated goal task.**

I. Introduction

Trimanipulation, the use of a robotic third arm for manipulation, has been proposed as a method to extend the number of degrees of freedom (DoF) of a single human user [1]. To support trimanipulation, researchers have developed a number of wearable supernumerary arms [2]–[4]. These systems offer the potential for a single user to perform tasks such as industrial assembly [2], [5] and robotic surgery [6], which today require coordination within a team, leading to possible issues caused by miscommunication [7], [8]. Can humans learn to perform trimanual coordination efficiently? If so, how much training is required to gain this new skill?

For trimanipulation to be beneficial in everyday life, it should enable users to perform tasks both independently of the natural limbs and in combination with them. The ability of users to perform trimanual coordination has only recently begun to be explored [9], [10]. These studies have shown that users can learn to perform trimanual reaching tasks with virtual foot-controlled supernumerary limbs. This has considered both independent and coordinated hand motion [9], [10], and applied these motions to simplified surgical tasks [11], [12].

The motor skill learning process is dependent on numerous factors including the task difficulty, the similarity to pre-existing skills, the training type and the subject's motivation [13]. Learning trimanual skills will require users to learn to both independently control their supernumerary limb and to coordinate its motion with the natural limbs [1]. It is known that unimanual training cannot completely teach bimanual skills due to the additional coordination requirements [14]. Therefore, it is likely that the learning of coordinated trimanual motions cannot be completely understood from unimanual and/or bimanual learning. While initial studies have shown a learning effect during trimanual coordination [15], this has only been evaluated over one or two sessions conducted during a short time frame. Furthermore, it is not known how training impacts different trimanual actions.

In this paper, we evaluate the impact of learning on two trimanual tasks. We consider tasks requiring independent and dependent trimanual motion, analogous to pick-and-placement or triangulation activities. Compared to existing trimanual studies, this study extends our understanding of human trimanual coordination ability in several aspects: First, a virtual reality platform with a three-DoF spatial tasks was used to study human multi-limb operation. Second, we evaluated the impact of trimanual operation over a five-week extended training duration. Third, we compared the impact of two different types of trimanual training tasks. 24 subjects were recruited and separated into two groups, one for each trimanual training task. The results show that training improved the participants' trimanual coordination in both tasks but with different motion patterns.

The remainder of the paper is as follows: Section II overviews the study methods and protocol. The results are then presented in Section III, discussed and concluded in Section IV and Section V.

II. Methods

The experiment was approved by the Imperial College London ethics committee (21IC6935). 24 subjects without motor impairment (11 male, 13 female; age = 24.2 ±3.15 years) participated in the study. Their hand and foot dominance was determined using the Edinburgh handedness inventory score [16] and the ball-kick dominant leg test [17]. 21 participants were right-side dominant, 2 left-side dominant, and 1 had mixed dominance (right-handed and left-footed). Twelve participants (4 male; age = 23.5 ± 1.6) were randomly assigned to the *independent trimanual group* and the other twelve participants to the *dependent trimanual group* (7 male; age = 24.9 ± 4.1).

A. Experiment setup

The setup (Fig. 1a) consisted of a HTC Vive Pro headset *(HTC Corporation, Taiwan)*, its two hand controllers and a

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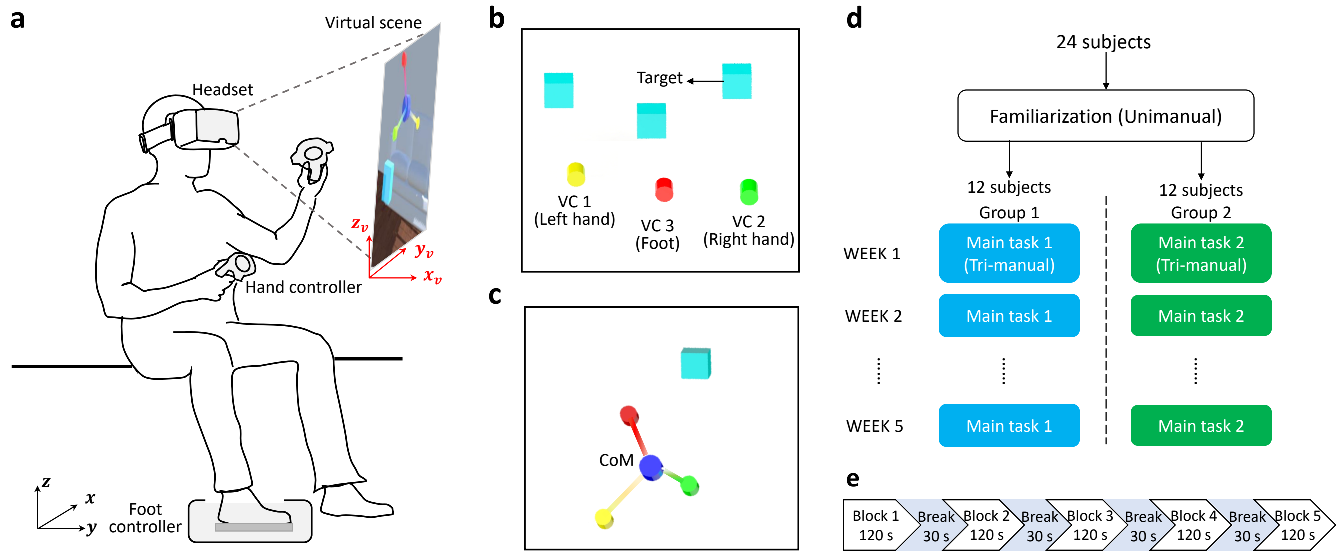

Fig. 1. The experimental setup and protocol. (a) Experimental setup and virtual scenes for the (b) independent trimanual task and (c) dependent trimanual task. Experiment procedure flow chart of (d) five-week overview and (e) procedure in each session/week.

foot interface [12]. The foot interface consists of a base, a mobile plate, and a pedal with an adjustable foot fixture that can collect four-DoF position and force signals. The operator sat on a chair wearing the headset, holding both controllers and placing their dominant foot in the interface.

The virtual scene was displayed $1.5\,m$ in front of the participant. The left hand controlled the yellow cursor, the right hand the green cursor, and the foot the red cursor. All three virtual cursors (VCs) were controlled in three-DoF translational motions. The natural hands' positions were directly scaled to the position of VC1 and VC2. The foot position was instead mapped to the velocity of the third virtual cursor. VC3's $x_v - y_v$ plane motion was controlled by the foot pedal's planar $x - y$ translation, and the z-axis motion by foot dorsiflexion and plantar flexion. To calibrate the VR position, the subjects were asked to place their hands and foot controllers into a neutral position at task activation. The initial position of the VCs corresponding to the fixed base frame was then set to the same initial position (1.2, 0, 0.75).

B. Procedure and tasks

Fig. 1d depicts the experimental procedure. The experiment required participants to train on a trimanual task within the VR system over a duration of five successive weeks. They were randomly assigned to two groups, either training by independent or dependent trimanual tasks. In the first week, all the participants were initially given 5 minutes to familiarize with the trimanual system by conducting a unimanual reaching task with each VC. They then conducted one session of their respective training task which consisted of five blocks, each lasting for 2 minutes with a break of at least 30 seconds between the blocks (Fig. 1e)[1]. In each of the subsequent weeks the participants performed the assigned trimanual training task, where each subsequent session took place roughly a week apart (7.6 $\pm$ 2.1 day). In the first and last weeks, all the subjects also performed a virtual spaceship game using both hands and the foot to improve the VR immersion and investigate the transfer effect.

A description of the two training tasks is given below:

Independent trimanual task (Fig. 1b): The participant had to move each VC concurrently to reach all three of the displayed blue target cubes. The subject was free to allocate any VC to any target. When all targets had been concurrently reached or ten seconds had elapsed, another three targets would appear in new locations. This task simulated pick and placement of multiple objects.

Dependent trimanual task (Fig. 1c): The participant was required to move the center of mass (CoM) of the three VCs, to reach a blue target cube as fast as possible. The motion of the VCs were unconstrained, and therefore the operator had freedom to choose the coordination strategies of three hands to move the CoM efficiently. The target locations were selected such that all three hands would be required to move for some targets. The target cube location would be updated after either the target was reached or ten seconds had passed.

C. Performance metrics

Subject performance was analyzed through the subjects' *trimanual task performance*, their *individual hand motion characteristics* and through a *questionnaire* to consider load.

1) Trimanual task performance: The trimanual performance was assessed by checking the *score* and average *normalized completion time*. A block's score was defined as the total number of successfully reached target sets, where for the independent task this required all three targets to be concurrently reached. A target was considered reached at the time instant at which the VC and the target were in

[1]The demonstration video of unimanual and trimanual tasks can be found at https://www.youtube.com/watch?v=_5spkDP-f4U&t=23s

contact. The completion time represented the time from the moment that the target was shown in the VR environment to the moment that the target set was successfully reached, which was only count in the successful trials. This was then normalised by a characteristic distance corresponding to the maximum of the Euclidean distance from each VC's initial position to their optimal final location for the given target set.

2) Individual hand motion characteristics: Within group metrics were defined to check the trimanual motion patterns in different training tasks. In the independent group, we explored the *target preference* for the x, y and z axes. For the x-axis target preference, the sub-trial targets were differentiated based on their relative x-axis position (left, center, right). Then for each limb, we computed the number of times it reached one of these three types of targets, and divided it by the number of targets reached during the session. We similarly differentiated the y-axis target preference (back, center, front) and z-axis target preference (bottom, center, top). In the dependent task, we instead checked the *CoM distance*, given by the average distance of the hand to the CoM.

In addition, each hand's motion characteristics were also evaluated across groups through *motion efficiency* and *hand coordination*. The *motion efficiency* was the ratio of the real distance travelled to reach a target to the Euclidean distance between the initial position and the reached target. In the optimal case, the efficiency ratio is equal to 1. The larger the efficiency ratio, the less efficient of the motion. The *hand coordination* was computed as the % of time when the hands were moved concurrently (or alone). Here, a hand was seen to be moving if the VC velocity it controlled was larger than $25\,cm/s$. This value was chosen ad hoc based on empirical observation.

3) Questionnaire: Questionnaires were provided to evaluate trimanual operation during five weeks after each week's training session. The NASA Task Load Index (TLX) [18] was used to evaluate load including the mental load, physical load, temporal demands, performance, effort, and frustration.

D. Statistical analysis

Learning was analyzed during the five training sessions. Kolmogorov-Smirnov tests were employed to check the normality of each experimental group for each metric. Depending on the results, we used non/parametric statistical tests for the analysis.

For performance metrics that were unique to the training group, such as the score and completion time, a one-way ANOVA with repeated measures on the session factor was used. The other metric analysis included comparison between the different tasks. The total motion efficiency accounted for the task condition and employed a 5×2 ANOVA. The motion efficiency per limb used a 5×2×3 ART ANOVA considering the sessions, training conditions and limb (left/right hand/foot). The data for each objective metric was averaged over all blocks in each session. One subject in the dependent trimanual group missed one session, therefore we used a

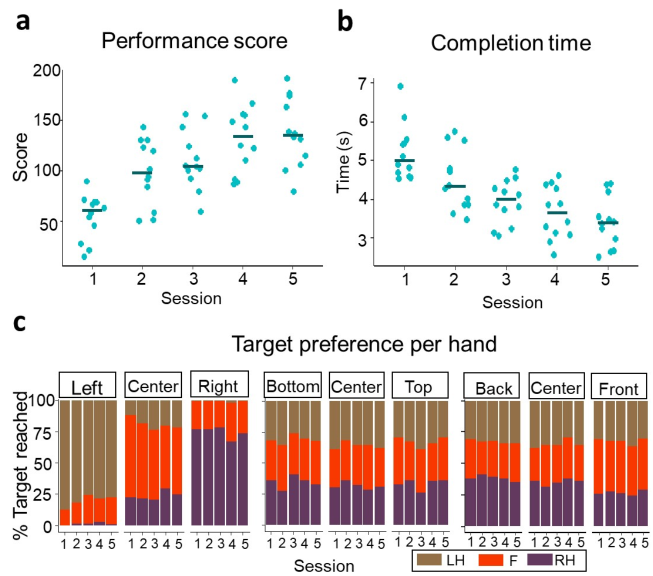

Fig. 2. The performance results for subjects in the independent task for the (a) score, (b) completion time and (c) target preference per hand (left panel show preference lateral direction; middle panel is vertical direction; right panel is longitudinal direction). LH-left hand, F-foot, RH-right hand.

mixed-effect linear fit for all statistical modeling involving the data for the dependent task.

We investigated the coordination patterns separately for each task. For the independent task, we analyzed the target preference ratio for each hand over all training sessions using a 3×3 repeated measures ART ANOVA on the factors of the limb and target choice. For the dependent task, we investigated the distance between each limb and the center of mass using a 5×3 repeated measures ANOVA with session and limb factors. The hand coordination between the two tasks was compared with 5×2×8 ART ANOVA with the condition as an in-between predictor, and two within factors being the session and the uni/bi/trimanual hand combination. The questionnaire data were analyzed with a 5×2 ART ANOVA with factors of session and training condition.

For each evaluation, to compare single conditions we conducted tailored post-hoc tests with the Holm-Bonferroni correction for multiple comparisons. For the parametric ANOVA we used t-test contrasts and for the ART ANOVA we used the Wilcoxon signed-rank test and Mann–Whitney U-test for paired or independent groups correspondingly.

III. Results

A. Independent trimanual task

The score and completion time for the independent task are shown in Fig. 2a,b. An ANOVA revealed that the session had an effect on the score ($F(4, 44) = 90.69$, $p < 0.0001$), where the score was higher after five weeks of training ($t(44) = -83$, $p < 0.0001$). It improved with every consequent session from the first to the fourth (all $p < 0.03$). A similar tendency was observed for the completion time: with the growing session number, subjects took less time

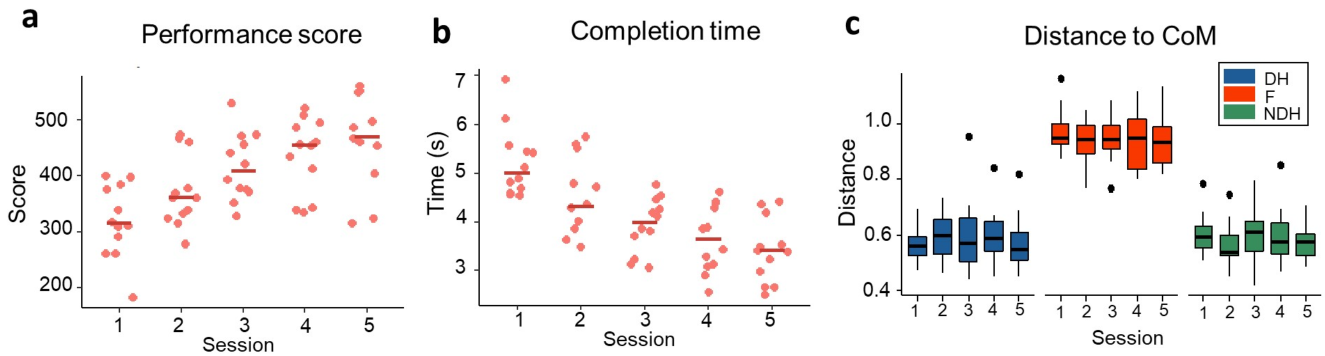

Fig. 3. The performance results of subjects in the dependent task for the a) score, b) normalized completion time and c) distance from each hand to center of mass. DH-dominant hand, F-foot, NDH-non-dominant hand.

to complete the task ($F(4, 44) = 25.43$, $p < 0.0001$). A post-hoc comparison showed that the time was reduced from session 1 to 5 ($t(44) = 1.986$, $p < 0.0001$). Furthermore, the most improvement was observed between sessions 1 and 2, as well as 2 and 3 (both $p < 0.0002$).

The target preference ratio was analyzed through the relative position of the limbs during the trials (see Fig. 2c). For the preferred x-axis positions, the targets on the right were more often chosen by the right hand (RH) than by the left hand (LH) or foot (F) (both $p < 0.0001$), also the F went more often to the right compared to the LH ($W = 1653$, $p < 0.0001$). Similarly, left targets were more frequently reached by the LH than by the other two limbs (both $p < 0.0001$). Furthermore, the F was used more to go to the left-placed targets than the RH ($W = 1770$, $p < 0.0001$). For the central targets, all limbs were used, however, clear differences were seen even for this placement: The F was used more often than RH ($W = 1666$, $p < 0.0001$) or LH ($W = 1722$, $p < 0.0001$), and the RH was used more than LH ($W = 522$, $p = 0.03$).

For the preferred y-axis positions, the targets on the back were more often chosen by the RH than by the LH or the F (both $p < 0.0005$). Moreover, the LH went more often to the back compared to the F ($W = 539$, $p = 0.46$). Similarly, front targets were more frequently reached by the F than by the other two limbs (F - LH: $W = 1396$, $p = 0.0012$ and F - RH: $W = 1636$, $p < 0.0001$). Furthermore, the LH was used more to go to the front-placed targets than the RH ($W = 1561$, $p < 0.0001$). For the central targets, the F was used less often than RH ($W = 378$, $p = 0.0004$) or LH ($W = 389$, $p = 0.0012$).

Finally, an interaction effect was observed between the limb and the target choice, showing an effect on which z-axis position subjects preferred ($F(4, 520) = 8.19$, $p < 0.0001$). Nothing was found concerning the bottom and top target positions. However, for the central targets, the LH was used more often than RH ($W = 1290$, $p = 0.0021$).

B. Dependent trimanual task

The score and the completion time for the dependent task are shown in Fig. 3a,b. Statistical analysis showed that, similar to the independent tasks, the score was influenced by the session number ($F(4, 43.06) = 30.67$, $p < 0.0001$). Indeed, after five weeks of training, the score was higher compared to the initial performance ($t(43.1) = -142.1$, $p < 0.0001$). Changes in the performance were also identified from session 1 to 2 and 2 to 3 (both $p < 0.01$). The normalized completion time also changed from session to session ($F(4, 43.04) = 28.09$, $p < 0.0001$): improvement was found from session 1 to 5 ($t(43.1) = 27.42$, $p < 0.0001$). Comparing consecutive sessions, a time reduction was found only between session 1 and 2 ($t(43) = 14.75$, $p = 0.0001$).

The distance from the limbs to CoM (see Fig. 3c) was relatively constant over the training and was not influenced by the session factor ($F(4, 151.25) = 0.44$, $p = 0.7770$) or the interaction between limb and session ($F(8, 151.06) = 0.48$, $p = 0.8669$). However, a difference was identified between the limbs ($F(2, 151.06) = 414.25$, $p < 0.0001$). The CoM - F distance was higher than the CoM - DH ($t(151) = 24.94$, $p < 0.0001$) and CoM - NDH ($t(151) = 24.92$, $p < 0.0001$) distances, no difference was found between DH and NDH ($t(151) = -0.019$, $p = 0.9846$).

C. Comparison

The interaction between the session and the task influenced the motion efficiency ($F(4, 87.08) = 10.59$, $p < 0.0001$) (see Fig. 4a). For each training session, the motion efficiency was larger for the independent task (all $p < 0.0002$). However, while in the dependent task the motion efficiency did not change during the training (session 1 - 5: $t(109) = 0.42$, $p = 0.6746$), subjects trained in the independent condition could reduce the distance from session 1 to 5 ($t(109) = 4.89$, $p < 0.0001$).

The motion efficiency for each limb was influenced by the interaction of the limb and the task ($F(2, 305.003) = 117.99$, $p < 0.0001$) as well as by the interaction of the task and session ($F(4, 305.268) = 5.850$, $p = 0.0002$) (see Fig. 4b). Subjects had relatively efficient motion in the common-goal task compared to independent-goal task with F and DH (F: $U = 285$, $p < 0.0001$; DH: $U = 1131$, $p = 0.0041$), no differences were found between the tasks for the NDH ($U = 1334$, $p = 0.0618$). However, the motion

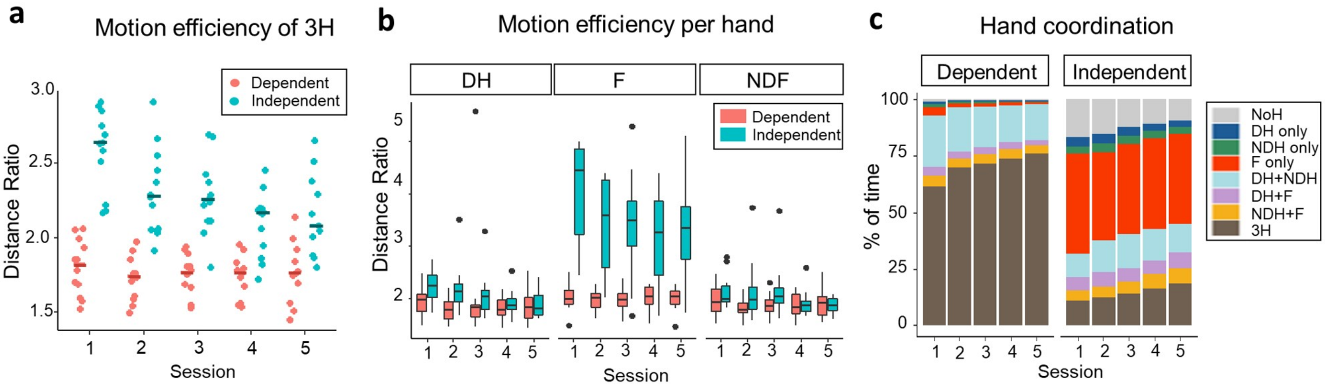

Fig. 4. The performance comparison between the independent and dependent operations on the motion efficiency of (a) the three hands together and (b) each hand, and (c) the coordination.

efficiency in the independent group improved over all limbs from session 1 to session 5 ($W = 599$, $p < 0.0001$), this improvement was not observed for the dependent task group ($W = 336$, $p = 0.6600$).

Moreover, in the independent task the motion was less efficient for F than DH ($W = 90$, $p < 0.0001$) or NDH ($W = 1730$, $p < 0.0001$) over all training sessions. The NDH and DH showed similar motion efficiency ($W = 994$, $p = 0.5630$). For the dependent task, the motion was less efficient for the foot than the DH ($W = 382$, $p = 0.001$) or NDH ($W = 1299$, $p = 0.008$). And interestingly, the NDH has more efficient motion than the DH ($W = 457$, $p = 0.005$).

Hand coordination (Fig. 5c) was influenced by the interaction of the hand combination and the task ($F(7, 850) = 550.73$, $p < 0.0001$), the interaction of the hand combination and the session ($F(28, 850) = 5.93$, $p < 0.0001$) and by the interaction of all three factors ($F(28, 850) = 4.12$, $p < 0.0001$). For the independent task, the percentage of time with active trimanipulation (3H) increased from the first to the last session ($W = 0, p = 0.0010$). A similar tendency was also observed for the dependent task ($W = 0$, $p = 0.0009$). Over all sessions, the percentage with active trimanipulation was higher for the dependent task than for the independent task ($W = 3540$, $p < 0.0001$).

D. Questionnaires

The perceived workload evaluated by the NASA-TLX questionnaire (Fig. 5) was influenced by the training session ($F(4, 87.1) = 13.65$, $p < 0.0001$) and the interaction between the session and the task ($F(4, 87.1) = 3.21$, $p = 0.0166$). Interestingly, the overall load for the independent task reduced from session 1 to session 5 ($W = 66$, $p = 0.0160$), while it was remaining unchanged for the group trained with the dependent task ($W = 51.5$, $p = 0.3270$). However, no differences in the score were found between both tasks at the first ($U = 93$, $p = 0.4720$) or the last sessions ($U = 52.5$, $p = 0.4720$).

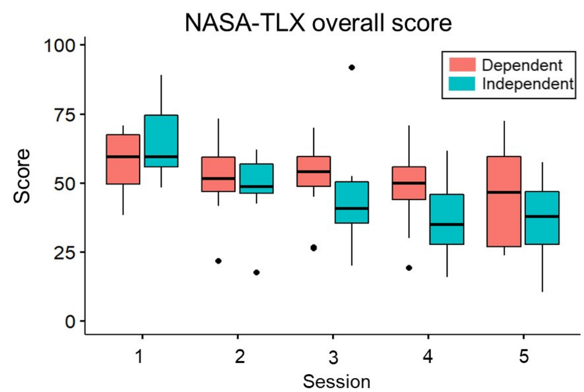

Fig. 5. NASA-TLX overall score.

IV. Discussion

In this paper, we studied the influence of three-DoF independent or dependent trimanual training tasks on multiple-hand coordination through a five-week experiment with 24 subjects. The results showed that both subject groups improved their task performance across the different sessions which is consistent with our previous study [15]. Critically while the task performance metrics showed improvement between the initial sessions, no clear difference was observed after session 4 for any metric, and only the independent task score showed improvement from session 3 to 4. This suggests that the motor skill performance may be saturated within five sessions, such that the experiment captures most of the learning dynamics.

However, it is unclear whether the improvements in the task performance were derived from improved coordination across all limbs or improvements specific to individual limb. The result of the hand coordination show that the portion of time spent coordinating all three limbs concurrently increased with practice for both groups. In the meanwhile, the motion efficiency per hand also improved with session for each type of limb control in the independent task. It is reasonable to assume that the task performance improvement may come from both trimanual coordination and single hand performance improvement.

Compared to the independent group, the dependent group did not show clear improvement in motion characteristic metrics such as the motion efficiency and subjective metrics of load. This may be because the independent task required continuous active use of each hand, while the dependent instead offered more flexibility on the control strategy e.g. the more skilled limbs could choose to compensate for the relatively unskilled limb. This can be observed from the results of the distance to the CoM where subjects favored the use of the natural hands since the CoM was found closer to the natural hands than the third hand. This strategy appeared to be consistent across all sessions.

Considering the motion pattern of the independent group, the findings are similar with our previous 2-DoF motion study [19], subjects predominately placed the left hand on the left, right hand on the right and foot controlled virtual hand in the center. The results extend this by considering preferred placement across all three dimensions. However, in contrast to clear pattern of x-axis, there are no clear preference and pattern for z-axis and y-axis.

V. Conclusion

Participants showed improvement in task performance for both the independent and dependent training groups that appeared to have saturated before the completion of the five-week training period. Different from training in the independent group, training with the dependent task did not appear to result in changes in motion characteristics.

Future work will look to address some limitations of the current study. First, the study currently only considers learning with respect to a subset of the possible trimanual tasks identified in [1]. To better understand learning across trimanual tasks this will be expanded to include the complete set of identified tasks, and will incorporate an evaluation of long-term retention and/or a test of skills for a transfer task. Second, the third VR hand in our setup was controlled by foot and a foot interface, it is still unknown how the third-hand control source and interfaces affect the operator's trimanual performance. The impact of third interfaces will be further investigated to ensure generalization of the results to other systems.

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References

[1] J. Eden, M. Bräcklein, J. I. Pereda, 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, p. 1345, 2022.

[2] F. Parietti and H. H. Asada, "Supernumerary robotic limbs for aircraft fuselage assembly: Body stabilization and guidance by bracing," in *IEEE International Conference on Robotics and Automation*, 2014, pp. 1176–1183.

[3] P. H. Nguyen, C. Sparks, S. G. Nuthi, N. M. Vale, and P. Polygerinos, "Soft poly-limbs: Toward a new paradigm of mobile manipulation for daily living tasks," *Soft Robotics*, vol. 6, no. 1, pp. 38–53, 2019.

[4] C. Véronneau, J. Denis, L.-P. Lebel, M. Denninger, V. Blanchard, A. Girard, and J.-S. Plante, "Multifunctional remotely actuated 3-dof supernumerary robotic arm based on magnetorheological clutches and hydrostatic transmission lines," *IEEE Robotics and Automation Letters*, vol. 5, no. 2, pp. 2546–2553, 2020.

[5] C. Xu, Y. Liu, and Z. Li, "Biomechtronic design of a supernumerary robotic limbs for industrial assembly," in *IEEE International Conference on Advanced Robotics and Mechatronics*, 2019, pp. 553–558.

[6] F. Zhong, P. Li, J. Shi, Z. Wang, J. Wu, J. Y. K. Chan, N. Leung, I. Leung, M. C. F. Tong, and Y.-H. Liu, "Foot-controlled robot-enabled endoscope manipulator (freedom) for sinus surgery: Design, control, and evaluation," *IEEE Transactions on Biomedical Engineering*, vol. 67, no. 6, pp. 1530–1541, 2020.

[7] M. Nurok, T. M. Sundt, and A. Frankel, "Teamwork and communication in the operating room: Relationship to discrete outcomes and research challenges," *Anesthesiology Clinics*, vol. 29, no. 1, pp. 1–11, 2011.

[8] L. Lingard, R. Reznick, S. Espin, G. Regehr, and I. DeVito, "Team communications in the operating room," *Academic Medicine*, vol. 77, pp. 232–237, 2002.

[9] 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.

[10] 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.

[11] E. Abdi, M. Bouri, E. Burdet, and H. Bleuler, "Development and comparison of foot interfaces for controlling a robotic arm in surgery," in *IEEE International Conference on Robotics and Biomimetics*, 2018, pp. 414–420.

[12] Y. Huang, E. Burdet, L. Cao, P. T. Phan, A. H. T. Meng, and L. Phee, "A subject-specific four-degree-of-freedom foot interface to control a surgical robot," *IEEE/ASME Transactions on Mechatronics*, vol. 25, no. 2, pp. 951–963, 2020.

[13] M. A. Guadagnoli and T. Lee, "Challenge point: a framework for conceptualizing the effects of various practice conditions in motor learning," *Journal of Motor Behavior*, vol. 36, no. 2, pp. 212–224, 2004.

[14] D. Nozaki, I. Kurtzer, and S. H. Scott, "Limited transfer of learning between unimanual and bimanual skills within the same limb," *Nature neuroscience*, vol. 9, no. 11, pp. 1364–1366, 2006.

[15] Y. Huang, J. Eden, E. Ivanova, S. J. Phee, and E. Burdet, "Trimanipulation: Evaluation of human performance in a 3-handed coordination task," in *IEEE International Conference on Systems, Man, and Cybernetics*, 2021.

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

[17] N. van Melick, B. M. Meddeler, T. J. Hoogeboom, M. W. G. Nijhuis-van der Sanden, and R. E. H. van Cingel, "How to determine leg dominance: The agreement between self-reported and observed performance in healthy adults," *PLoS ONE*, vol. 12, p. e0189876, 2017.

[18] S. G. Hart, "Nasa-task load index (nasa-tlx); 20 years later," *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, vol. 50, no. 9, pp. 904–908, 2006.

[19] Y. Huang, E. Ivanova, J. Eden, E. Burdet, and S. J. Phee, "Identification of multiple limbs coordination strategies in a three-goal independent task," *IEEE Transactions on Medical Robotics and Bionics*, 2021.