


Research article

Vibrotactile feedback improves performance in 3-coupled trimanual tasks

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ARTICLE INFO

Dataset link: <https://data.mendeley.com/datasets/jmccbz9cw8/1>

Keywords:

Human movement augmentation
Vibrotactile feedback
Supernumerary robotic limbs

ABSTRACT

Human Movement Augmentation (HMA) provides users with the means (e.g., supernumerary robotic limbs) to enhance their motor abilities with additional degrees of freedom, enabling trimanual tasks among other feats. While recently researchers have shown that humans may be capable of performing trimanual activities, the studies conducted so far on augmented tasks neglected a fundamental aspect of the sensorimotor loop, i.e., the sensory feedback related to supernumerary limbs. Hence, we investigated how supplementary vibrotactile feedback can impact on the performance while completing a trimanual task. We engaged participants in trimanual reaching tasks that could be completed either alone or in collaborating dyads, by using virtual effectors that could be differently coupled together through virtual elastic links. Performance indexes (i.e., score, fails, smoothness and effectors' coupling) demonstrated that vibrotactile feedback significantly improves participants' performance when the three effectors were virtually coupled together, and especially when participants were acting alone. This result is particularly relevant in the augmentation scenario, as it suggests that supplementary feedback can significantly aid the user who single-handedly controls a supernumerary limb.

1. Introduction

Human Movement Augmentation (HMA) has been the topic of science fiction for decades and it has recently become possible thanks to the development of Supernumerary Robotic Limbs (SRLs), along with a variety of techniques to efficiently control them [1,2].

Several studies have been conducted to design both the hardware and the related control and feedback approaches, but only recently researchers have started investigating the feasibility of augmentation tasks (e.g., trimanual tasks). These tasks are indeed more complex than common unimanual or bimanual tasks, since they require the coordination of three or more effectors, thus increasing the cognitive load and the need of attention for an efficient management of all the limbs. Yet, assessing the human ability to perform such tasks underlies the whole field of human movement augmentation.

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<https://doi.org/10.1016/j.heliyon.2025.e44008>

Received 20 June 2024; Received in revised form 24 September 2025; Accepted 30 September 2025

The few studies conducted in this respect showed that it seems possible for people to simultaneously control three limbs in a virtual environment [3,4], and in a demanding catching task to even achieve higher performance compared to using two hands, with negligible physical and mental efforts [5], especially after a prolonged training. While participants were found to generally achieve better performance in trimanual tasks by sharing the control of the three limbs with another individual, this performance gap significantly decreases when the three (virtual) limbs are mechanically coupled together [6]. Furthermore, following appropriate training, participants showed an improvement of their initial augmented skills [7] in trimanual tasks both with and without mechanical coupling among the limbs, achieving performance comparable to the one of two collaborating persons when all the three limbs are coupled together [8].

Although providing a valuable contribution to the knowledge of the human ability to perform augmented tasks, these studies neglect a fundamental aspect of the sensorimotor loop, i.e., the sensory feedback related to the supernumerary limb. Indeed, sensory feedback has proven to be essential in closing the sensorimotor control loop and improving motor performance [9–11].

When concerning our natural body, the central nervous system plans movements according to an internal model which is built by the brain to describe the relationship between the body and the environment [12]. As the dynamics of the body itself or the external environment change, the brain adjusts this internal model to maintain motor performance. These essential adjustments are made according to the feedback, which comes from sensory receptors [13].

However, supernumerary robotic limbs cannot naturally provide proprioceptive or haptic signals, and their control so far relied mostly on vision to close the sensorimotor loop. Nevertheless, during manipulation, the vision is typically focused on the task itself, rather than the arms' movements and postures, and the need of visual feedback from the SRL might instead constitute an additional cognitive load, as reported by patients with proprioceptive impairment [14,15]. Moreover, vision could be very easily occluded in a real-life applicative scenario because of moving objects; in most cases, it provides poor information, if any, on the interaction forces; and it has proven to be almost discarded in favour of proprioception in some direction of the space [16]. Similarly, auditory feedback, while an interesting option for alarms or for signalling meaningful events, would be a cognitive cumbersome cue if used continuously. Auditory feedback would also present other drawbacks, similar to visual feedback: for example, in a real-life applicative scenario, it could interfere with sounds coming from the environment, which could be potentially dangerous for the user. Thus, delivering supplementary feedback that carries information on the state of the supernumerary limb becomes extremely important [17], especially to regulate the interaction forces exerted by the SRL on the environment, even when the SRL is worn in contact with the user's body, as proven in [18].

Therefore, in this work, we aim to address the relevance of supplementary haptic feedback in human augmentation, since haptics exploit a more discreet sensory channel, whose information travels along our nervous fibers faster than other sensory modalities, such as vision [19]. Specifically, we investigated how the vibrotactile feedback affects the performance in trimanual reaching tasks where virtual effectors could be differently coupled together and where participants could be either acting alone or collaborating with a partner [6].

Vibrotactile feedback was chosen because it is painless and can be easily modulated and delivered, since it does not require a subject-specific calibration (as it happens with electrotactile feedback). Additionally, vibrotactile feedback has proven to be effective as supplementary feedback to improve motor control and motor learning in both healthy and impaired people [20–22]. Moreover, while it could provoke adaptation in the long run, our extensive experience with this vibrotactile feedback has proven that it is never the case when continuous stimulation is frequently interrupted, as in experimental protocol when switching between trials [17,23,24]. The interested reader can find a detailed discussion of different types of supplementary sensory feedback in a recent review published by our group [25].

We delivered supplementary feedback in the form of a vibrotactile stimulation encoding, with different patterns, the force applied to the effectors by the virtual mechanical coupling, the event of the breaking of this link and the collision between effectors. We evaluated the effect of the supplementary feedback on task performance, both in terms of task-specific indexes (e.g., score) and motion characteristics (e.g., smoothness); moreover, we collected several physiological measures (such as electrocardiography, breathing frequency and electrodermal activity) to monitor the physical and cognitive burden caused by the augmented task, and to compare such measures with the subjective perception of enjoyment, difficulty and workload assessed through questionnaires.

2. Results

We tested here the effect of vibrotactile feedback on human performance during trimanual tasks. 20 healthy participants performed three different 2D tasks, named *Uncoupled*, *2-Coupled* and *3-Coupled*, which required to reach three, two or one independent targets, respectively (see Fig. 1 A). To complete the tasks, participants controlled three virtual limbs by moving their hands and dominant foot, tracked via infrared cameras. The three tasks represent different real-world scenarios where coordinated multi-limb interaction is required [26]. For example: the uncoupled task corresponds to multi-object pick and place; the 2-coupled task can be observed when holding a tray while opening a door with the third arm; the 3-coupled task is relevant when holding and manipulating a particularly large and fragile object, such as a TV screen or a painted canvas. The “coupled” tasks presented additional mechanical constraints, i.e., a virtual elastic band that links the virtual effectors (the two hands in the 2-coupled task or the two hands and the foot in the 3-coupled task). Indeed, besides target reaching, these coupled tasks required the preservation of such a virtual mechanical constraint, by keeping the limbs' distance within a defined range. If the distance exceeds this range, the virtual elastic bands break, and the score is decreased by one point.

As in previous studies, we compared the performance of participants controlling the three limbs alone, with the performance of dyads sharing the control of the effectors (one participant controls the hands while the other controls the foot; see Fig. 1 B), to assess

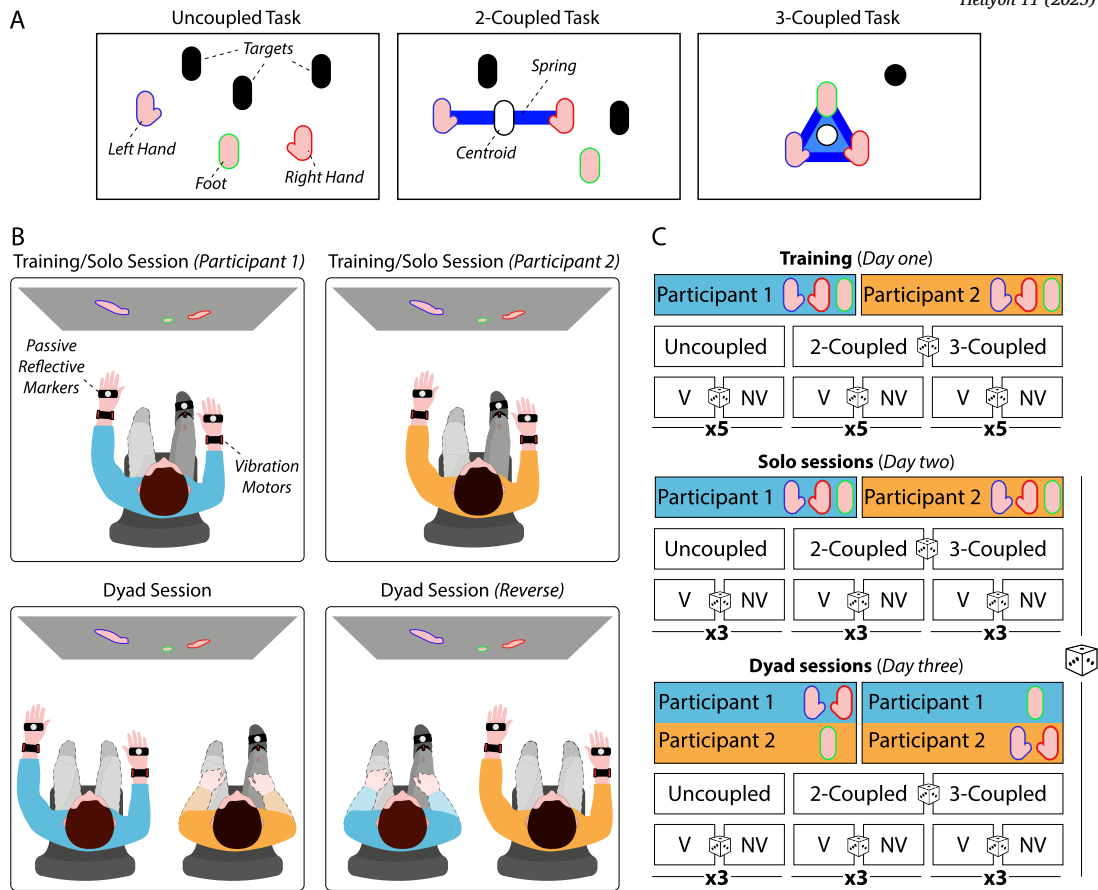


Fig. 1. Experimental setup and protocol. Panel A shows experimental conditions of the three trimanual tasks (Uncoupled, 2-coupled and 3-coupled). Virtual effectors were controlled with left hand, right hand and foot. The blue band represented the virtual elastic band connecting the effectors, which could be extended or compressed up to the breaking point. Black shapes represent targets that had to be reached with the virtual effectors (in Uncoupled) or with the centroid of the virtual elastic band (in 2-coupled and 3-coupled), represented by the white shape. Panel B shows experimental sessions. Each participant completed a training and solo session (with full control of the effectors) and two dyad sessions with the partner (shared control), in which their control roles were reversed. To increase visual clarity of the figure, limbs not involved in the task are outlined with a dotted line. Each couple of vibrator motors was used to encode information on the virtual force exerted by the elastic band connected with the respective effector (one motor for compression force, the other one for extension force). Panel C shows the experimental protocol. Effector icons show which effector participants were able to control during each session. Dice icons indicate a random condition order. Uncoupled condition was always performed first. “V” and “NV” letters indicate the presence or absence of vibrotactile feedback, respectively. Numbers below blocks show how many repetitions (i.e., trials) were performed. Solo and Dyad sessions were performed in a pseudo-randomized order among participants. The familiarization carried out during the first day is not shown in the figure for clarity purposes.

whether the inclusion of the feedback affects motor outcomes differently in the two cases. The foot-driven control is coherent with the concept of augmentation by transfer, which allows to easily achieve movement augmentation without intense training, by exploiting the motion of a body part not directly involved in the task [1]. Each participant performed a training session on the first day [8], followed by the solo and dyadic sessions in random order on days two and three (see Fig. 1 C).

In half of the total trials, participants were provided with vibrotactile feedback (represented in Fig. 1 C with the letter “V”) [23] through pairs of eccentric rotating mass (ERM) motors placed on the wrists and ankle of the controlling limbs (see Fig. 1 B). The supplementary feedback conveyed the amount of elastic force exerted on each virtual limb in the coupled tasks, encoded in terms of vibration intensity, i.e., the higher the force exerted, the higher the intensity. Additionally, single or multiple vibration bursts were provided in the case of collision among virtual limbs or elastic band breaking, respectively. More details are provided in the Methods section.

Performance was evaluated in terms of score (number of sets of targets successfully reached minus the number of fails), fails (number of times the virtual band has been broken for overcompression or overextension), average variation of the virtual elastic band length and smoothness of each virtual limb movement.

Since the supplementary feedback conveys diverse information in diverse tasks, its effect on the performance was analyzed separately for each task through repeated measures ANOVA. In fact, while in the uncoupled task the vibrotactile feedback only provides an alert signal in case of effectors’ collision, it becomes richer in the 2-coupled task, where the vibrators continuously transduce the elastic force applied on the effectors by one spring, as well as in the 3-coupled task where the feedback conveys the elastic force exerted by three different springs.

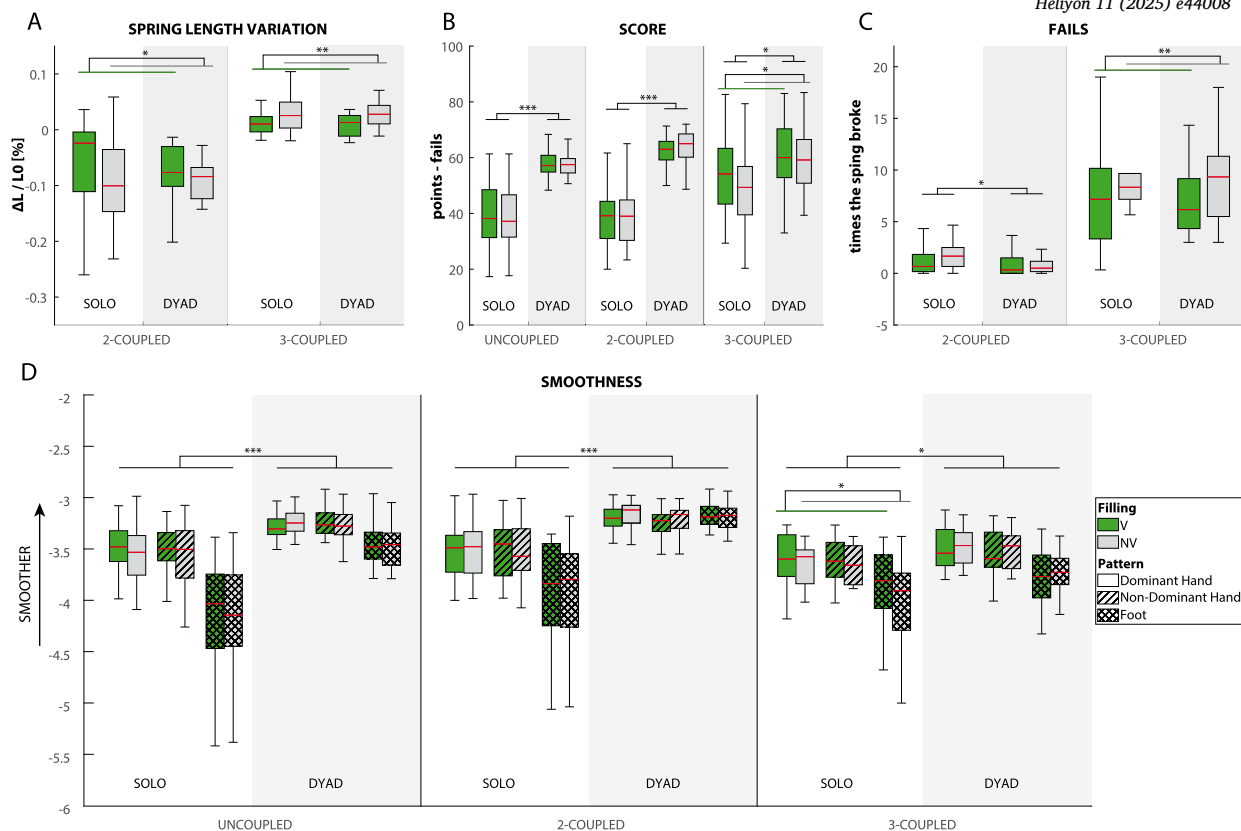


Fig. 2. Performance obtained by participants during tasks. The figure shows the average length variation of the virtual elastic band (Panel A), where negative values indicate a compression and positive values an extension of the virtual band; the score (Panel B); fails (Panel C), meant as the number of times the virtual elastic band broke due to overcompression or overextension; smoothness (Panel D) of participants movements in controlling the effectors. All measures reported are dimensionless and they are averaged across trials. The sample size is $n=20$. In all panels, green filling indicates trials with vibrotactile feedback, while grey filling without and the red lines indicate the median. In panel D, the absence of a filling pattern indicates performance obtained by controlling an effector with the dominant hand, the single-lined filling indicates a non-dominant hand and the crossed filling indicates the foot. Asterisks indicate a p-value <0.05 (*), <0.01 (**) and <0.001 (***).

Additionally, physiological measurements (i.e., heart rate, heart rate variability, breathing rate and electrodermal activity) were collected throughout the whole study and normalized with respect to a baseline condition (during which participants were asked to sit still and relax, with their eyes closed, for two minutes) recorded ahead of each session.

Perceived enjoyment, difficulty, overall workload and vibration usefulness were evaluated through questionnaires, and analyzed through Friedman, comparing the three tasks performed within each session among each other, and the sessions among each other, the task being equal.

2.1. Game performance

Overall, dyads outperformed solo participants in all the tasks and most of the evaluated metrics, even though this effect was much less pronounced in the 3-coupled task. Most importantly, providing vibrotactile feedback improved the performance of participants in all metrics during the 3-coupled task.

Specifically, the feedback significantly improved the **score** ($F=10$, $p=0.012$) and reduced the number of **fails** ($F=20$, $p=0.002$) compared to no-feedback condition, in the 3-coupled task (see Fig. 2). In particular, within the solo session the score increased on average by 5.87 points, i.e., by the 13% and the fails decreased on average by 2.15 times, which corresponds to a 22% decrement. Moreover, the vibrotactile feedback improved the **smoothness** in the solo session of the 3-coupled task ($p=0.035$, Bonferroni correction used for multiple comparisons; improved by 3% on average).

The feedback significantly impacted the **average length variation** of the virtual elastic band (Fig. 2 A), in both the tasks with virtual elastic coupling. Indeed, the vibrotactile feedback helped participants maintain the virtual elastic band length and avoid both its compression and extension, compared to the no-feedback condition, in the 2-coupled ($F=6$, $p=0.041$) and the 3-coupled task ($F=15$, $p=0.004$). On average the length variation decreased by 2%, although this value is likely flattened as it results from successive means among conditions and participants, in turn obtained from the average along both the whole trial duration of 100 seconds and the total number of trials. Except for the average length variation, providing feedback did not affect the performance in the uncoupled and 2-coupled tasks.

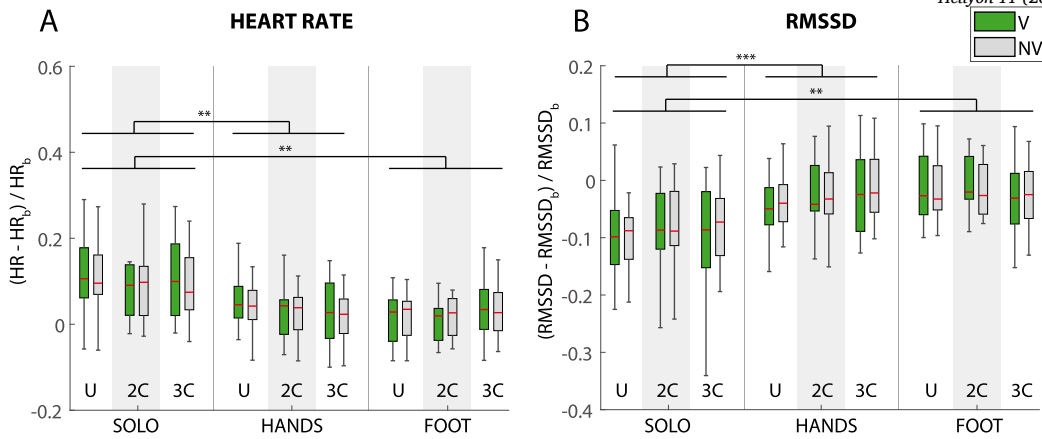


Fig. 3. Physiological measures. Panel A shows the heart rate of participants during tasks while Panel B shows the heart rate variability expressed as the root mean square of the standard deviation (RMSSD). Both measures are normalized with respect to the baseline as value = (measure-baseline)/baseline. Thus, measures represent the percentage variation with respect to the baseline. The sample size is $n = 20$. In both panels, green filling indicates trials with vibrotactile feedback, while grey filling without and the red lines indicate the median. Asterisks indicate a p -value $< 0,01$ (**) and $< 0,001$ (***).

Participants, in general, obtained higher **score** (see Fig. 2 B) in dyad condition compared to solo, and this gap resulted smaller in the 3-coupled task ($F = 10$, $p = 0.011$) compared to the uncoupled ($F = 62$, $p < 0.001$) and 2-coupled ($F = 75$, $p < 0.001$) ones.

Considering the number of **fails** (Fig. 2 C), i.e., times the virtual elastic band broke for overcompression or overextension, we found no significant difference between solo and dyad sessions in the 3-coupled task, while in the 2-coupled task, participants obtained more fails during solo compared to dyads ($F = 6.36$, $p = 0.033$).

Similarly to the score, participants showed higher **smoothness** (see Fig. 2 D), when working in dyads compared to solo session in the uncoupled ($F = 49$, $p < 0.001$), 2-coupled ($F = 40$ and $p < 0.001$) and 3-coupled ($F = 10$, $p = 0.011$) tasks.

No significant differences emerged between solo and dyad concerning the average length variation. It is worth noting how participants tended to compress the band in the 2-coupled task (negative values of the variation $\Delta L/L_0$, with L and L_0 the actual and initial length) and to extend it in the 3-coupled task (positive values).

2.2. Physiological measures

Physiological measurements were analyzed in terms of heart rate, heart rate variability (evaluated as RMSSD [27]), breathing rate and skin conductance, all normalized with respect to the corresponding average baseline value. We evaluated the results through the Generalized Linear Mixed-Effect model (due to the number of factors to take into account in this analysis) considering the session (solo, dyad controlling hands, dyad controlling foot), the feedback (vibrotactile or without vibrotactile) and the task (uncoupled, 2-coupled and 3-coupled) as fixed effects and the participants as a random effect.

No significant differences emerged among fixed factors in terms of **breathing frequency** or **skin conductance**. Conversely, both the **heart rate** ($p = 0.004$) and the RMSSD ($p = 0.001$) show an effect of the session, as depicted in Fig. 3 A and B, respectively. In particular, participants increased their heart rate during the solo session, compared to the dyadic sessions, regardless of whether they controlled the hands ($p = 0.001$) or the foot ($p < 0.001$). No significant difference emerged between the two dyadic sessions. Accordingly, the RMSSD decreased (thus suggesting a state of high focus/stress/arousal [27]) in the solo session compared to the dyad session controlling the hands ($p < 0.001$) and the dyad session controlling the foot ($p < 0.001$).

2.3. Subjective perception

Participants provided in general high enjoyment scores for all the tasks, with no differences among the sessions or the tasks (see Fig. 4 A-B).

The vibration was found useful in all the sessions when performing the 3-coupled task, but only in the solo and dyad-hand session in the 2-coupled task and not useful at all in the uncoupled one (see Fig. 4 C-D). Specifically, in the coupled tasks, vibration usefulness was perceived as higher both in the solo session (all $p < 0.007$) and in the dyad when controlling the hands (all $p < 0.023$). Conversely, in the dyad when controlling the foot, the feedback was perceived as more useful in the 3-coupled task compared to the others (all $p < 0.046$).

Interestingly, participants perceived the difficulty increasing from the uncoupled task, to the coupled ones (Fig. 4 E-F). In particular, when performing the task alone they refer to the uncoupled task as the least difficult (all $p < 0.048$), with no significant differences between the two coupled ones. When sharing the control they perceived the 3-coupled task as the most difficult one (all $p < 0.044$).

In the solo session, participants did not perceive significant differences between the 2-coupled and 3-coupled tasks for any of the considered metrics. On the other hand, they perceived both the coupled tasks as more demanding in terms of difficulty and overall workload compared to the uncoupled one (Fig. 4 G-H).

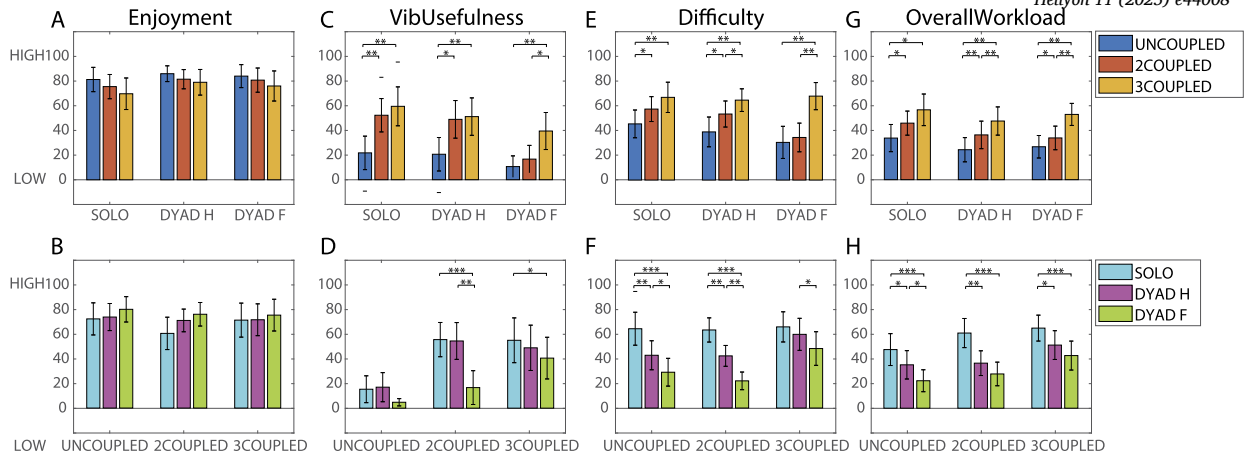


Fig. 4. Questionnaires. The top row shows the average evaluation participants provided after each session for the three tasks performed; the bottom row shows their evaluation at the end of the experimental protocol to assess each task across the different sessions. Participants scored the Enjoyment (A and B), the usefulness of the vibrotactile feedback (C and D), the perceived difficulty (E and F) and the overall Workload (G and H), with values ranging from 0 (low) to 100 (high). Colored bars represent average values and error bars show the 95% confidence intervals. The sample size is $n=20$. Results were analyzed through Friedman test within each session/task and Bonferroni correction was used for multiple comparisons among tasks/sessions, respectively. Asterisks indicate a p-value <0.05 (*), <0.01 (**) and <0.001 (***).

In general, in both the uncoupled and 2-coupled tasks, the solo session resulted to be the most difficult and demanding. The 3-coupled task represented instead the case in which the least difference was perceived among the sessions, except the solo was perceived as more demanding in terms of overall workload.

3. Discussion

In this work, we tested the effect of vibrotactile feedback on human performance in trimanual tasks. Overall, we confirmed previous results found in [6] by showing that i) dyads generally outperform participants who control the three limbs on their own and ii) 3-coupled task allows for the highest performance compared to other tasks and the lowest gap in performance between solo and dyads.

We demonstrated a significant improvement in the 3-coupled task performance when the vibrotactile feedback was provided. This outcome represents a solid finding recurring in several indexes such as score, length variation of the virtual elastic band, number of fails and smoothness.

It is worth noting how the feedback benefits emerge particularly in the management of the virtual physical interaction, i.e., when dealing with the virtual spring. This is evident from the reduced number of fails in the 3-coupled task and the reduced variation of the spring length even in the 2-coupled task. Importantly, for some indexes such as the smoothness, the vibrotactile feedback showed a useful impact only in the solo session, suggesting that this feedback could be particularly useful in the augmentation scenario, in which a single user is required to perform augmented (e.g., trimanual) tasks, controlling three effectors, alone.

Differently from what showed in previous literature, as in [8], the initial training did not allow solo participants to reach the performance level of dyads. This can be due to the different approaches used for the training in the two studies. Indeed, in our case, the training involved three different tasks and part of it was dedicated to becoming confident with the vibrotactile feedback. This means the individual amount of time assigned to the 3-coupled training only was lower than in [8] and, thus, probably not sufficient for reaching a plateau in performance similar to dyads. In total, the net training duration was less than 1 hour, including all three tasks and different conditions. Although such short amount did not induce sufficient learning to level solo and dyad performance as in [8], it was enough to observe the significant improvement achieved with the vibrotactile feedback.

Summing up, when performing trimanual tasks which involve physical constraints like the 3-coupled task, providing vibrotactile feedback significantly improves the performance in several respects. These findings point out the importance of providing supplementary feedback (e.g., vibrotactile) when dealing with physical interactions in augmented tasks. In other words, our results suggest that the design of SRLs, and in general interfaces for HMA, should embed haptic feedback to convey the interaction forces of the supernumerary effector to guarantee good performance in augmented tasks involving physical interactions and constraints.

At first glance, this might seem in contrast with previous attempts in the control of an extra virtual limb where supplementary feedback did not improve the performance [28]. However, despite the intended application in augmentation contexts, Dominijanni and colleagues tested their platform in unimanual and bimanual tasks rather than in actual trimanual tasks. We reckon that this aspect and the limitations of their control approach (e.g., limited number of controlled DoFs, latency and encoded feedback information) might be the main reason haptic feedback did not produce significant improvements in their case. In [18] instead, users regulated the SRL interaction force (along one direction) significantly better when provided with vibrotactile feedback, compared to relying solely on the inherent feedback from physical contact between the worn SRL and the users' body. Our results support these findings, i.e., the

relevance of supplementary feedback when the SRL physically interacts with the environment, and extend them to a 2D trimanual task.

A further contribution of the present work is the assessment of the physical and cognitive burden through quantitative physiological measures. As expected, the electrocardiographic signal shows that trimanual tasks are more demanding and challenging when performed alone rather than in partnership with someone else (regardless of the controlled limb/s). However, other physiological indexes collected here, such as skin conductance response and breathing frequency, do not show any statistical significant difference. It is worth noting that both these signals were particularly affected by noise and motion artefacts during the data collection, requiring the exclusion of several trials in the data analysis. Thus, further analyses with a bigger amount of data are necessary to deepen this aspect.

Contrarily, and contrary to what ECG data suggest, participants perceived the 3-coupled task as the most difficult and demanding and the uncoupled task as the easiest and the most enjoyable. This result is in contrast with our previous study [6] and also opposite to the quantitative measures of performance. This could be due to the slight difference with respect to the previous work concerning the scaling between the real and virtual limbs' movements. Specifically, in the present study, participants had to perform bigger movements with their hands. This choice was made to perform motions more similar to a real task, where the two hands have to cover quite a big workspace, whereas the foot movement, used for the SRA control, can be scaled and reduced to avoid fatigue. This aspect may have somehow made the 3-coupled task more difficult compared to the previous work due to the higher coordination required among the limbs covering different distances. Conversely, the uncoupled task may have been perceived as easier and thus performed with less attention, leading to worse performance.

Future studies should address similar tasks in real scenarios with supernumerary robotic limbs, focusing on the actions involving physical interactions, in which information related to contact forces (conveyed through haptic - e.g., vibrotactile - feedback) may play a critical role in the augmented sensorimotor loop. Furthermore, more effective training approaches should be investigated, considering the differences between virtual and real environments.

4. Methods

4.1. Experimental setup

The participants were comfortably seated on a chair positioned in the centre of a metallic structure equipped with 6 infrared cameras (Prime 13W by OptiTrack) operated with Motive software (NaturalPoint, Corvallis, Oregon, USA). Passive reflective markers were placed on participants' hands and dominant foot (determined according to the ball-kick dominant leg test [29]) so that cameras could track their movements. To avoid foot fatigue, the foot was also fixed to a slippery shoe liner which allows it to easily slide on the floor. Foot was selected as a controller for moving the third effector because lower limb movements are one of the most commonly employed control approaches in human augmentation [3,4,30], leading to good performance with a relatively short training time, even in dexterous and complex tasks such as laparoscopy [31]. Indeed, previous work in HMA demonstrated that other, more complex approaches (e.g., based on neural signals), although promising, at present lead to poor performance and require extensive training and calibration [32].

Each participant wore a Zephyr BioHarness 3™ (Zephyr Technology Corporation, Annapolis, MD, US) used to acquire their electrocardiographic (ECG) signal and respiratory frequency, with a sampling rate of 250 Hz and 18 Hz, respectively. The skin conductance (SC) was recorded with a sampling frequency of 16 Hz using a Shimmer3 GSR+ Unit (Shimmer, Dublin, Ireland) with electrodes placed on the index and middle finger of the right hand of each participant.

The vibrotactile system developed in [23] was employed to provide vibrotactile feedback. Although used in [23] with 2 pairs of motors, this system allows to control up to eight pairs of Eccentric Rotating Mass motors (ERM, Model: 307-103 by Precision Microdrives Inc.). In the present study we used three pairs of motors, which were placed on the wrists and the ankle of the dominant foot (Fig. 1B). Within each couple of motors, only one could be activated at a time. It is worth noting that ERMs were chosen for their affordability, compactness, and wearability, ensuring reliable feedback without restricting movement. Although they lack independent control of frequency and amplitude, they are more practical than bulkier, expensive voice coils, which are better suited for static studies. Given the focus of this study on movement performance, ERMs provide an effective solution.

The 2D task, developed in C# language and Unity3D environment, was projected onto a wall facing the participants. Three virtual cursors (Fig. 1) were designed as smoothed hand-shaped rectangles of different colours. The participants could control the cursors' position by moving their real limbs on the horizontal plane. A lateral limb movement produced lateral movements of the virtual effectors (i.e., along the horizontal axis), whereas moving limbs away and toward the body produced up and down effectors' movements (i.e., along the vertical axis of the screen), as it normally happens with a mouse cursor. Real limbs up and down movements were not constrained, but they did not produce any movement of the virtual cursors and participants quickly learned to minimize them. The virtual cursors were allowed to move throughout the whole screen and targets were limited to appear in a centred 30 cm × 30 cm square (referred to the virtual coordinate system) in order to have the same range on both axes. Before starting the experiment, the height of each participant was recorded and used to personalize the scaling factors both for hands ($S_h = 0.21 h/SD$) and foot ($S_f = 0.164 h/SD$) movements, where h represents the subject's height and SD is a parameter associated with screen size intended to facilitate the subject's ability to reach all points in the space. The remaining constants are obtained from average anthropometric values corresponding to the length of the arm and the lower leg, normalized to the height [33]. At the beginning of each trial, participants could start with their limbs at the most comfortable distance, which was equal to 10 cm in the virtual environment but not constrained in the real world.

4.2. Trimanual tasks

The task was a two-dimensional (i.e., only planar translations without rotations) trimanual reaching task where three virtual cursors had to be properly moved by one (i.e., *solo session*) or two collaborating participants (*dyad session*). In each session, three tasks corresponding to different mechanical constraints (i.e., virtual coupling between cursors) and different numbers of concurrent objectives (i.e., targets to reach) were evaluated:

- *Uncoupled* (U): participants have to reach three different targets independently moving their hands and dominant foot (Fig. 1A, left); no clue is provided on which limb has to reach which target, although the trial is successful if at the same time each target is covered by one cursor. Each set of 3 concurrent targets reached increases the score by one point.
- *2-coupled* (2C): the cursors controlled with the hands are coupled through a virtual spring whose centroid has to be moved on one target while the foot reaches for the second target (Fig. 1A, centre). The two hands have to be simultaneously moved to avoid excessive compression/extension (i.e., more than 30%) of the virtual spring, otherwise the band breaks and a penalty is given (each fail decreases the score by one point).
- *3-coupled* (3C): all three cursors are coupled together via a virtual triangular elastic band (Fig. 1A, right); participants have to bring the centroid of the elastic band on one single target. Similarly to the 2C, all three virtual springs must avoid excessive changes in length (i.e., in the range of $\pm 30\%$ variations). Overcompression and overextension cause the breaking of the spring and the score decreases by one point.

The choice of these three tasks derives, in general, from the selection of the three most representative different conditions of the diverse coordination types in the case of manipulation with three limbs [1]. Moreover, it allows the comparison with previous studies which employed equal or similar tasks [6–8].

It is worth noting that the aforementioned coupling was not a physical connection between the real hands or hands and foot, but instead, it was a virtual elastic band presented in the virtual scenario only (Fig. 1). This band was visualized as a blue segment which changed in thickness and colour depending on the amount of their extension or compression, i.e., the higher the extension, the thinner the band and lighter the colour and vice-versa.

A target was considered reached when the distance between it and the cursor was less than 1 cm (measured in the virtual reference system). However, to succeed participants had to catch simultaneously all the targets presented at once. Each time they succeeded, their score increased by one point and a “coin” sound was played as a reward. Conversely, if they broke the virtual spring the score decreased by one point and a “buzzer” sound effect was played.

Each task repetition (trial) lasted 100 seconds, during which participants had to reach as many target sets as possible. Participants had a maximum of 3 seconds to reach each set of targets. After that time (or as soon as they reach all the targets shown) targets’ position randomly changed. The timeout did not affect the score.

4.3. Vibrotactile feedback

The pivotal novelty with respect to the previous work [6] is the presence of vibrotactile feedback encoding information about physical interactions, not perceivable through the virtual environment. A similar approach showed control performance improvements in HMA context, although with different hardware [34]. In particular, the feedback encoded the following information:

- *Virtual elastic force* (present in 2-coupled and 3-coupled): when the virtual spring is compressed or extended, the resulting elastic force applied to the connected cursors is fed back to the corresponding real limb through a vibration whose intensity is proportional to the magnitude of the force. Depending on the force direction, a different motor within each pair is activated (i.e., the medial motor corresponds to spring compression, whereas the lateral motor to the spring extension). In the 3-coupled task, we considered the resulting force acting on each cursor. For example, in the 2-coupled task, if the hands’ cursors maintain their initial distance (spring neither compressed nor extended), no feedback is provided. If their distance increase, causing an extension of the virtual spring, the two ERMs on the lateral side of the wrists start vibrating with an intensity proportional to the amount of the extension, i.e., the elastic force.
- *Collision between cursors* (present in all tasks): when two cursors overlap during their motion, the participant is provided with a 500 ms vibration with high intensity on the correspondent limb. For example, if the right hand cursor collides with the foot cursor, one ERM on the right hand and one ERM on the ankle provide a single burst of vibration. The 500 ms duration was empirically determined to provide a distinctly perceptible vibration while preventing habituation or discomfort.
- *Elastic band breaking* (present in 2-coupled and 3-coupled): when the participant breaks the virtual elastic band the failure is fed back through a 1-second train of ERM’s burst vibration with high intensity on the limbs connected to the spring.

Vibration amplitude and frequency are coupled. When conveying the occurrence of discrete interaction events such as a collision or the band breaking, the vibration frequency was set to 250 Hz, which corresponded to the highest value the ERMs could reach and to the optimal frequency for human tactile perception [35]. When conveying the elastic force exerted by the virtual springs, the vibration intensity varied proportionally between 0 and 250 Hz, where the minimum value corresponds to a null elastic force and the maximum value to the spring breaking. According to the sign of the force acting on each cursor, we activated either the medial or

lateral ERM of the corresponding limb. The frequency range for the vibration covers the one perceivable by the human skin receptors [36].

It is worth underlying how, due to the diverse nature of the constraints in the three tasks, the feedback conveys diverse information from one task to the others (i.e., in the uncoupled task there are no mechanical constraints, thus no virtual elastic forces acting on the cursors and thereby no feedback related to such information).

4.4. Experimental protocol

Twenty healthy participants (aged 26.34 ± 6.6 years, 14 women, 18 right-handed), randomly organized into dyads, were enrolled in the study after having provided written informed consent. The experimental protocol was conducted according to the Declaration of Helsinki and approved by the Ethical Committee of Università Campus Bio-Medico di Roma (HUROB protocol).

The experiment was performed in 3 different days as detailed below:

Day 1: Familiarization. This phase consists of three exercises to make participants confident with the setup and the tasks:

- 1) Participants are asked to reach a single target with a specific limb. They can independently control the 3 cursors with their hands and foot. One target at a time is presented with the shape and colour of the cursor that should be used to reach it. If it is not reached within 3 seconds it changes colour and location. The exercise lasts 100 seconds and it is repeated twice.
- 2) Participants control the two hands virtually coupled together. They are asked to extend and compress the virtual spring according to displayed instructions while paying attention to the corresponding vibrotactile feedback. All possible spring states are presented (i.e., extension, compression and spring breaking). This phase lasts 100 seconds.
- 3) Similarly to exercise 2, participants experience the spring deformation and related feedback, but in the case of 3 cursors coupled through the triangular elastic band. All springs configurations are experienced by the participant.

Training. Each participant performs a training session consisting of the three main tasks (uncoupled, 2-coupled and 3-coupled) described above. The three tasks were repeated ten times each (the single repetition, lasting 100 seconds, is hereafter called *trial*), of which five with the vibrotactile feedback and five without, in a pseudo-random order (permuted block randomization).

Day 2: Solo. Similar to the training, in the solo session each participant performs the tasks alone, controlling the movement of all three cursors. Each task is repeated six times (i.e., three times with vibrotactile feedback and three without, in a pseudo-random order).

Day 3: Dyad. Participants perform the tasks in dyads, sharing the control of the three limbs. The session is repeated twice, first with *participant 1* controlling the hands and *participant 2* controlling the foot, and then vice-versa (see Fig. 1 B). Likely to the solo session, for each dyad's session they repeat each task six times, three of which with the vibrotactile feedback.

Familiarization and training sessions were always performed first, while the order of Solo and Dyad sessions on day 2 and day 3 was pseudo-randomized. Half of the dyads started with the Dyad session on day 2, followed by the Solo session on day 3 and vice-versa for the rest of the participants. Within sessions, the uncoupled task was always performed first, to avoid any bias in limbs' control due to the virtual coupling, whereas the 2-coupled and 3-coupled were completed in random order. The order of the tasks, as well as the order of the trials with vibrotactile feedback, was kept constant throughout all the sessions (i.e., solo and dyad) for the members of the same dyad. To rule out the seating position from having an effect, participants kept the same chair during all sessions. Participants were not allowed to verbally communicate throughout the session. It is worth noting there was no difference between the training and the main experimental tasks, except for the number of repetitions completed. The training aimed at participants learning the tasks and the feedback, while potentially improving their augmented motor skills as in [7,8].

4.5. Data analysis

We evaluated different measures to assess the participants' skills (e.g., task performances, motion characteristics, etc.), arousal level (e.g., heart rate, etc.) and subjective experience (e.g., questionnaires).

The performance measures include:

- **Score:** the total number of sets of targets successfully reached in one trial, minus the total number of fails in the same trial.
- **Fails:** the number of times the participant breaks at least one virtual elastic band (this measure only applies to the 2-coupled and 3-coupled tasks) during one trial.
- **Smoothness:** the spectral arc length of each cursor's velocity [37].
- **Spring length variation:** the root mean square (RMS) of the virtual spring's length variation at each time point divided by the initial spring's length. This measure was only considered in the 2-coupled and the 3-coupled (here, as average among the three virtual springs).

The selected metrics allow us to evaluate participants' performance from diverse points of view: score and fails show participants' ability to complete the tasks according to their requirements and constraints; on the other side, spring length variation and smoothness reveal participants' specific motor coordination during the execution of an augmented task.

The participants' physiological state was evaluated through the electrocardiographic (ECG) signal, band-pass filtered between 0.67 Hz and 40 Hz, the breathing signal and the skin conductivity signal, which was band-pass filtered between 0.05 Hz and 2 Hz [38]. From these signals, we computed the following indexes within each trial:

- Heart Rate (HR): the average Interbeat interval (IBI);
- RMSSD: the root mean square of successive differences between normal heartbeats (IBI) expressed in milliseconds [27]. This measure represents an index of heart rate variability, which is typically lower the higher the subject's attention and/or stress;
- Breathing frequency: the average interval between two successive breathing waves;
- Nonspecific skin conductance standard deviation (SCSD): the standard deviation value of the nonspecific skin conductance signal over each 100-second trial [38].

We selected these metrics as indicators of the participants' mental and physical state for their well-known correlation with different states such as relaxation/stress or rest/activity.

We analyzed the subjective experience of the participants through the questionnaires, asking them to rate between 0 and 100 the sessions and tasks in terms of their perceived enjoyment, difficulty, overall workload and usefulness of the vibrotactile feedback.

4.6. Statistical analysis

For the statistical analysis, we treated each dyad as a singular unit by averaging their performance in the two solo and two dyadic sessions. Sphericity and normality of all data distributions were evaluated respectively with Mauchly's and Shapiro-Wilks tests. In the case of the average Spring length variation, the analysis was conducted after having normalized data with the log10 operation.

Since the vibrotactile feedback conveyed qualitatively different information in the different tasks, we ran separate analyses for each task (i.e., one for uncoupled, 2-coupled and 3-coupled respectively). Indeed, in the uncoupled task the feedback only alerted the participant in case of effectors collision. Conversely, in the 2-coupled task participants were provided with a continuous feedback on the elastic force exerted on the effectors by the virtual spring, plus an alert signal in case of elastic band breaking. In the 3-coupled task the continuous feedback on the elastic force is provided for three virtual springs rather than one. Thus, we analyzed the data through a 2-way repeated measures ANOVA with vibrotactile feedback (vibrotactile, no-vibrotactile) and session (solo, dyad) as factors to analyse the score, fails and spring length variation indexes. The smoothness index was analysed with a 3-way RM ANOVA, with an additional factor accounting for the different cursors (i.e., dominant hand (DH), non-dominant hand (NDH) and dominant foot (DF)). Multiple comparisons were corrected with Bonferroni.

Physiological measures were normalized with respect to the average baseline value b as $(x - b)/b$ considering x the evaluated index and analyzed through Generalized Linear Mixed-Effect Models, in order to take into account all the factors (i.e., tasks, sessions and feedback).

Questionnaires were evaluated separately for each index with the Friedman test considering as factors the tasks (i.e., uncoupled, 2-coupled and 3-coupled) performed within each session (i.e., solo, dyad controlling the hands, dyad controlling the foot) and then the sessions, compared for the same task. Multiple comparisons were corrected with Bonferroni.

Abbreviations

Abbreviation	Definition
HMA	Human Movement Augmentation
SRL	Supernumerary Robotic Limb
ERM	Eccentric Rotating Mass
RMSSD	Root Mean Square of the Standard Deviation
ECG	Electrocardiographic
SC	Skin Conductance
U	Uncoupled
2C	2-Coupled
3C	3-Coupled
IBI	Interbeat Interval
SCSD	Skin Conductance Standard Deviation
DH	Dominant Hand
NDH	Non-Dominant Hand
DF	Dominant Foot
V	Vibrotactile feedback
NV	No Vibrotactile Feedback

List of abbreviations used in the manuscript.

CRediT authorship contribution statement

Alessia Nocco: Writing – review & editing, Writing – original draft, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Davide Deiana:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis. **Mattia Pinardi:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis. **Giovanni Di Pino:** Writing – review & editing, Writing – original draft, Conceptualization. **Domenico Formica:** Writing – review & editing, Writing – original draft, Supervision, Funding acquisition, Conceptualization.

Ethics statement

Participants provided written informed consent prior to the experiment. The experimental protocol was conducted according to the declaration of Helsinki and approved by the Ethical Committee of Università Campus Bio-Medico di Roma (HUROB protocol, ref. number 001.22(25.21) approved in date 19/07/2022).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported in part by the European Commission under H2020 grant NIMA (FETOPEN 899626) and by the Royal Academy of Engineering and the Office of the Chief Science Adviser for National Security under the UK Intelligence Community Postdoctoral Research Fellowships programme (ICRF2324-7-111).

Data availability

Data are available at Mendeley repository (doi: <https://doi.org/10.17632/jmccbz9cw8.1>) <https://data.mendeley.com/datasets/jmccbz9cw8/1>.

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