Hybrid Robotic and Electrical Stimulation Assistance Can Enhance Performance and Reduce Mental Demand

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***Abstract*—Combining functional electrical stimulation (FES) and robotics may enhance recovery after stroke, by providing neural feedback with the former while improving quality of motion and minimizing muscular fatigue with the latter. Here, we explored whether and how FES, robot assistance and their combination, affect users' performance, effort, fatigue and user experience. 15 healthy participants performed a wrist flexion/extension tracking task with FES and/or robotic assistance. Tracking performance improved during the hybrid FES-robot and the robot-only assistance conditions in comparison to no assistance, but no improvement is observed when only FES is used. Fatigue, muscular and voluntary effort are estimated from electromyographic recording. Total muscle contraction and volitional activity are lowest with robotic assistance, whereas fatigue level do not change between the conditions. The NASA-Task Load Index answers indicate that participants found the task less mentally demanding during the hybrid and robot conditions than the FES condition. The addition of robotic assistance to FES training might thus facilitate an increased user engagement compared to robot training and allow longer motor training session than with FES assistance.**

***Index Terms*—Neurorehabilitation, robotic assistance, functional electrical stimulation.**

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I. INTRODUCTION

STROKE is the most common neurological disorder in adults and results in upper-limb impairments in over 70% of post-stroke individuals [1], [2]. Rehabilitation is needed after stroke to help reduce disabilities but current services do not meet the patients' expectations in many areas, including reduction of arm impairment [3], [4] and less than 15% of them achieve complete functional recovery of the paretic arm at 6 months [5], [6]. There is thus a need to provide more efficient motor training and enhance recovery of upper-limb function. Technologies such as robotics and functional electrical stimulation (FES) have thus been introduced within the rehabilitation process to improve the outcomes.

FES has been used in this context to assist patients during training, by contracting the relevant muscles and stimulating the peripheral nerves. It can also strengthen neural pathways through orthodromic and antidromic neural activation [7]. Meta-analysis studies found that upper-limb motor function is improved after FES-based therapy in acute and chronic stroke patients [8], [9] and some studies also report improvements in activities of daily living (ADLs) [10], [11].

On the other hand, rehabilitation robots have been used to provide assistance during movement [12], [13], [14]. However, the literature suggests that upper-limb robotic-based training only slightly improves motor functions compared to conventional interventions [14], [15] and does not necessarily translate to improvement in ADLs [14], [15], [16], [17].

Although there is evidence that FES training is beneficial for upper-limb motor recovery, it can be uncomfortable, tiring, and usually does not produce strong and smooth motion [18], [19], [20], [21]. Could robotic systems be used to complement FES by providing power and mitigating discomfort and fatigue? Such hybrid system could help users perform smooth and well controlled limb motion. They would also provide a more complete sensorimotor experience than robotic training alone by eliciting additional mechanoreceptors and muscle activity through the stimulation, which may benefit functional recovery. Recently, novel hybrid controllers for upper-limb assistance have been developed, using model predictive control to distribute the actuation between both systems more optimally [22] and adaptive cooperative con-

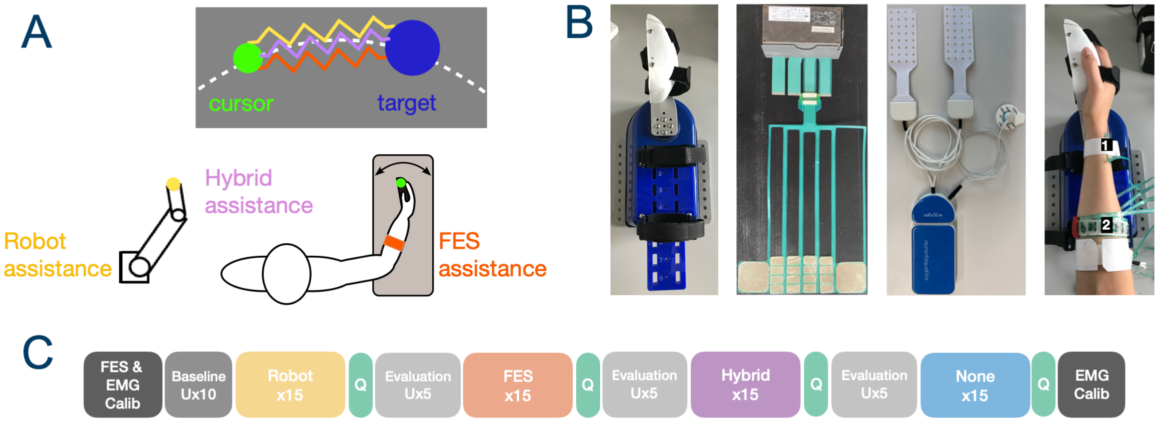

Fig. 1. Experiment description. **A.** Participants track a randomly moving target on-screen with wrist flexion/extension and receive four different assistance conditions: no assistance, robot-only assistance, FES-only assistance and hybrid (robot + FES) assistance. **B.** Hybrid robot-FES system (from left to right): HRX-1 wrist robotic device; FES device with 16-electrode array; EMG recording device with ground electrode and two high-density 32-channel electrode arrays; hybrid set-up where the FES anode electrode, shown as 1, is placed on the dorsal side of the wrist near the ulnar head and the cathode electrodes array, shown as 2, are around the arm inline with the wrist flexor and extensor muscle belly with the EMG electrodes placed distally. **C.** Overview of experimental protocol, where four assistance conditions were presented randomly to each participants: no assistance, FES-only assistance, robot-only assistance and hybrid assistance. Each block represents one trial of the target tracking task.

trol where FES-induced muscle fatigue is considered in the control loop [23], [24]. Although the results from these developments and preliminary testings are promising, most of these systems have not been tested with clinical populations and only report the effect of hybrid assistance on users' performance and motor torque reduction. Additionally, existing systems deployed in the stroke rehabilitation environment are relying on FES as the main means of assistance and using a robotic device only to promote gravitational support [25], [26], [27], [28], [29], [30], [31], [32], or to contribute to other joint motion than the one supported by FES [25], [26], [27].

To evaluate whether a system that combines robotic assistance and FES to the same joint motion can be truly useful to clinical populations, we first need to understand how each mode of assistance alters performance, motor behaviours, as well as user experience in a healthy cohort. To this end, we developed a simple one degree-of-freedom interface for wrist flexion/extension that can provide FES and robotic assistance, based on users' performance during the tracking of a moving target. The aim of this work was to explore whether and how FES, robot assistance, and their combination, alter users' performance, their physiological responses and their workload perception in a target tracking task, where continuous assistive feedback is required. More specifically, we investigated tracking performance, quality of motion, muscular and voluntary effort, fatigue and user experience. While we expected a general performance improvement with assistance, we also anticipated differences among the various modes. Here, we hypothesised that robotic assistance could lead to reduced fatigue and tracking error but also lower effort than FES. While we hypothesised that the combination of these two modalities would additively improve the tracking performance, we further explored how it would impact the resulting motor behaviours and physiological responses.

II. METHODS

A. Participants

This study was approved by the Research Ethics Committee of Imperial College London (approval number: 21IC6935). 15 healthy participants (6 female) aged 27.8 ± 3.41 years old were recruited for this study. The participants signed an informed consent form and filled out a demographic questionnaire prior to participating in the experiment. 13 participants were right handed and two were left handed as was assessed using the Edinburgh Handedness Inventory [33].

B. Robotic Interface

The HRX-1 one degree-of-freedom wrist robotic interface (HumanRobotiX, UK) used in the study is shown in Fig. 1B. It is actuated by a brushless low friction motor, which delivers up to 4 Nm of torque and is controlled by the Epos4 70/15 motor controller (Maxon Motors, Switzerland). Torque measurement is provided by the embedded torque sensor (with 0.014 Nm resolution) and the user's wrist angle is recorded using the embedded optical encoder (0.01° resolution). The hand is attached to an ergonomic handle while the forearm is strapped to an adjustable arm support to ensure joint alignment. The robot is programmed in Matlab and ran at a frequency of approximately 100 Hz.

C. FES System

The CLASS V1.0 FES device 16-electrode array (Tecnalia Research & Innovation, Spain) was used (Fig. 1B), and controlled remotely via Bluetooth communication. A hydrogel layer is placed on the electrodes to improve the conductivity of the array with the skin and additional Velcro straps are positioned around the electrodes to tighten the array around the forearm. The anode electrode is positioned on the dorsal side of the wrist near the ulnar head and the cathode array is positioned around the arm inline with the belly of the wrist flexor and extensor muscles for comfortable and effective stimulation (Fig. 1B). The frequency of the stimulation is set to 35 Hz and the pulse width to 300 μs as these values are used clinically [34]. The amplitude of the stimulation varies (with 1 mA resolution) during the experiment.

D. EMG Recording

Muscle activity is recorded using two 32-channel EMG electrode arrays (GR10MM0804, OT Bioelettronica, Italy) with a Sessantaquattro amplifier (OT Bioelettronica, Italy) (Fig. 1B). We used two electrode arrays that covered the forearm proximally to the FES electrodes (Fig. 1B), which recorded the activity in muscles such as the extensor carpi radialis longus, the extensor digitorum, the flexor carpi radialis and the flexor digitorum superficialis. The EMG data is sampled at 2000 Hz and stored on a PC for analysis.

E. Experiment Task

The participants tracked a moving target on a computer monitor placed in front of them using wrist flexion/extension movements of the right hand while being assisted by a robot or FES (Fig. 1A). The target trajectory was defined as:

$$q^*(t) = 38.6^\circ \sin\left[2.0308(t^+)\right] \sin\left[1.0927(t^+)\right] \quad (1)$$

where $t^+ = t + t_0$, t is the elapsed time and t_0 is the starting time. q^* is the target angle. The target was programmed and updated in Matlab and $t_0 \in \{0, 3.094, 14.375\}$ s was randomly selected every trial to minimise prediction of the target trajectory by the participants. Participants were instructed to track the target as accurately as possible and told that they may feel haptic interaction from the robot and/or electrical stimulation.

F. FES and EMG Calibration

An *FES calibration* was performed at the start of the experiment. Two cathode electrodes within the cathode array are selected to generate the flexion movements and two other cathode electrodes for the extension movements. The electrode location and corresponding maximum stimulation are selected individually for the flexion and extension side, such that the stimulation is comfortable and the generated movement covers the participant's full range of motion. The FES amplitude is capped at the maximum comfortable stimulation determined by the user for the flexion s_f^{max} and extension movements s_e^{max}. The torque generated by each of these stimulation amplitudes while the participant is relaxed is also recorded as τ_f^{max} and τ_e^{max}. The minimum FES amplitude is defined as the participant's sensory threshold through self-report, individually for the flexor stimulation s_f^{min} and the extensor stimulation s_e^{min}. We assume a linear mapping between the stimulation amplitude s_f and s_e and the produced torque τ_f and τ_e for amplitudes above s_f^{min} and s_e^{min} for the flexion and extension movements respectively [35] such that:

$$\tau_f(t) = \alpha_s\, s_f(t) \quad \tau_e(t) = \alpha_s\, s_e(t) \quad (2)$$

with the linear coefficient α_s defined as:

$$\alpha_s = \frac{s_f^{max} - s_f^{min}}{\tau_f^{max}} \quad (3)$$

An *EMG calibration* was then performed to obtain a measure of effort, by linearly regressing muscle activity with torque produced during isometric contraction. During this calibration, participants were asked to resist each of the four increasing torque levels: $\{0.4, 0.8, 1.2, 1.7\}$ Nm during 2.5 s in flexion and extension at the fixed angle q = 30°. This was repeated four times with a 3 s rest in between to prevent fatigue.

G. Control of Robot-FES System

The task considered in this study is a continuous target tracking task with a pseudo-random trajectory, that requires continous assistive feedback. Therefore, the torque exerted on the wrist flexion/extension by the robot is described as:

$$u_r(t) = K_r\, e(t) \qquad e(t) = q(t) - q^*(t) \quad (4)$$

where $e(t)$ is the tracking error between the participant's trajectory q and the target trajectory q^*. The robot control stiffness K_r = 0.0097 Nm/° corresponds to a soft-middle interaction stiffness [13]. It has been selected after preliminary testings in order to observe tracking improvement with assistance, while preventing slacking.

The stimulation amplitude provided to the wrist flexor or extensor is described as:

$$s(t) = \begin{cases} s_e(t) = -K_s\, e(t) + s_e^{min} & e(t) < 0 \\ s_f(t) = K_s\, e(t) + s_f^{min} & e(t) > 0 \end{cases} \quad (5)$$

where $s_e(t)$ refers to an extensor muscle stimulation and $s_f(t)$ a flexor muscle stimulation. K_s (in mA/°) is the FES control stiffness and is the same for the extensor and flexor stimulation in order to match the robot assistance behaviour. It is defined from the linear mapping α_s between the FES amplitude and torque ranges of the flexor as it was found to be more comfortable during preliminary tests:

$$K_s = \alpha_s\, K_r \quad (6)$$

The four assistance conditions of the experiment are defined as follows: {hybrid, robot ($s_e \equiv 0, s_f \equiv 0$), FES ($u_r \equiv 0$), no assistance ($s_e \equiv 0, s_f \equiv 0$ and $u_r \equiv 0$)}. In the hybrid condition, participants receive the same robot assistance as in the robot condition as well as the same FES assistance as in the FES condition.

H. Protocol

The experimental protocol is outlined in Fig. 1C. The experiment started with an FES and EMG calibration as detailed in Section II-F. This EMG calibration was also carried out at the end of the experiment to examine potential changes in muscle activity due to fatigue. The participants first completed ten trials of the trajectory tracking task without assistance.

They then completed four blocks of the trajectory tracking task, each block using one of four conditions of assistance: {hybrid, robot, FES and no assistance}. The conditions were presented in random order, with each block containing 15 trials consisting of 15 s of target tracking and a 3 s rest. Each block was followed by a questionnaire (see Appendix) that evaluated the workload with the NASA-TLX ten-point ordinal Likert Scale [36] and the comfort and usefulness of the stimulation and robot torques using five-point ordinal Likert Scale questions [37]. Subsequently, a block of five trajectory tracking trials with no assistance was performed, including a first washout trial and four evaluation trials.

I. Performance Analyses

Task performance was quantified by the Root Mean Square Error (RMSE) [°] between the target trajectory $q^*(t)$ and the participant's trajectory $q(t)$: $\sqrt{\frac{1}{T}\int_0^T e(t)^2\,dt}$, $T = 15\,s$. Other metrics were used to quantify the participant's performance more specifically. The time delay [s], tracking error due to a temporal shift between the target's and participant's trajectories, was calculated using the cross-correlation between the two trajectories. Smoothness, quantified with the SPARC (Spectral Arc Length) metric, was also explored as it is a marker of the quality of sensorimotor control, often impaired after stroke [38]. Understanding how each assistance condition affects motion smoothness in healthy individuals is relevant for later application to stroke rehabilitation, where smoothness is linked with functional recovery [39]. A SPARC value closer to zero corresponds to a smoother motion.

J. Effort and Fatigue

Fatigue and effort during the task were estimated using recorded EMG signals of the flexor and extensor muscles from the participants. Mains noise was attenuated using a Notch filter (Matlab function *iirnotch* with notch at 50 Hz). A low-pass and high-pass second order Butterworth filters (with cut-off frequencies $f_c = 10$ Hz and $f_c = 500$ Hz, respectively) were applied in the forward and reverse directions. The EMG signal was rectified and the envelope was obtained using a low-pass second order Butterworth filter with cut-off frequency $f_c = 5$ Hz. The channel on the extensor and flexor arrays with the highest envelope amplitude during the EMG calibration were used for the following analyses. For both time-domain effort metrics, the torque-normalised EMG signal was used. The torque-muscle activity relationship was obtained by linearly regressing the envelope of the fully-rectified EMG during the EMG calibration procedure with the corresponding torque.

Fatigue was estimated by computing the median frequency of the filtered EMG signal [40]. A decrease in EMG median frequency corresponds to an increase in fatigue. The EMG frequency during the EMG calibration at the start and end of the experiment, and across conditions were compared. For the latter, the median frequency was averaged for the last four trials of the previous and following evaluation blocks and their difference was taken to quantify fatigue changes.

For the muscular effort metric, the EMG signal containing both the FES-induced muscle activity, i.e. the evoked M-wave, and the volitional activity were considered. Although the evoked M-wave is not a voluntary contribution, it is resulting in the recruitment of motor units leading to muscle contraction, as with volition. We used a Hampel filter, where outliers away by 1.5 standard deviations from the median of 30 surrounding samples are replaced by that median; this filtered the FES artefacts. The envelope of the signal was obtained and the total effort was evaluated from the mean amplitude of the envelope of the torque-normalised EMG signal, averaged across trials. Muscular effort levels during the EMG calibration at the start and end of the experiment were compared as well as during each training condition.

The volitional contribution was also considered as it can inform about the effect of each modality on user engagement, which is relevant for stroke rehabilitation. Adaptive filters can be used to filter the EMG corrupted by the FES artifact and the M-wave contribution [35], [41], [42]. In this work, we used an adaptive filter designed for EMG-based torque estimation under stimulation of wrist flexor and extensor with the same setup as here [35]. The torque-normalised EMG was obtained from the envelope of this signal, and averaged across trials.

K. Statistical Analysis

For the comparison of performance metrics, effort, fatigue levels and questionnaire answers between the conditions, we used a one-way repeated measures ANOVA or a non-parametric Friedman test when the data was not normally distributed. A one-sample Shapiro-Wilk test was used to test the null hypothesis that the data comes from a normal distribution. Post-hoc paired sample t-tests or paired Wilcoxon sign-rank tests were used for comparisons of performance metrics, effort and fatigue levels and questionnaire answers between each condition, controlling for the family-wise error rate with Bonferroni-Holm correction. For the comparison of the fatigue level before and after the experiment, a paired Wilcoxon sign-rank test was used as data was not normally distributed. Similarly, for questions comparing the FES and hybrid conditions, and the hybrid and robot conditions, paired Wilcoxon sign-rank tests were used. For the statistical analysis of performance, effort and fatigue metrics, the average across trials in one condition was calculated for each participant. In the box plot figures, the whisker lines above and below the box indicate the 1.5 interquartile range. Outliers are displayed by a red + sign. Comparisons not shown are not significant.

III. RESULTS

A. Performance Results

The assistance condition affects participants' tracking performance ($F(3, 56) = 20.38$, $p < 0.001$). RMSE is smaller with hybrid or robot assistance relative to the no assistance and FES conditions (all $p < 0.001$) (Fig. 2A). There is no significant difference between hybrid assistance and robot assistance

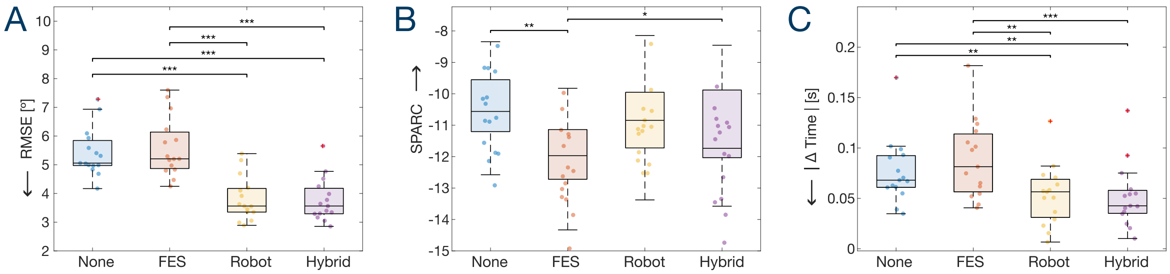

Fig. 2. Performance, motor adaptation and quality of motion metrics during the tracking task with four different assistance conditions. (**A**) Tracking performance indicated by the Root Mean Square Error (RMSE). (**B**) Smoothness of participant's trajectory, evaluated using Spectral Arc Length (SPARC) [38]. A SPARC value closer to zero corresponds to a smoother motion. (**C**) Time Delay indicates the temporal shift between the target's and participant's trajectories. $*: p < 0.05, **: p < 0.01, ***: p < 0.001$. Comparisons not shown are not significant.

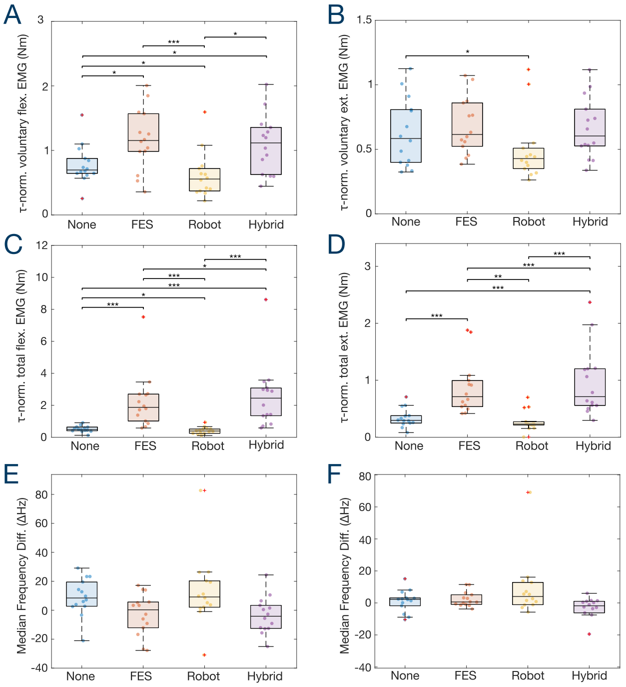

Fig. 3. Voluntary effort (A,B), muscular effort (C,D) and changes in muscle fatigue (E,F) during the tracking task assisted with four different assistance conditions. The effort metrics are estimated as the mean envelope amplitude of the torque-normalised EMG signal. Fatigue is obtained from the median frequency of the EMG signal, a decrease in frequency indicates increased fatigue. (**A**) Voluntary effort in the flexor muscles. (**B**) Voluntary effort in the extensor muscles. (**C**) Total muscular effort in the flexor muscles (including M-wave contribution). (**D**) Total muscular effort in the extensor muscles (including M-wave contribution). (**E**) Fatigue changes in the flexor muscles. (**F**) Fatigue changes in the extensor muscles. $*: p < 0.05, **: p < 0.01, ***: p < 0.001$. Comparisons not shown are not significant.

($p = 0.74$). The effect of assistance condition on smoothness was also investigated ($F(3, 56) = 3.82$, $p = 0.015$) and results indicate that FES assistance leads to decreased smoothness compared to the hybrid condition ($p < 0.05$) but other differences are not significant (all $p > 0.075$) (Fig. 2B). The hybrid and robot assistance also reduce time delays compared to none and FES conditions (all $p < 0.01$) and there is no statistical difference between the hybrid and the robot conditions ($p = 0.93$) (Fig. 2C). When investigating performance improvement on evaluation trials before and after each assistance condition, we do not find statistical differences ($F(3, 56) = 0.37$, $p = 0.77$) (Appendix, Fig. 6).

B. Effort and Fatigue

The EMG recording for one participant was corrupted and thus EMG-based metrics are reported as $N = 14$. When comparing the total level of muscle activity in the flexor muscles during the assisted tracking task ($\chi^2(3) = 37.46$, $p < 0.001$) (Fig. 3C), we find that it is lower with robot assistance compared to all other assistance conditions ($p < 0.001$ with FES and hybrid and $p < 0.05$ with none). Higher muscular effort is observed in the FES and hybrid assistance compared to no assistance, with higher muscle activity in the hybrid condition ($p < 0.05$ with FES). Similar trends are found for the extensor muscles ($\chi^2(3) = 24.26$, $p < 0.001$) (Fig. 3D), although there is no statistical difference between the robot and no assistance conditions ($p = 0.90$) and total muscle activity is highest in the hybrid condition ($p < 0.001$ with FES).

Regarding the voluntary effort (Fig. 3A, B), similar trends are found in the flexor muscle ($\chi^2(3) = 25.00$, $p < 0.001$), where higher volition is observed in the FES and hybrid assistance conditions, while these differences are not present in the extensor muscle ($\chi^2(3) = 16.54$, $p < 0.001$). The voluntary contribution is similar in the FES and hybrid conditions for both flexor ($p = 0.46$) and extensor muscles ($p = 0.53$). In the robot condition, the volitional contraction is lowest ($p < 0.05$ with none in flexor and extensor muscles).

Regarding fatigue, we observe that the median frequency of the flexor muscle activity increases in the none and robot conditions, suggesting muscle recovery and does not change after the FES and hybrid condition when looking at the mean (Fig. 3E). These differences are not as clear in the extensor muscles (Fig. 3F). The comparison of the change in muscle fatigue between conditions is not statistically different for the flexor ($\chi^2(3) = 5.40$, $p = 0.15$) or the extensor ($\chi^2(3) = 7.71$, $p = 0.052$)). No statistical differences are found when comparing muscle fatigue before and after the experiment during the EMG calibration (Appendix, Fig. 7).

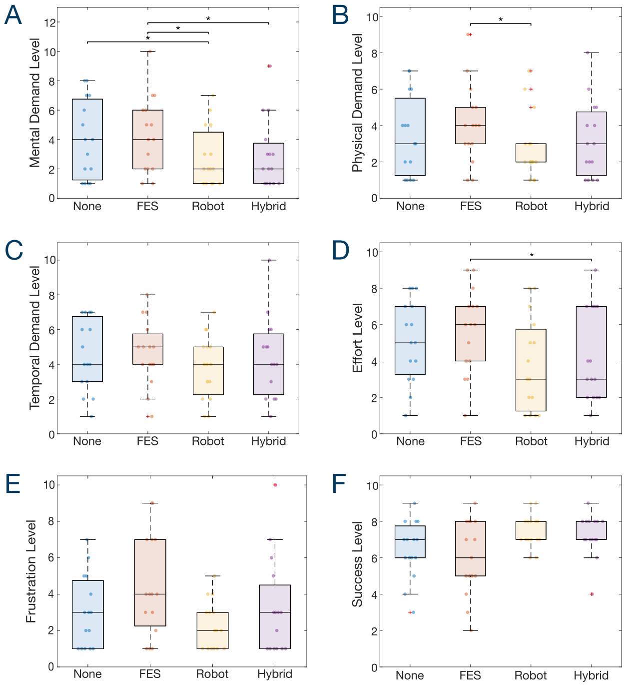

Fig. 4. Answers to the 10-point NASA-TLX questionnaires on perceived workload after the trajectory tracking task with four different assistance conditions, with answers from very low (1) to very high (10). $*: p < 0.05$. Comparisons not shown are not significant.

C. Questionnaire Answers

The answers to the NASA-TLX questions are shown in Fig. 4. The assistance type affected participants' mental demand ($\chi^2(3) = 16.18$, $p = 0.001$) (Fig. 4A). It is lower in the robot and the hybrid conditions in comparison with the no assistance and FES assistance conditions ($p < 0.05$). Participants also perceived the lowest physical demand in the robot condition, but this difference is statistically significant only with respect to the FES condition ($p < 0.05$) (Fig. 4B). Moreover, participants indicated that their effort was lowest in the robot and hybrid conditions and the latter is significantly different from the FES condition ($p < 0.05$) (Fig. 4D). Their frustration level during the assisted task was lower in the hybrid and robot assistance conditions than in the FES condition but differences are not statistically significant ($\chi^2(3) = 7.68$, $p = 0.053$) (Fig. 4E). The responses to the statement "The electrical stimulation was comfortable" are similar in the hybrid and FES conditions ($p = 0.94$) but participants thought that their performance increased thanks to the stimulation with the hybrid assistance but not with FES only, although this difference is not statistically significant ($p = 0.57$) (Fig. 5). The robotic forces were rated as comfortable and useful in both the hybrid and robot conditions.

IV. DISCUSSION

Literature suggests that adding FES to robotic assistance could improve motor recovery during stroke rehabilitation. However, there is a need to understand how FES and robotic assistance alter performance, physiological measures and subjective experience, such that the benefits of these modalities can be fully exploited for clinical applications. This work thus used a simple wrist flexion/extension interface to explore these aspects in healthy participants in a target tracking task, requiring continuous assistance FES and robot assistance proportional to the tracking error.

Performance and quality of motion increases when robotic assistance is present. Tracking performance is higher when participants receive hybrid and robot assistance compared to no assistance or FES assistance. Hybrid assistance does not improve tracking performance more than robot assistance. We find that the assistance modes improve tracking performance except the FES assistance alone. However, it is not disturbing participants' performance, even though we used a simple controller. On the other hand, we expected that the additive effect of FES and robotic assistance would further improve performance, even though the goal of the hybrid controller was not focused on improving tracking performance but rather made simple to investigate the effects of assistance. The stimulation thus does not seem to contribute to performance improvement in the hybrid condition. These observations could be extended to the use of more advanced strategies, where the goal is to optimise for control objectives such as tracking performance or learning. However, few studies have tested other strategies to assist users in ADLs, such as shared control approaches, where the action of one modality has knowledge of the other, and similarly they did not always find performance improvements in the hybrid compared to the robot-only condition [22], [23].

In this work, we additionally investigated the effect of each modality and their combination on various quality of motion metrics. We found that participants' movements are smoother with the hybrid assistance than with the FES assistance and there is no significant difference in movement smoothness in the hybrid, robot and no assistance conditions. We see similar trends for other objective metrics, such as time delay and under/overshoot. Adding FES to a robotic-based assistive device thus does not impede motion quality in our experiment, even though the controller used is simple and does not account for the delay between the trigger of the stimulation and the resulting muscle contraction (e.g. 10-140ms [7], [43]). It is useful to understand how smoothness is affected by different assistive modalities as it captures motor control abilities which are affected in stroke population, and is linked with functional recovery [39], [44]. Furthermore, this analysis can then be used as a reference to later interpret data from stroke patients performing similar tasks with these assistance modes. In the hybrid context, it can also be used to inform on the assisted motion quality and as an indicator of possible counteracting effects between the stimulation and robot torque [45]. As no difference was found in participants' smoothness during the no-assistance and hybrid conditions, it seems that the electromechanical delay did not affect participants' motion.

Total muscular effort is higher when stimulation is applied while it does not induce more fatigue, and voluntary effort is lowest in the robot-only condition. The amount of muscular effort, quantified by the total level of muscle activity, both from the stimulation-induced M-wave and the voluntary

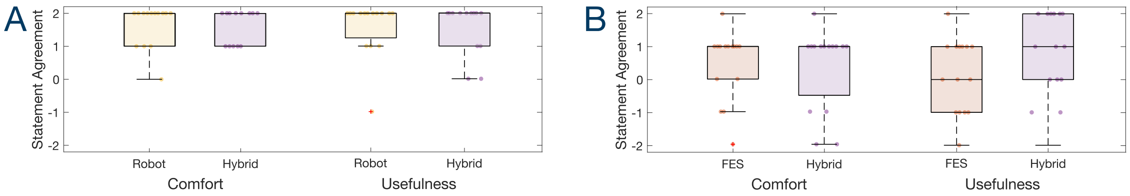

Fig. 5. Answers from a 5-point ordinal Likert scale questionnaire on comfort (**A** and **C**) and usefulness (**B** and **D**) of robotic force (top row) and electrical stimulation (bottom row) after trajectory tracking with four different assistance conditions. Agreement level from 'Strongly Agree' (2) to 'Strongly Disagree' (−2) was provided for each statement.

contribution, is generally higher in the conditions with electrical stimulation (FES and hybrid) compared to the other two conditions; this is due to the M-wave contribution of the stimulation. Although it is common to disregard the M-wave and only investigate the voluntary contribution, we chose to also explore the total EMG activity as the stimulation also leads to the activation of motor units and thus affects the characteristics of the muscles [46].

We also observe that voluntary effort is lowest in the robot condition. This suggests the potential value of integrating FES assistance into robotic-based therapy as it leads to increased total muscle contraction but also higher voluntary contribution, thus enhancing user engagement which could potentially promote recovery in stroke patients. Additionally it could prevent slacking that seems to occur here when robot-only assistance is provided. On the other hand, we find that the total muscular effort is higher in the hybrid than in the FES condition. This could be due to the electromechanical delay between the stimulation and the resulting muscle contraction, which is not present when a robotic torque is applied to the handle. In some cases the stimulation could lead to overshooting of the trajectory although the target is already moving towards the other direction. Although we do not see a difference in performance and smoothness between the robot and hybrid condition, it might be that the two assisting systems are counteracting each other, which could cause increased muscle activity level for the user to drive the handle in the desired direction. Similarly, the higher voluntary contribution of the flexor muscles in the hybrid and FES conditions could be a consequence of a counteraction between the user's intention and the delayed contraction resulting from the stimulation. These trends were observed in another hybrid training study with stroke patients where EMG activation levels in the flexors and extensors were lower with FES compared to hybrid assistance [47]. Models of the muscle response to electrical stimulation are available and could be incorporated as a feedforward element to the existing controller to ensure muscle contraction resulting from FES occurs in a similar time range as the robotic torque assistance for the motion to be produced [48], [49], [50], [51]. Recent works have also targeted the development of controllers to reduce the effect of the electromechanical delay of the stimulation [52], [53], which would lead to a better alignment of the motion resulting from the two actuation systems. However, these approaches for delay compensation are not considering the time-varying nature of the electromechanical delay [43], and are applied to cyclic gait motion or to the tracking of pre-determined trajectories, hence they would not be suitable for this pseudo-random tracking task.

Regarding fatigue, there are no significant changes before and after the experiment in the flexor and extensor muscles. Neither do we find that the FES and hybrid conditions lead to higher fatigue than the other conditions when investigating fatigue changes for each condition individually. Although FES is commonly described as fatiguing, we do not find such trends in these healthy participants who performed a task that is not physically demanding – average rating below 4 for all conditions in the 10-point NASA-TLX questionnaire. This could be in part due to the dynamic nature of the task, which did not require sustained stimulation, as well as the relatively short duration of each trial and training block. FES is also mostly used and evaluated in clinical populations, where rehabilitation activities that make use of FES assistance can require higher stimulation amplitudes and training duration than these able-bodied individuals were prescribed. Moreover, the response to stimulation amplitudes and duration might be different in healthy participants who already have the capacity to move and stroke patients who may have weakness and lack the ability to contract their muscles as intended.

Mental demand is rated as lowest in the hybrid and robot conditions. The NASA-TLX questionnaire answers also indicate that in this study, participants did not feel more frustrated when training with FES or hybrid assistance compared to robot or no assistance. The electrical stimulation was rated as comfortable on average but participants perceived that the stimulation in the hybrid assistance was more useful in improving their performance than in the FES condition. This finding resonates with the tracking error results, where performance in the hybrid condition is higher than in the FES condition, although this increase might not be due to the stimulation directly. Robot-assisted training is perceived as the least physically demanding, but is only significantly different to FES-assisted training, whereas the effort is perceived significantly lower in hybrid than FES conditions. Indeed, the effort rating could be considered by users as a compound of mental and physical demand [54], and here mental demand is rated lower in the hybrid and robot conditions.

These answers only partly translate to the physiological differences on voluntary effort that we observe, where in the flexor muscles, we do find differences between most conditions. Although previous studies have found relationships between task difficulty, NASA-TLX ratings and muscle activity amplitude, these were investigated in more demanding and tiring tasks such as repairing a pump gearbox [55], controlling traffic density [56], and performing surgical procedures [57]. For instance in the repair task, the complex task resulted in significantly higher physical demand ratings and EMG levels compared to the simple task, with a significant correlation between these two metrics [55]. The average physical demand rating of this task was higher than 6, whereas our target tracking task was rated below 4 on average in all conditions. The absence of consistent findings between physical demand ratings and EMG levels in our work could be explained by the low demand of the target tracking task we investigated. The results from the subjective workload assessment motivate the use of hybrid assistance for motor training: although total muscle activity level is higher than with FES assistance, perceived effort is lower, which could lead to longer and more enjoyable training. On the other hand, hybrid and robot assistance are rated as less mentally demanding than FES and they are not significantly different from each other. The trends observed in these answers seem to follow those of the tracking performance, which suggests that they could be related. This is in agreement with previous motor task studies investigating the relationship between mental load and motor performance [58], [59]. This indicates that using hybrid assistance could reduce mental demand, thus enhancing user experience.

V. CONCLUSION

The present study explores how FES and robot assistance and their combination affects performance, effort, fatigue and user experience in a wrist target tracking task. The results suggest that the addition of the two modalities in a hybrid device reduces mental demand while increases performance compared to FES assistance only and could prevent slacking, occuring during robot-only training. Future work will aim at testing the efficacy of this hybrid device in stroke patients, where training benefits of hybrid rehabilitation technologies could be observed.

APPENDIX I
ADDITIONAL FIGURES

See Figs. Fig. 6 and Fig. 7

APPENDIX II
QUESTIONNAIRE

- What is your level of muscle fatigue? (1 = fatigued; 10 = not fatigued)
- What is your level of mental fatigue? (1 = fatigued; 10 = not fatigued)
- How mentally demanding was the task? (1 = very low; 10 = very high)
- How physically demanding was the task? (1 = very low; 10 = very high)
- How hurried or rushed was the pace of the task? (1 = very low; 10 = very high)
- How successful were you in accomplishing what you were asked to do? (1 = very bad; 10 = very good)

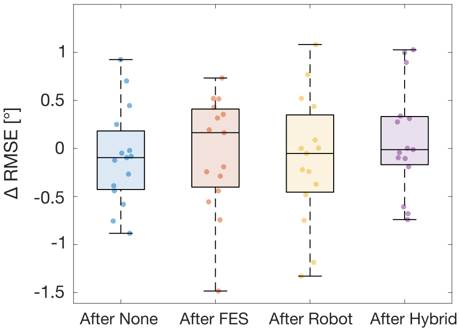

Fig. 6. Motor adaptation during the tracking task with four different assistance conditions. Tracking performance improvement indicates the difference in participant's tracking performance before and after training; a positive result indicates that they are performing better after training.

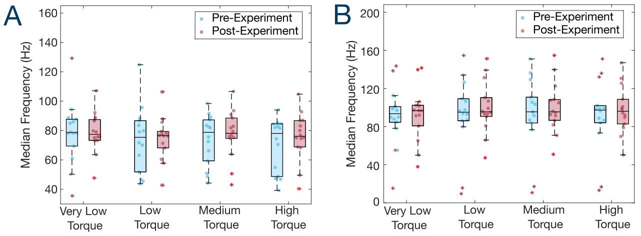

Fig. 7. Muscle fatigue was evaluated during the EMG calibration at the start and end of the experiment, where participants had to track four different levels of torque. Fatigue is calculated as the median frequency of the EMG signal, a decrease in frequency indicates an increased fatigue. Level of fatigue for (A) the flexor muscles and (B) the extensor muscles.

- How hard did you have to work to accomplish your level of performance? (1 = very low; 10 = very high)
- How insecure, discouraged, irritated, stressed, and annoyed were you? (1 = very low; 10 = very high)
- The forces were comfortable. (from 'strongly disagree' to 'strongly agree')
- The forces improved my performance. (from 'strongly disagree' to 'strongly agree')
- The electrical stimulation was comfortable. (from 'strongly disagree' to 'strongly agree')
- The electrical stimulation improved my performance. (from 'strongly disagree' to 'strongly agree').

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