Hybrid Functional Electrical Stimulation and Robotic Assistance for Wrist Motion Training after Stroke: Preliminary Results

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***Abstract*— This work presents preliminary results of a clinical study with sub-acute stroke patients using a hybrid system for wrist rehabilitation. The patients trained their wrist flexion/extension motion through a target tracking task, where electrical stimulation and robotic torque assisted them proportionally to their tracking error. Five sub-acute stroke patients have completed the training for 3 sessions on separate days. The preliminary results show hybrid assistance improves tracking performance and motion smoothness in most participants. In each session, patients' tracking performances before and after training were evaluated in unassisted tracking trials, without assistance. Their unassisted performance was compared across sessions and the results suggest that moderately to severely impaired patients might benefit more from hybrid training with our system than mildly impaired patients. Subjective assessments from all sessions show that the patients found the use of the device very comfortable and the training enjoyable. More data is being collected and future work will aim at verifying these trends.**

I. INTRODUCTION

Hybrid technology combining FES with active or passive robotics has been developed for upper-limb stroke rehabilitation in order to provide optimal assistance and improve functional recovery. In comparison to conventional therapy and robot-only rehabilitation, studies found greater improvements in the Box & Block test [1]–[3] and the Wolf Motor Function Test [4] with the hybrid system. However, due to the technical complexity of combining two active devices in a stroke rehabilitation scenario, some of the current systems have used robots only to provide support on other joint motions, thus not exploiting the full potential of hybrid system for rehabilitation [5]. Moreover, simple solutions such as push-buttons have been used to trigger assistance [5], which can limit the therapeutic benefits as the patient might not be engaged in the task [6]–[9].

On the other hand, advanced controllers have been introduced recently to provide more optimal combinations of FES and robotic assistance, and have been successfully tested in healthy participants [10]–[12] and simulations [13]. Results show that the use of these controllers could delay the onset of fatigue, [12], [13], reduce power requirements [10], [11], [13] and improve tracking accuracy [10], compared to FES or robot alone. However, they have not yet been tested in a rehabilitation scenario with stroke patients. Moreover, other studies that have investigated the use of a simple hybrid controller in stroke populations, such as Hu and colleagues [3] have not reported qualitative data. The goal of this work is thus to collect quantitative and qualitative data during the use of simple hybrid systems in the context of stroke rehabilitation, which is said to be crucial to achieve successful rehabilitation outcomes [14]. This patient-centred approach will allow us to gather further evidence towards the use of active robotic and FES assistance on the same joint motion to inform the development of controllers for stroke rehabilitation, where adaptive and optimal shared control can be used where beneficial.

This work presents preliminary results from a stroke study, where patients trained their wrist flexion/extension during a target tracking task with assistance from a hybrid system. In this work, a simple proportional control algorithm is used, where the intensity of FES and the amount of robotic torque provided to a patient is proportional to their tracking error. We investigated (i) how hybrid assistance affects patients' performance and quality of motion, (ii) how hybrid training affects these metrics over time and (iii) patients' experience of hybrid assistance and training.

II. METHODS

A. Participants

The study is run at the Schoen Clinic Bad Aibling and was approved by the Ethics Committee of the Ludwig-Maximilians University (LMU) Munich, Germany (registration number: 22-0297). All participants or their legal representatives signed an informed consent form prior to participating in the experiment. The study participants are sub-acute stroke patients staying at the inpatient rehabilitation hospital after an ischemic or hemorrhagic infarction.

The inclusion criteria are as follows: age > 18 years old, cognitively able to follow instructions, with functional impairments in the wrist or fingers as assessed by the Medical

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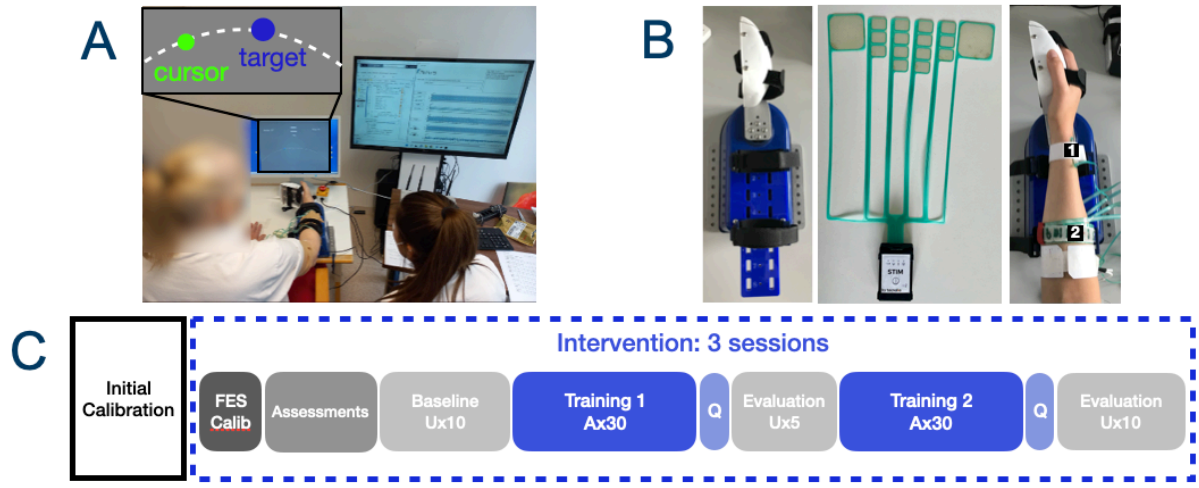

Fig. 1. Experiment description. **A.** A patient tracks a randomly moving target on-screen with wrist flexion/extension. **B.** Hybrid system (from left to right): HRX-1 wrist robotic device; FES device with 16-electrode array; hybrid set-up where the FES anode electrodes, shown as 1, are placed on the dorsal and ventral side of the wrist near the ulnar head and the cathode electrodes array, shown as 2, are placed inline with the wrist flexor and extensor muscle belly. **C.** Overview of experimental protocol, where a patient performs a series of calibration and assessment steps followed by unassisted trials (U), where no stimulation or robotic assistance are provided, and assisted training trials (A), where patients receive hybrid assistance. 'x10' refers to the number of trials for each block, here ten. 'Q' refers to the questionnaire step.

Research Council score (MRC ≤ 3) and low level or no pain in the wrist or fingers (Numeric Rating Scale < 4). Exclusion criteria can be divided in robot-related and FES-related exclusion criteria. Robot-related exclusion criteria are: severe contractures or muscle tone resulting in the operator's inability to position the patient's arm in the device and flex or extend the wrist more than 20°. FES-related exclusion criteria are: pregnancy, presence of implantable devices or other metal implants in the stimulated area, no motion or muscle contraction resulting from FES, patients with severe epilepsy and cancer or wounds in the stimulated area. Patients were also excluded if they had a severe psychiatric disorder or had no function as well as no deep sensitivity in the fingers or wrists.

Preliminary data from five patients (Table I) is presented in this work. Two patients are severely impaired (Fugl-Meyer Upper-Extremity score (FM-UE)≤25), two are moderately impaired (25≤FM-UE≤40) and one is mildly impaired (FM-UE>40) [15].

TABLE I
PATIENT DEMOGRAPHICS

Patient ID	Sex	Age (years)	Side of paresis	Time since stroke (weeks)	FM-UE
1	Female	78	Right	14	29
2	Male	68	Left	5	2
3	Female	81	Right	7	38
4	Male	73	Left	8	13
5	Male	59	Right	4	45

FM-UE: Fugl-Meyer Upper-Extremity score, maximum score: 66.

B. Protocol

The experimental protocol is outlined in Fig. 1C. Once recruited, an initial calibration session was scheduled for the patients to familiarise themselves with the system and to perform the first FES calibration. 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 as much of the participant's ROM as possible. 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 minimum FES amplitude is defined as the participant's sensory threshold through self-report, calibrated individually for the flexor stimulation s_f^{min} and the extensor stimulation s_e^{min}. Once found, the electrode locations were marked on the patient's skin if there were no counter-indications and the minimum and maximum amplitudes were noted down for the next sessions. After that, the patient was asked to relax while the stimulation amplitude was increased from s_{min} to s_{max}, with a resolution of 1 mA, and the generated torque was recorded. This was done in order to empirically identify the coefficients of the mapping between the stimulation amplitudes s_f and s_e and the produced torques τ_f and τ_e (Eq. 1) in each session. Preliminary testing indicated that the relationship between stimulation amplitude and torque could be approximated by a second order exponential for the flexion and extension movements respectively, such that:

$$\begin{aligned} s_f(t) &= f(\tau_f(t)) = \alpha_f\, e^{\beta_f\, \tau_f(t)} + \delta_f\, e^{\gamma_f\, \tau_f(t)} \\ s_e(t) &= f(\tau_e(t)) = \alpha_e\, e^{\beta_e\, \tau_e(t)} + \delta_e\, e^{\gamma_e\, \tau_e(t)} \end{aligned} \tag{1}$$

with α, β, γ and δ coefficients of the exponential terms. This mapping is used to determine the required FES amplitude when the patients are assisted by the hybrid system, to ensure that the FES and robot assistance provide the same amount of torque.

Following this initial calibration session, the patients participated in three intervention sessions of around one hour

each, separated by at least one break day. Each session was identical: it started with the FES calibration described above, followed by a ROM calibration.

The ROM calibration was performed as an assessment of patient's progress but also to adjust the target trajectory amplitude to each patient's capability. It started with a passive calibration, where the experimenter moved the handle of the robot in the flexion direction until they felt a resistance or a discomfort reported by the patient. This was also done in the extension direction and the cycle was repeated three times. After that, an active calibration, where patients were asked to move their wrist as far as they could in flexion and then extension was repeated three times.

In the remaining parts of the session, the patients performed a target tracking task with the wrist flexion/extension movements of their impaired hand, either unassisted (baseline and evaluation trials in Fig. 1C) where no FES or robotic assistance is provided, or assisted by the hybrid system (two training blocks), where the patient received both FES and robotic assistance. Ten unassisted trials were first completed by the patient as a baseline. The first training block consisted of 30 assisted trials, and was followed by five unassisted trials as intermediate evaluation. A second training block of 30 assisted trials was performed and followed by the final evaluation block of ten unassisted trials. Each trial lasted 12 seconds with a 3 second break. The rest time could be prolonged as desired by the patient. After the first training block and the first evaluation block, the patients answered a set of questions.

The patients tracked a moving target on a computer monitor placed in front of them. The target trajectory was defined as the product of two sinusoids, as it has been extensively used in human-robot interaction with healthy participants [16]–[18]. Here the frequencies have been adapted to the stroke population, following preliminary testings with clinicians and patients, for the target to be slower. We used:

$$q^*(t) = q^*_{mid} + q^*_{max}\,\sin\big(0.2586\,t^+\big)\,\sin\big(0.1860\,t^+\big) \quad (2)$$

where $t^+ = t + t_0$, t is the elapsed time and t_0 is the starting time. q^* is the target angle. q^*_{mid} is the middle point of the target range and the amplitude from that point to the maximum range is q^*_{max}. These are determined from the maximum target amplitude in flexion q_f^{max} and in extension q_e^{max}, where the target was defined to go up to 30% beyond the active ROM of the patient but capped by their passive ROM:

$$q^*_{max} = \frac{|q_f^{max} - q_e^{max}|}{2} \qquad q^*_{mid} = \frac{q_f^{max} + q_e^{max}}{2} \quad (3)$$

The target was programmed and updated in Matlab and t_0 is randomly selected to disrupt prediction. The patients were instructed to track the target as accurately as possible and told that they may feel haptic interaction from the robotic device and/or electrical stimulation.

C. Hybrid Robot-FES system

The robot used in the study is the HRX-1 one degree-of-freedom wrist robotic interface (HumanRobotiX, UK [19]) (Fig. 1B). It is actuated by a brushless low friction motor, located below the metal plate of the handle, 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), connected between the metal handle plate and the motor shaft using a shaft collar. 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. To maintain hygiene standards, device-specific cleaning protocols were followed. The robot is programmed in Matlab and ran at a frequency of approximately 75 Hz.

The stimulation device used in this study is the STIM 2.0 FES device 16-electrode array (Tecnalia Research & Innovation, Spain) (Fig. 1B), controlled remotely via Bluetooth communication. A hydrogel layer is placed on the electrodes to improve the conductivity of the array with the skin and straps are used to tighten the array around the forearm. Each patient uses an individual set of electrodes throughout the study. The pulse frequency of the stimulation is set to 35 Hz and the pulse width to 300 μs as these values have been used clinically [20]. The amplitude of the stimulation varies (with 0.1 mA resolution) during the experiment.

The control of the hybrid system determines the torque required from the robot and the FES, during assisted training, where both systems are concurrently providing torque $\tau(t)$ to the patient:

$$\tau(t) = K\,e(t) \qquad e(t) = q(t) - q^*(t) \quad (4)$$

where $e(t)$ is the tracking error between the participant's trajectory q and the target trajectory q^*. A negative/positive error indicates that the target position is further in extension/flexion than the patient's position. The control stiffness $K = 0.42$ Nm/rad corresponds to a soft-medium interaction stiffness [16]. It has been selected after preliminary testings with clinicians and patients to assist them in the task while preventing slacking. The robot torque $u_r(t)$ exerted on the wrist flexion/extension and the stimulation amplitude provided to the wrist flexor $s_f(t)$ or extensor $s_e(t)$ are defined as:

$$u_r(t) = \tau(t) \qquad s(t) = \begin{cases} s_e(t) = f(\tau_e(t)), & e(t) < 0 \\ s_f(t) = f(\tau_f(t)), & e(t) > 0 \end{cases} \quad (5)$$

where $s_e(t)$ and $s_f(t)$ are a function of $\tau_e(t)$ and $\tau_f(t)$, as defined in Eq. 1.

D. Data Analysis

The Root Mean Square Error (RMSE) [°] between the target trajectory $q^*(t)$ and the patient's trajectory $q(t)$ was used to evaluate the tracking performance: $\sqrt{\frac{1}{T}\int_0^T e(t)^2\,dt}$, $T = 12\,s$. It has been used previously to characterize the sensorimotor control strategies of stroke patients during target tracking tasks [21] and as an indicator of their motor recovery [22]. The Pearson's linear correlation between the

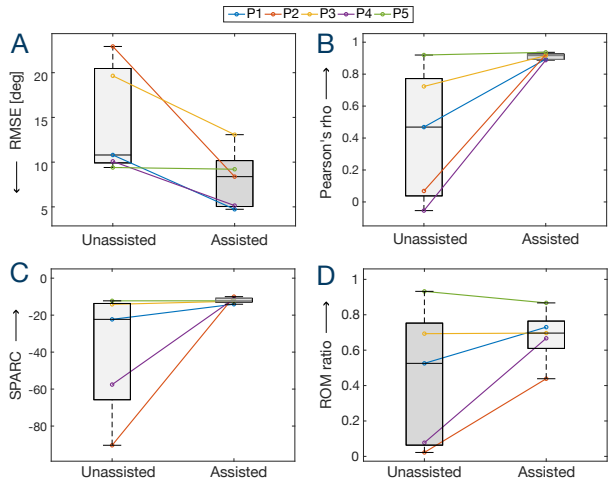

Fig. 2. Performance metrics during the tracking task while patients are receiving hybrid assistance, with arrows indicating score improvement direction. (**A**) Tracking performance. (**B**) Pearson's correlation. (**C**) Motion smoothness. (**D**) Tracking ROM ratio. The whisker lines above and below the box extend beyond the 25th or 75th percentiles of the data to the maximum or minimum value within the 1.5 interquartile range.

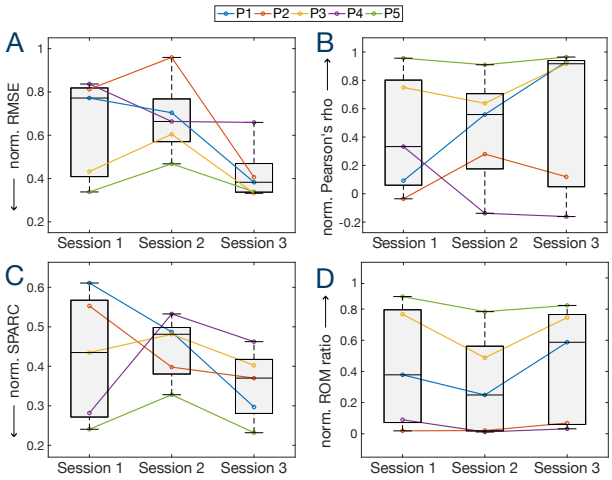

Fig. 3. Normalised performance metrics during the tracking task in the three sessions, with arrows indicating score improvement direction. (**A**) Tracking performance. (**B**) Pearson's correlation. (**C**) Motion Smooothness. (**D**) Tracking ROM ratio. The whisker lines above and below the box extend beyond the 25th or 75th percentiles of the data to the maximum or minimum value within the 1.5 interquartile range.

target and the patient's trajectory was also used. Correlation metrics between a target and patient's trajectories have previously been used in wrist tracking task and have shown to be associated with patients' functional scores [23]. Additionally, we investigated patient's motion smoothness, as there is evidence that it could be linked with motor recovery [24]. SPARC is used for this purpose [25], as it has been shown to be the most valid to investigate motion smoothness [26]. Finally, the ratio of the patients' ROM over the corresponding target ROM was used to quantify amplitude-related tracking performance. All metrics were calculated for each trial during the ten baseline trials and the 30 trials of the first training block. The average across the baseline trials and the training trials were obtained and compared across the three sessions. To allow for comparisons across patients, patient's metrics were normalised by their maximum metric value across all trials from the baseline and the first training block.

The answers of questions about the comfort and usefulness of the assistance and of two questions taken from the enjoyment section of the Intrinsic Motivation Index, are qualitatively analysed for each session.

III. RESULTS

A. Hybrid assistance

When comparing performance metrics during the assisted and unassisted trials (Fig. 2), we observe that hybrid assistance leads to increased performance for severely and moderately affected patients (i.e. FM-UE 2-38). The improvement is clear with the RMSE (Fig. 2A), subject-target correlation (Fig. 2B) and motion smoothness (Fig. 2C). The hybrid assistance only leads to an increase in ROM ratio during the tracking task for patients who are able to reach less than half of the target amplitude in the unassisted trials, i.e. two severely impaired patients, P2 and P4, and one moderately impaired patient, P1. However, even with assistance, most patients were not able to reach the target's full range.

B. Hybrid training

Patients repeated the training over three sessions and their baseline performance during the ten unassisted trials was recorded at the start of every session. The evolution of each performance metric, normalised within-patient by their maximum score for that metric, can be seen in Fig. 3. The tracking error has decreased for most patients from the first to last session and the median of session 3 is lower, with smaller interquartile range (Fig. 3A). P5, who has a high score in the first session and mild impairment, did not improve their performance with training, and this was the case for all metrics. The correlation between the patient's and target trajectory has improved for some patients (Fig. 3B). It has improved greatly from session 1 to 3 for P1 (ratio of 10.11) and slightly for P2 (ratio of 3.36) and P3 (ratio of 1.22). Similarly, P5, who has a large ROM ratio in session 1 already, did not improve (Fig. 3D). Severely impaired patients who have a low ROM ratio also did not improve their score. Regarding motion smoothness, all patients' performance improved from session 2 to session 3 (Fig. 3C). Although the median is lower in session 3 than in session 1, patients with a low normalised SPARC value did not improve, similarly as the other metrics.

C. User experience

All patients found that the use of the device and hence the assistance provided by the FES and the robot was comfortable in most sessions (Fig. 4). They also felt assistance in the majority of cases but did not always find this assistance useful for improving their performance in the target tracking task. All patients found the activity highly enjoyable and fun.

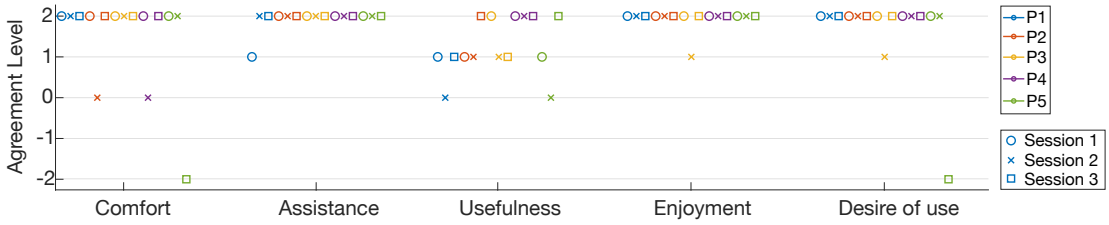

Fig. 4. Answers to 5-point Likert Scale questionnaire. Patients answered from 'Strongly disagree' to 'Strongly agree' to the following questions (figure from left to right): 'The use of the device was comfortable', 'During the experiment, I felt assistance', 'The use of the device improved my performance', 'I enjoyed doing this activity very much', 'I would like to use this sustem for my upper-limb therapy in the clinic'.

IV. DISCUSSION

This work presents preliminary results from a study investigating the use of a hybrid robotic and FES device for wrist flexion/extension in a rehabilitation setting. This device assists patients proportionally to their performance when tracking a target.

We first investigated the effect of hybrid assistance on performance and quality of motion. We found that both task-related metrics, the subject-target RMSE and correlation, improved when assistance was provided to the patients. Although patients reached high correlation scores, this metric only captures gross ability to follow the target rhythm and does not encompass finer differences such as in amplitude. For the RMSE, the variability remains higher even in the assisted case but severe patients who cannot move can have a lower RMSE than other patients who are intending to follow the target and are out of phase with it. Investigating additional metrics to get a clearer understanding is thus necessary. Some data-driven approaches have previously been used in order to mitigate this issue. A new score, that is a standard deviation away from the worst existing score can be assigned to paralysed patients, ensuring the metric is properly floored [27]. Motion smoothness and ROM ratio increased for patients with moderate to severe impairments. With assistance, patients still did not reach 80% of the target amplitude. This might be due to the stiffness values chosen for the strength of the robot and FES assistance. Indeed a soft-medium stiffness has been chosen in order to promote patient engagement and avoid slacking. A greater connection stiffness in the FES controller could also induce discomfort by providing strong stimulation in alternating directions. P5 who is mildly impaired rated the assistance as uncomfortable in the last session for this reason. Furthermore, the current data does not allow us to disentangle the impact of the FES and the robot assistance on the improvement in performance and quality of motion. To do so, additional intervention groups where patients train with each modality separately should be included, in order to understand, e.g. whether the performance improvement is due to the robot action alone.

Second, we investigated how training with the hybrid system could improve unassisted task performance and motion quality over time. Some patients' performance decreased in session 2 and increased again in session 3, this change might be due to spontaneous recovery, hence the need to collect data from a control group and more participants. The limited number of sessions also restricts the possibility to generalise about the effect of hybrid training. Additionally, results show RMSE decreased from session 1 to 3 in all patients but P5 who has the highest FM-UE score and highest tracking performance in the first session. Although the task difficulty was individually tuned as the target trajectory is based on a patient's own ROM, the least affected patient did not improve in any of the metrics, thus suggesting that the task difficulty should be further adapted to each patient. One approach used in many serious games is to adapt the difficulty of the task (e.g. robot and FES assistance, target speed and ROM) based on the challenge point framework or the 'flow channel' where users' scores should be maintained at a certain level to keep them optimally engaged [28], [29]. Similar results were found with other metrics, hence suggesting that moderately to severely impaired patients benefit from the training while the performance of mildly impaired patients do not change. Other studies explored the effect of hybrid rehabilitation on moderate to severe stroke patients and found positive training effects [1], [3], [30], [31]. These studies have investigated the effect of hybrid rehabilitation on FM-UE and have used controllers where the FES is triggered at the start of the task and the robot is passive [1], or with EMG-driven controllers [3], [30], [31]. On the other hand, recent research aims at implementing more optimal control algorithms. In this work, task performance and clinically-relevant quality of motion metrics are evaluated during hybrid training, where the results could inform the development of new patient-centred hybrid controllers. We would suggest to include adaptive stiffness gains, based on patients' abilities and preferences, as some may find FES more uncomfortable over time, as observed here. We also found that patients had a smooth motion when the same amount of FES and robot assistance is provided. Controllers providing less robotic assistance than FES could thus be tested in stroke population, as they could maintain high motion smoothness while increasing the benefits of FES.

Results from subjective assessments indicate that regardless of their impairment severity, patients highly enjoyed using this system, found it comfortable and would like to use it further for their upper-limb rehabilitation. Most studies did not consider subjective assessment of the assistance as part of their system evaluation, but a few investigated its usability [2], [32]. In a study where electrical stimulation was applied and a passive robotic system was used for support, patients found the stimulation comfortable and the

training enjoyable [32], while patients training with another passive exoskeleton with FES assistance found this system only moderately usable [2]. Our qualitative results thus complement existing work and are promising for the field. However, the answers to the statement 'The use of the device improved my performance' are mixed, even within subjects across sessions. Although patients found they felt assistance during the assisted trials, they did not evaluate it as useful. It is possible that the assistance did not match patients' intended motion as it was controlled to follow the target. This has been reported previously in a robot rehabilitation study where patients found that the robot was resisting their voluntary movement [33].

In summary, this hybrid robot-FES device has been used in five patients in a clinical setting for wrist flexion/extension training. Overall, patients found the device very comfortable and enjoyable to use. Additional patients are recruited and further analysis with a larger population size and in comparison to a control group is required to investigate the trends observed here and provide further recommendations for the development of hybrid controllers.

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