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EXECUTIVE SUMMARY OF THE THESIS

Adaptive Hybrid FES-Force Controller for Elbow Exosuit

LAUREA MAGISTRALE IN BIOMEDICAL ENGINEERING - INGEGNERIA BIOMEDICA

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1. Introduction

Neuromuscular diseases, such as spinal cord injury or stroke, can lead to motor disabilities and loss of strength, hindering affected patients in producing functional movements and execution of activities of daily living. Robotic devices and Functional Electrical Stimulation (FES) proved their capabilities to assist and restore motor functions. Despite rigid exoskeletons allow adaptable training intensity and higher accuracy and repeatability of movements, they are generally bulky, expensive, and they require the perfect alignment between the user and device joints. Contrarily, soft robotic suits (or exosuits) do not present this necessity, thus they hinder movements less, they are lightweight, cheaper and more comfortable. However, in case of patients with high level of impairment the rehabilitation effect of robotic devices is limited to only passively guide the task, without inducing the activation of patients' muscles.

On the other hand, Functional Electrical Stimulation (FES) actively stimulates muscles fibers by delivering short electrical stimuli to motor neurons reactivating paretic muscles, achieving functional tasks and restoring lost motor skills. Nonetheless, due to its working principle, the application of FES leads to muscle fatigue earlier in time and the highly non-linear muscle response to the stimulation could generate inaccurate movements.

Merging FES and robotic systems in Hybrid Robotic Rehabilitation Systems allows to exploit advantages of both systems and overcome their limitations. In particular, the assistance from robots improves the precision and the accuracy of FES-induced movements and postpones muscular fatigue. On the other hand, the inclusion of FES boosts the rehabilitative benefits and reduces the motor torque requirement. In order to achieve these goals the two systems must work in synergy, actuating cooperatively the same joint. Therefore, active robots are more suitable for this application since their assistance can be more finely modulated. In the literature, the majority of hybrid systems composed by active robots and FES assisting the same joint involve rigid exoskeletons and are designed for lower-limb. Indeed, only few studies developed active exoskeleton hybrid system to assist the elbow and none of these managed a balanced and coordinated actuation between FES and robot contribution. Moreover, these systems did not account for the FES-induced muscle fatigue. Concerning exosuits, only two studies have explored the possibility of combining them with FES [1, 2]. Nonethe-

Figure 1: FES-exosuit Hybrid System.

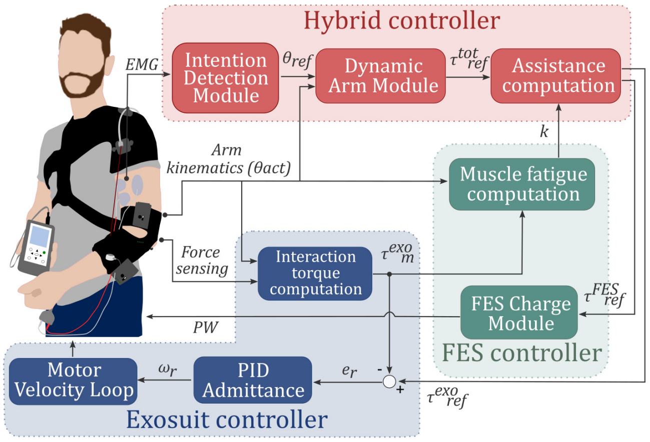

Figure 2: Real time control framework.

less, these studies shared the same limitations of the elbow active exoskeleton hybrid systems and none of them assisted the elbow. Guided by these literature limitations, this study designed for the first time in the literature a hybrid system integrating FES within an elbow exosuit. The goal of the system is to aid subjects in performing elbow flexion and extension, exploiting the rehabilitation benefits of FES, while assuring kinematics precision and accuracy provided by the elbow exosuit. In order to accomplish these goals, a coordinated and cooperative controller was developed, able to vary FES and robot assistance in order to limit, manage and postpone the FES-induced muscle fatigue.

2. Hybrid System design

2.1. Active elbow exosuit

The soft exosuit used in this work is a fully-embedded system built by ARIES Lab (ZITI, Heidelberg, Germany) [3], able to assist elbow movements (Fig.1). It comprises a textile harness that connects arm and forearm, made starting from a passive orthosis. The actuation stage aids elbow flexion/extension through a brushless motor (T-Motor, AK60-6, 24V, 6:1 planetary gear-head reduction, Cube Mars actuator, TMOTOR, China) which drives the pulley (35mm) around which the artificial tendon is wound (Black Braided Kevlar Fiber, KT5703-06, 2:2 kN max load). On the textile harness two anchor points are suited both on the distal and proximal side of the elbow and they are linked to the motor pulley via a Bowden cable (Shimano SLR, 5mm, Sakai, Japan). A force sensor (ZNLBM-1, 20 kg max load, China) is placed in between the connection of the cable with the distal anchor point and it measures the cable tension. Two Inertial Measurement Units (IMU, Bosch, BNO055, Germany) detect the arm kinematics and orientation. The actuation unit and the power supply (Tattu, 14.8V, 3700mAh, 45C) are screwed on the back protector. The control unit is driven by a microprocessor (Arduino MKR 1010 WiFi,Arduino, Ivrea, Italy) that receives sensors measurements via wireless protocol and sends the signals to the actuation stage via CAN-bus [3]. Moreover, a Bluetooth Low-Energy interface was developed to allow the Arduino to control the electrical stimulator.

2.2. Electrical stimulator

The electrical stimulator (KT motion, Medel, Hamburg, Germany) was used to stimulate the biceps inducing elbow flexion by means of two electrodes (Krauth+Timmermann, 4x6 cm area) placed over the muscle belly. When the stimulation is off, the EMG activity of the same muscle is measured. Biphasic electrial pulses at a frequency of 40 Hz were delivered to induce muscle contraction. The current amplitude was tuned for each subject as described in Section 3.5 and kept constant, whereas the pulse width (PW) was modulated during the movement.

3. Real time Control

The implemented real-time control consists in a hybrid approach that coordinates the assistance from the exosuit and from FES. Three main layers are interconnected in a close loop system (Fig.2): (i) *Hybrid Controller* that detects the subject's intention and computes the assistance for both the devices, (ii) *Exosuit Controller* which modulates the motor actuation, and (iii) *FES Controller* that manages the stimulation. The functionality of these layers is controlled by a state machine (Fig. 3), which defines the role of the robot and FES according to the state. In particular, during the *Break* phase the exosuit compensates for the gravity and the *Hybrid controller* identifies the intention of the subject. The *Flexion* state manages the flexion movement coordinating the exosuit and FES assistance. The *Compensation* phase accounts for the occurrence of muscle fatigue. Lastly, the *Extension* state is in charge of controlling the extension of the arm.

3.1. Hybrid controller

The *Hybrid controller* is the layer responsible of estimating the assistance needed to achieve the task. In the *Intention Detection Module* two thresholds are computed as 1.2 and 1.7 times the mean EMG value, which is calculated over a time window of 2 seconds in the *Break* phase. To each threshold a value of elbow flexion is associated:

60° and 90° respectively. The subject is asked to perform an isometric biceps contraction and once the EMG overcomes a threshold and the current EMG sample value is lower than the previous one, i.e. the EMG shows a downward trend, the subject's intention is mapped to a desired angle θ_{ref}, which is fed as input to the *Dynamic Arm Module*. This module computes the total elbow torque τ_{ref}^{tot} through an inverse dynamics approach, considering the subject's anthropometry, as described in [3]. Similarly to [4], the *Assistance computation* module splits τ_{ref}^{tot} into the reference torques of the exosuit (τ_{ref}^{exo}) and of the stimulator (τ_{ref}^{FES}) as follows

$$\begin{aligned} \tau_{ref}^{FES} &= \tau_{ref}^{tot} \cdot GainFES \\ \tau_{ref}^{exo} &= \tau_{ref}^{tot} \cdot GainEXO \end{aligned} \tag{1}$$

$GainFES$ and $GainEXO$ have values between 0 and 1 and $GainEXO = 1 - GainFES$. Their modulation is performed as explained in Sec. 3.3.

3.2. Exosuit controller

In order to deliver the motor command to the exosuit, the *Exosuit controller* estimates the error between the reference torque τ_{ref}^{exo} and the interaction torque between the wearer and the device (τ_{m}^{exo}), which is computed multiplying the force sensed by the load cell by the moment arm as described in [3]. The PID-admittance maps this error into the reference velocity w_r, which enters into the velocity loop of the motor, whose output is the mechanical actuation provided to the user.

3.3. FES controller

The *FES controller* involves two modules aimed at (i) modulating the pulse width according to the reference torque τ_{ref}^{FES}, and (ii) estimating the fatigue over time in order to adjust $GainFES$ and $GainEXO$.
The *FES Charge Module* defines the PW corresponding to τ_{ref}^{FES}, as follows:

$$PW = -\frac{\log(\frac{a}{\tau_{ref}^{FES}} - c)}{b} + \frac{PW_{off} \cdot \tau_{ref}^{FES}}{\tau_{max}^{FES}} \tag{2}$$

where a,b,c are subject-specific parameters tuned after a calibration procedure, PW_{off} is the term that accounts for the variation of this equation due to fatigue and τ_{max}^{FES} is the FES-induced torque at the maximum PW (500 µs). The *Muscle fatigue computation* estimates the actual torque provided by FES (τ_{m}^{FES}) through the torque balance equation

$$\tau_{m}^{FES} = \tau_{m}^{tot} - \tau_{m}^{exo} \tag{3}$$

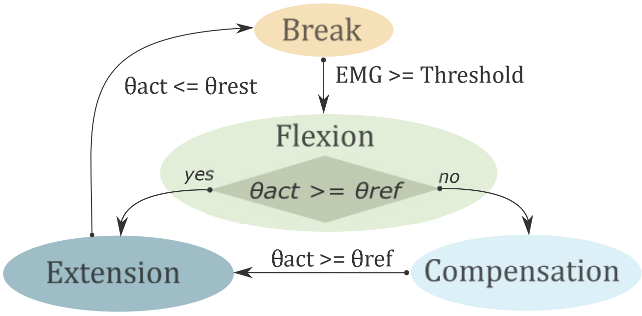

Figure 3: Illustration of the state machine.

with τ_{m}^{tot} being the actual elbow torque, computed using the arm kinematics. Subsequently, the FES-induced muscle fatigue k over the task is determined as follows

$$k = 1 - \frac{\tau_{m}^{FES}}{\tau_{ref}^{FES}} \tag{4}$$

Based on k, $GainFES$ and $GainEXO$ are tuned for the next movement as follows

$$\begin{aligned} GainFES(n) &= (1-k) \cdot GainFES(n-1) \\ GainEXO(n) &= 1 - GainFES(n) \end{aligned} \tag{5}$$

3.4. State Machine

The functionality of the hybrid system is coordinated by a state machine, which involves four main states: Break, Flexion, Extension and Compensation (Fig.3).

Break phase The *Break phase* is the phase in which FES does not provide stimulation ($GainFES$=0) and the assistance is delivered only by the exosuit ($GainEXO$=1). The input to the *Dynamic Arm Module* is the arm kinematics, used to compute the torque τ_{ref}^{exo} necessary to compensate for the gravity. The biceps EMG activity is acquired and its mean value is computed: when it reaches one of the two thresholds, the subject's movement intention is detected and the state machine switches to the *Flexion phase*.

Flexion Phase In this phase the elbow movement is totally driven by the hybrid system to get to the desired angle θ_{ref}, following a minimum-jerk trajectory of 3 seconds. The *GainFES* and *GainEXO* values define the two systems assistance levels. If at the end of the trajectory the desired angle is reached, the state machine switches to the *Extension phase*. Otherwise, the state machine enters into the *Compensation phase*.

Compensation Phase The state machine enters into the *Compensation phase* when FES is incapable of providing the required torque, due to muscle fatigue. Hence, the *Muscle fatigue computation* module determines the fatigue level and updates the gains for the next stimulation. Lastly, ramping up the PW, the system tries to get to θ_{ref}. The difference between the final PW value which allows to accomplish the task and the initial PW value (i.e. the one at the beginning of the *Compensation phase*) corresponds to the value of PW_{off} that appears in Eq. 2. Nevertheless, in case during the increase of the PW its maximum value (500 µs) is achieved, the exosuit compensates. When θ_{ref} is reached, the state machine moves into the *Extension phase*.

Extension Phase During the *Extension phase* the stimulation is gradually reduced and the Bowden cable tension is progressively released in order to extend the patient's elbow till a rest angle θ_{rest}. Ultimately, the state machine switches back to the *Break phase*.

3.5. Calibration Procedure

The calibration procedure was carried out for each participant before every trial in order to estimate the parameters of Eq. 2 of *FES charge Module*. During this procedure, the exosuit was not used and the voluntaries wore only the IMUs in order to record the arm kinematics. As first step, the current amplitude able to flex the elbow at 90° with a value of PW of 250 µs was selected and kept fixed. The wearer was then stimulated in sequential trials, with increasing PW values, from 20 µs to 500 µs, in steps of 20 µs. For each PW value, the initial position of the subject's arm was the resting one. Based on the arm kinematics, the elbow torque for each value of PW was estimated by means of the *Dynamic Arm Module* output τ_{ref}^{tot}. Finally, the data were used to find the subject-specific coefficients a,b,c in Eq.2. The whole calibration procedure lasts around two minutes.

4. Experiments

Six healthy participants with no evidence or known history of musculoskeletal or neurological diseases, exhibiting normal joint range of motion and muscle strength, were enrolled in the experiment (four males/two females, age 27±2.53 years, mean±SD, body weight 83±21.16kg, and height 180.83±11.90cm). All experimental procedures were carried out in accordance with the declaration of Helsinki on research involving human subjects, and were approved by the IRB of Heidelberg University (Nr. S-311/2020). All subjects provided explicit written consent to participate in the study. The study consisted in repetitions of tracking trajectory tasks, performed in three different conditions: (i) *Exo*, where the movement was entirely guided by the exosuit (*GainEXO=1, GainFES=0*), (ii) *FES* in which only FES provided assistance (GainEXO=0, GainFES=1) and (iii) *Hybrid* during which both the systems worked cooperatively to provide assistance. For each condition, a total of thirty repetitions of elbow flexion with amplitude of 60° and 90° in equal number were performed. Both the order of the conditions and the sequence of the angles repetitions were randomized between subjects to avoid biased behaviours. To avoid fatigue, subjects rested for at least two hours between conditions. For each repetition, the supervisor asked the subjects to reach a specific threshold, i.e. the one corresponding to the pre-set angle for that repetition (60° or 90°), performing a biceps isometric contraction. Despite the threshold triggered by the subject, the variable θ_{ref} was set equal to the pre-set angle, so that the accuracy of the intention detection method was assessed comparing the requested and triggered angles, while ensuring the same amount of repetitions with both angles. Subsequently, they had to remain completely relaxed throughout the elbow flexion to avoid any voluntary compensation. For the *Hybrid* condition, the initial *GainFES* was set equal to 0.8.

5. Data Analysis

For every conditions the coefficient of determination R^2 and the Root Mean Square Error (RMSE) were computed considering all the trajectories of one subject, between the target and the actual elbow angle and between the target and the actual total torque provided by the systems . The FES-induced fatigue was assessed for *FES* and *Hybrid* as the ratio between torques after and before the trial, generated by stimulation (same current amplitude, PW=500 µs) and obtained mapping the elbow angle into the torque through the *Dynamic Arm Module*. This index was subtracted to 1 and express in percentage, i.e. percentage reduction of the FES torque due to fatigue. Moreover, the fatigue onset was evaluated as the first repetition of the trial that required an increase of PW in the *Compensation phase*. For *Hybrid* and *Exo* conditions the motor power, computed as product between the motor velocity and motor torque, was normalized by the subject's mass and integrated in time, obtaining the motor energy per unit of mass. Lastly, comparing the pre-set angle and the one actually triggered by the user, the accuracy of the intention detection method was evaluated, creating a confusion matrix. The statistical anal-

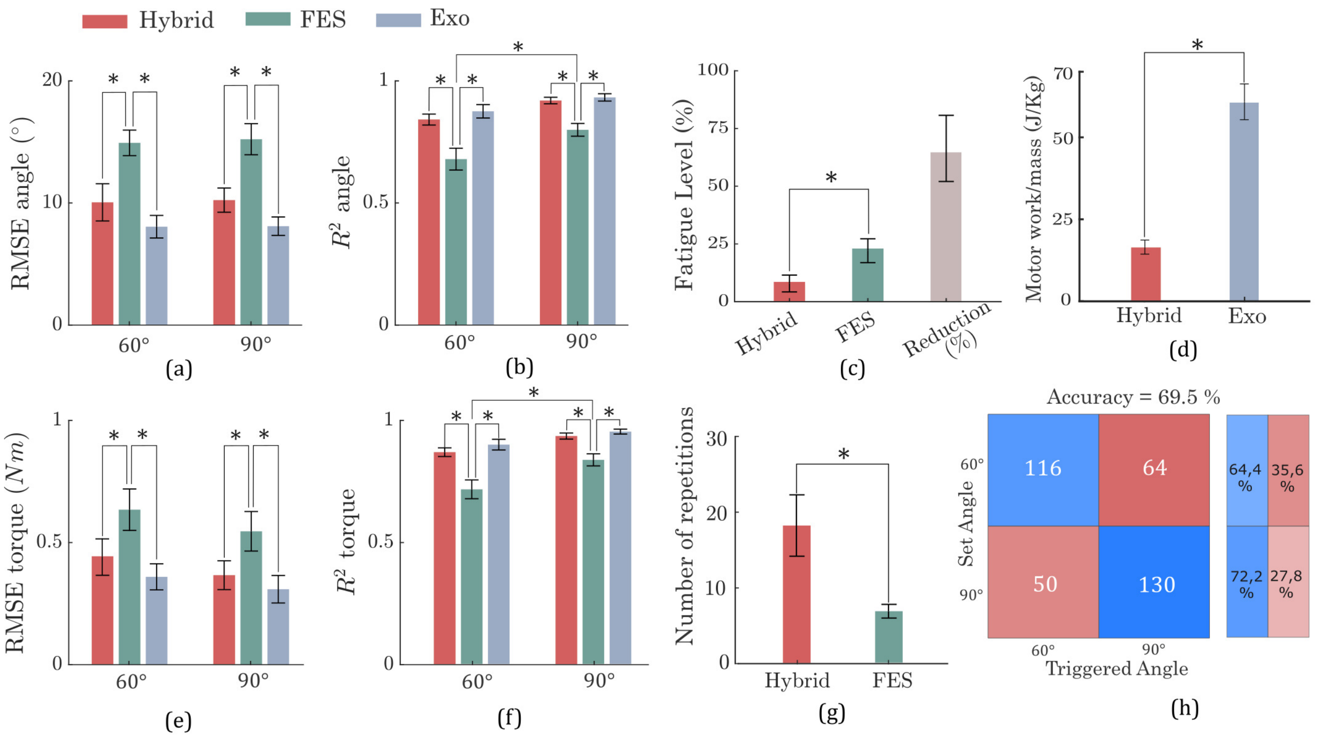

Figure 4: *Hybrid controller results.* RMSE and R^2 for elbow angle(a-b) and torque(e-f). (c)Fatigue level and percentage reduction of *Hybrid* fatigue compared to *FES*. (g)Fatigue onset (first repetition that displayed fatigue). (d)Motor work per unit of mass. (h)Intention detection confusion matrix.

ysis was performed with MiniTab. Data normality distribution was validated using Shapiro-Wilk test. Assistance indexes, which resulted to be normally distributed, were tested with a two-way ANOVA using the three conditions as the first factor and the two angles (60°, 90°) as second one. A two-samples T-test was used to compare both *Hybrid* and *FES* for the fatigue indexes and *Exo* and *Hybrid* for the motor energy index. When the ANOVA results were significant, a Fisher's LSD test was carried out to assess pairwise differences. For all the tests, the level of statistical significance was set to 0.05. Reported values and measurements are presented as mean ± standard error (SE). Significant differences in the results were highlighted with the symbol * in all figures.

6. Results

In Figure 4 the results obtained are reported. The RMSE and R^2 of the trajectory angle and torque showed significant dependency on the three conditions ($p < 0.003$). Furthermore, the R^2 of the *FES* condition had significant difference ($p < 0.007$) between the two angles, for both the kinematics and torque. For all the assistance indexes, the *Hybrid* condition did not show any significant difference ($p > 0.25$) with respect to the *Exo*. On the other hand, a significance difference ($p < 0.05$) was present for all the indexes between *FES* and *Hybrid* and between *FES* and *Exo*. For what concerns the fatigue level a significant difference ($p = 0.001$) was highlighted between the *Hybrid* (6.89 ± 2.90 %) and *FES* (22.37 ± 4.17 %). Moreover, the *Hybrid* condition significantly ($p = 0.008$) delayed the fatigue onset (14.50 ± 3.22 repetition number) with respect to *FES* (5.50 ± 0.72 repetition number). The motor work per unit of mass was significantly ($p = 0.005$) related to the conditions *Hybrid*(16.56 ±2.10 J/Kg) and *Exo* (60.83 ±5.45 J/Kg). Lastly, the intention detection module showed an accuracy of 69.5%, highlighting how the 90° threshold was more accurately triggered (72.2%) compared to the 60° one (64.4%).

7. Discussion

The maximum outcomes of patients rehabilitation in neuromuscular pathologies are obtained with active, intensive, repetitive and long-lasting rehabilitative sessions. Hybrid Robotic Rehabilitation Systems demonstrated their ability to fulfil these requirements, merging the rehabilitation benefits of FES with the precision, repeatability and adaptive intensity of robotic devices. Even thought exosuits seem to be a promising alternative to exoskeletons, few studies have explored the possibility of combining exosuits with FES. Would exosuits be a feasible option in hybrid systems? To address this question, an innovative hybrid system composed by FES and an elbow exosuit was proposed and its functionality was analyzed in terms of kinematics, FES-induced fatigue and motor torque requirement. As expected, the results highlighted how the solely use of FES produced both the highest torque and angle trajectory errors. Contrarily, the exosuit by itself was able to perform flexion movements with the lowest angular and torque error. No significant differences were found for these metrics between the exosuit and hybrid system, whereas the hybrid system significantly outperformed FES alone. This means that the hybrid controller was able to counterbalance the low precision and accuracy of FES, while preserving the assistance performances of the exosuit. Moreover, since the metrics were not significantly dependent on the amplitude of the movement angle, we can state that the hybrid controller performed with no significant difference with respect to the exosuit independently by the range of motion. Decreasing and delaying FES-induce muscle fatigue was one of the crucial goal of this study, since it is currently the biggest FES drawback. Comparing the torque generated by FES at the beginning and after the trials, a significant reduction of about 63±11.6% of the fatigue with the hybrid controller with respect to FES alone was obtained. This result is the direct consequence of the adaptive allocation of the assistance between the exosuit and FES in the hybrid system, according to the estimated fatigue. Moreover, with the hybrid controller the subjects were able to perform more repetitions before experiencing fatigue with respect to FES alone. This is a consequence of assisting the movement by both the exosuit and FES since the beginning of it, hence reducing the amount of stimulation required by FES and resulting in delayed onset of fatigue. Regarding the motor work for the *Hybrid*, the results showed a significant reduction of about 71.70±5.44% compared to *Exo*. These outcomes suggest the capability of the developed hybrid system to lower the energy and torque required by the motor, therefore enabling the system to include smaller actuators, hence increasing the portability of the system. Lastly, the data analysis carried out on the intention detection showed that the method had a satisfactory accuracy of about 69.5%, hence being suitable to recognize subjects' intention. Notwithstanding, this work presents some limitations. First of all, the control of FES is not implemented in a close loop, but it relies on the subject specific relationship between the FES-induced torque and PW. Even thought a modality to vary this relation accounting for the fatigue was proposed, due to the highly variability of FES outcomes a closed loop regulation of the stimulation would be more appropriate to manage its assistance. Secondly, the controller required the subjects to be completely relaxed throughout the movement. This requisite was necessarily introduced because the controller was tested on healthy subjects and without measuring continuously the biceps EMG signal, it was not possible to detect the subject's voluntary effort. Lastly, the developed controller was tested only on healthy subjects. In future studies another FES controller approach, either close-loop or EMG-proportional, should be implemented for this exosuit hybrid system. Moreover, further analysis should be conducted to validate the different outcomes between exoskeletons and exosuits in hybrid systems and their long-term rehabilitation achievements.

8. Conclusions

This study integrated for the first time in the literature FES with an elbow exosuit to investigate the possibility of using exosuits in hybrid systems. The results demonstrated that the hybrid controller managed cooperatively the assistance provided by the two systems, resulting in accurate and precise movements. Moreover, the proposed adaptive assistance allocation was able to detect and manage muscle fatigue, culminating in lower and delayed in time fatigue, decreasing also the motor torque requirement. These results reasonably suggest the feasibility of using exosuits in hybrid rehabilitation treatments of neuromuscular diseases in order to promote motion recovery.

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