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# Toward Dexterous Hand Functional Movement: Wearable Hybrid Soft Exoglove-FES Study

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***Abstract*— Functional electrical stimulation (FES), a lightweight wearable technology leveraging active muscle recruitment, can assist functional movement for rehabilitation and various activities of daily living. However, the intricate and user-specific nature of the neuromuscular response to FES, such as the induction of muscular fatigue and discomfort, can lead to incomplete or imprecise functional movements. On the other hand, soft exoskeleton gloves, another form of lightweight wearable technology for hand movement assistance, guide movement externally with higher precision. In this research, therefore, we present a novel hybrid system that combines a soft exoskeleton glove and FES technology. Such an augmented hybrid system could reinforce the advantages of active muscle recruitment as a primary source of actuation with external actuation of the exoskeleton compensating for the limitations of FES in torque generation. Our objective is to investigate the performance of this hybrid system compared to the standalone FES system through experimental evaluation.**

***Index Terms*— Hybrid soft exoglove, functional electrical stimulation, hand exoskeleton, soft exoskeleton glove, wearable assistive technology, grasping.**

## I. INTRODUCTION

Electrical stimulation of the nerves within the muscles results in muscle contraction and limb movement, which can be employed in functional tasks. This technique, called functional electrical stimulation (FES), is beneficial for rehabilitating patients with motor deficits, helping them regain their ability to perform activities of daily living (ADL) [1], such as grasping, opening, or dexterous hand movement [2]. Moreover, FES could promote neural plasticity of the central nervous system when it is used for a long-term [3]. However, due to the complex, nonlinear, user-specific, and time-varying behavior of the neuromuscular system in response to FES, controlling functional movements solely through FES is subject to significant stochasticity [4], [5]. Furthermore, ensuring the user's comfort when determining the maximum FES intensity often results in insufficient torque generation, leading to incomplete or imprecise functional movement. In contrast, external actuation devices, such as a hand exoskeleton, can compensate for hand weakness with more precise assistance in functional movements [6], [7]. However, the motion is generated from external torque, and the effectiveness of the exercise is often compromised unless users actively engage in the task [8]. In contrast to traditional exoskeletons, soft exoskeletons, despite facing control intricacy that may lead to lower accuracy, benefit from a combination of cost-effectiveness and flexible and lightweight design, which allows users to move with less hindrance, making them an ideal assistive device for ADL [9]. The hybrid system, which combines FES and a hand exoskeleton glove (exoglove), provides motion and support for functional hand movement while actively contracting relevant muscles in order to assist patients with impaired motor functions. Furthermore, the lightweight and wearable features of hand-assistive technologies significantly contribute to the usability and acceptance of the technology, especially in the context of ADL. Therefore, augmenting a soft hand exoskeleton [10], [11] with FES system represents a promising approach in the field of wearable assisting technologies [12], [13]. The integration of a tendon-driven glove [14] with a two-channel stimulator by Neto et al. [12] showcases a noteworthy approach in a hybrid soft exoskeleton, where the exoglove and two-channel FES are triggered based on force myography and force sensing resistor measurements. Although a growing trend is rising toward soft hybrid exoskeletons, the existing literature lacks a comprehensive understanding of the soft hybrid exoglove's capability in providing functional hand movement.

In this research, we investigate the advantages of the hybrid soft exoglove and evaluate its assistive capability. First, a novel lightweight wearable hybrid system consisting of multi-array FES and a soft exoglove is described, and a control method is proposed. The performance of the integrated system in generating grasping motion is subsequently tested on healthy participants, and the interactive effects of the hybrid system are analyzed.

## II. HYBRID SYSTEM

A wearable assistive system integrating multi-array FES with a soft exoglove (hybrid soft exoglove) is illustrated in Figure 1. The control architecture of the hybrid system, comprising low-level FES and soft exoskeleton control, assisting the hand functional movement, is depicted in Figure 2.

### A. Functional electrical stimulation

The goal of using FES in this study is to assist functional hand movement through multi-array FES electrodes. In general, in multi-array FES electrodes, the FES input control vector ($\mathbf{u}^F$) can be defined as

$$\mathbf{u}^F = [u_1^F \ u_2^F \ ... \ u_n^F]^T \quad (1)$$

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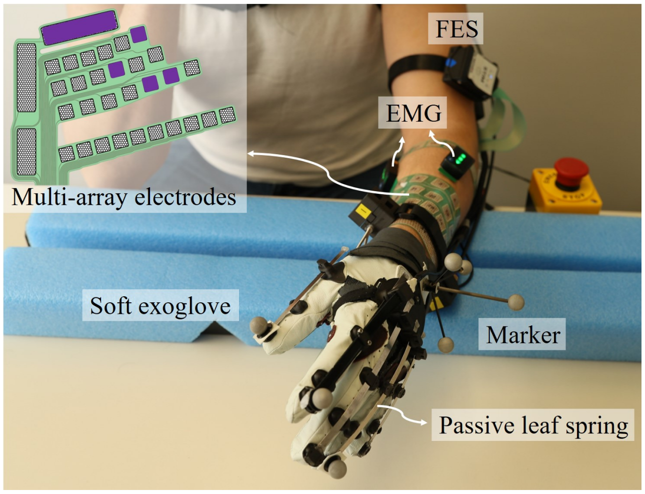


Fig. 1. Wearable hybrid soft exoglove system. The control system comprises a soft exoglove and FES with multi-array electrodes. EMG sensors and the marker-based tracking system measure muscle activities and hand motion for post-processing performance analysis, respectively.

where $u_i^F$ $(i \in \{1, .., n\})$ is the intensity of each FES electrode, and $n$ is the number of cathodes. The nonlinear static relation between the stimulation and finger flexion can be written as

$$y_{ss} = f(\mathbf{u}^F) \tag{2}$$

where $y$, $y_{ss}$, and $f(.)$ are the measured finger flexion, steady-state finger flexion in response to constant $\mathbf{u}^F$, and the nonlinear static map, respectively.

FES control system, shown as one of the sub-systems in Figure 2, consists of the selective movement calibration, learned FES-flexion map, and online FES control:

*Selective movement calibration:* It aims to find the electrode set producing desirable functional movement. To simplify and expedite the process of selective movement calibration, which is done manually, a similar FES intensity is considered for set of active electrodes, and the Eq. 1 is rewritten as follows

$$\begin{aligned} \mathbf{u}^F &= \mathbf{g}u^F \\ s.t. \quad 0 &\le u^F \le u^F_{max} \end{aligned} \tag{3}$$

where $\mathbf{g} = [g_1 \ g_2 \ ... \ g_n]^T$, and $g_i$ $(i \in \{1, .., n\})$ is either 0 or 1 for inactive and active cathodes, respectively. In other words, the objective of the selective movement calibration is to identify $\mathbf{g}$ as an electrode set capable of eliciting desirable functional movement. It also determines the maximum stimulation strength $(u^F_{max})$ that the participant reported to be acceptable before experiencing any discomfort.

*FES-flexion map:* Neuromuscular response to FES is user-specific and subject to a function of various complex and nonlinear factors [2], [4], [5]. In this research, a nonlinear user-specific map, denoted as $f$, models the static relation of FES intensity and flexion of the desirable finger. Figure 3 illustrates the user-specific FES-flexion map, $f$, for several healthy participants (Table I).

*FES control:* It consists of the user-specific learned FES-flex map $(f)$ in combination with a proportional differential (PD) control, which modulates FES intensity on a manually calibrated electrode set $(\mathbf{g})$. This FES control aims to maximize finger flexion while respecting the comfort and safe upper limit of stimulation intensity.

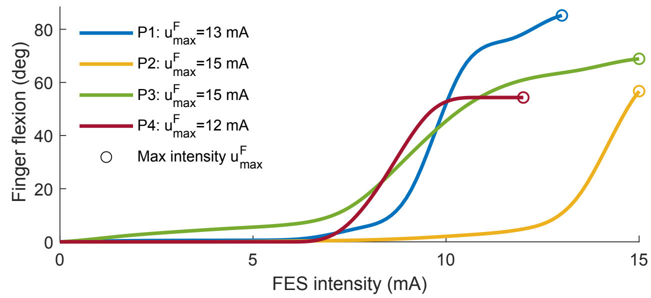


Fig. 3. User-specific FES-flexion map $(f(\mathbf{u}^F))$ and the maximum tolerable FES intensity $(u^F_{max})$ of four participants in Table I.

## B. Soft exoglove

*1) Hardware:* The development of the exoglove anchors the goal of faithfully replicating hand functions by assisting all five fingers. To simplify the complexity of the mechanism, we chose a one-to-many strategy that exploits the redundancy and synergies inherent in hand grasping. This enabled us to actuate the entire hand using three motors that actively aid in flexion while a passive leaf spring mechanism facilitates the extension. The textile base of the exoglove consists of a commercially available golf glove that underwent specific modifications to enhance its suitability for individuals affected by muscular deficits. The modifications divide the textile component into three parts covering the thumb, index/middle finger, and ring/little finger, allowing independent linking of these three parts. We implemented a guiding system sewn onto the glove, incorporating Teflon tubes secured by textile parts and 3D-printed components. This system guides the tendons along the palm, ensuring a uniformly distributed pulling force. To facilitate hand synergies, the tendons are directed around the fingertips of the assisted fingers, organized into three as shown in Figure 4a (thumb, index/middle finger, and ring/little finger), following the detailed approach outlined by In et al. [15]. To link the wrist and the actuation unit, we used a Bowden cable system that could be securely fastened magnetically using a custom 3D-printed system with a clutch mechanism [11].

To monitor the overall bending angle during flexion and provide position feedback, we integrated a Bend Labs Digital Flex Sensor (Bend Labs, Salt Lake City, UT, USA) at the index/middle finger level (hand group 3 in Figure 4a). This flex sensor measures the path-independent angular displacement. It internally estimates the angular displacement between its two clamped ends (here, the base and tip of the attached finger) with the limited effect of the path, bending radius, or strain and the repeatability of 0.18°.

Finger's kinematics, measured by the described flex sensor, is transmitted via Bluetooth Low Energy serial protocol


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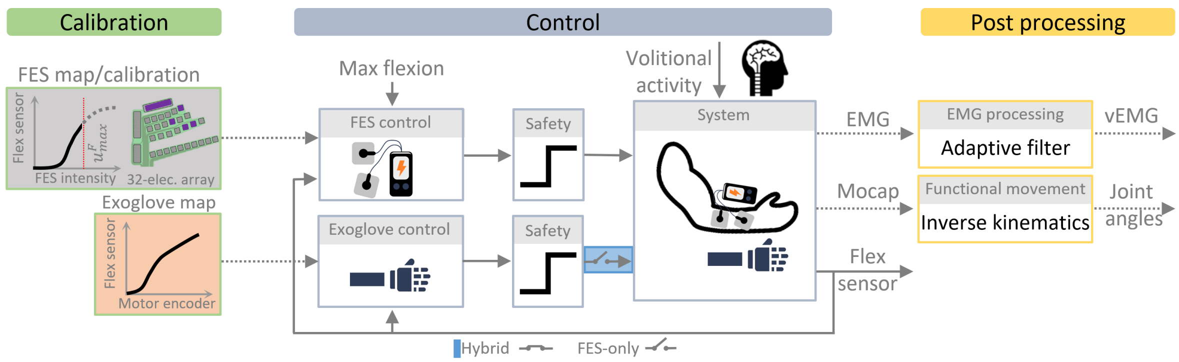


Fig. 2. Control architecture of the hybrid soft exoglove. A selection of solo FES or hybrid system is modulated by a switch. In addition to control, this diagram illustrates the calibration and post-processing blocks.

through two microcontrollers (Feather nRF52) to an Arduino MKR 1010 WiFi, functioning as the real-time control unit. Operating at $100\,\mathrm{Hz}$, the Arduino board executes the exoglove controller implemented in a MATLAB/Simulink application and dispatches motor commands via CAN-bus to the actuation stage. The actuation stage, responsible for enabling finger flexion, comprises three flat brushless motors (T-Motors, AK60-6). Each motor propels a pulley ($\varnothing 35\,\mathrm{mm}$) around which the artificial tendon, facilitating finger movements by providing up to $3.5N$ of force for each finger, is wrapped.

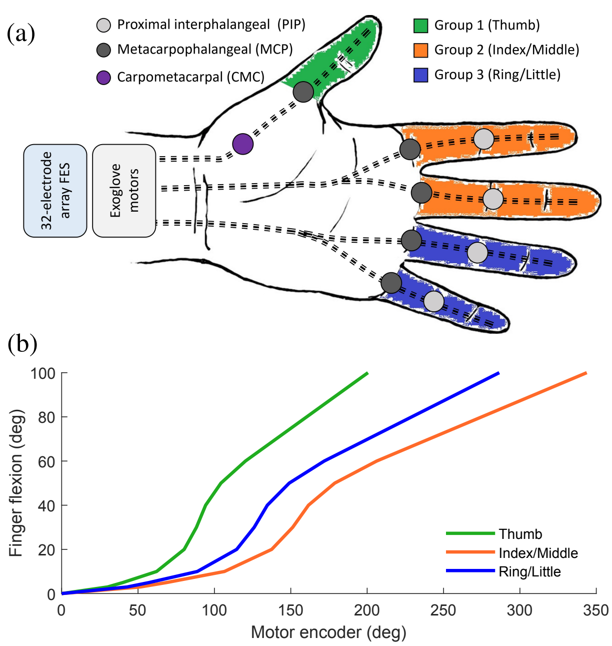


Fig. 4. (a) Schematic diagram of the three hand groups (thumb, index/middle finger, and ring/little finger) and considered joint angles in performance evaluation. The assistive devices control these three hand groups. Noted that the distal interphalangeal (DIP) joint of the fingers and the interphalangeal (IP) joint of the thumb are not considered in this figure and post-processing of the result. (b) Motor encoder-flexion map ($h(\theta^M)$) for three hand groups controlled by the three motors of exoglove.

*2) Soft exoglove control:* The control algorithm takes the flexion of the index/middle finger group measured by the flex sensor and maps it onto specific motor position commands. A damping contribution based on the angular velocity of the finger is introduced to improve the control system's stability and reduce oscillations. The angular velocity of the fingers is calculated by taking the time derivative of the measured finger angles. The damping contribution is then computed using a damping coefficient which determines the strength of the damping effect. The control system then calculates the required actuator commands from the input angle and maps them onto a position value based on the motor encoder. The motor commands and the damping contribution are sent directly to the exoglove's actuators in a feedforward manner. Therefore, the assistive control of the soft exoglove is formalized as

$$\begin{aligned} \theta_d^M &= k_p h^{-1}(y) + k_d dy/dt \\ s.t. \quad & 0 \le \theta_d^M \le \theta_{max}^M \end{aligned} \tag{4}$$

where $\theta_d^M$ is the desirable motor encoder value directly sent to the three motor units. $k_p$ and $k_d$ are the control gains, and $h^{-1}(.)$ is the inverse of the nonlinear motor encoder-Flex map shown in Figure 4b

$$y_{ss} = h(\theta^M). \tag{5}$$

## III. EXPERIMENTAL EVALUATION

### A. Study protocol

*1) Participants:* Four healthy individuals (all males) participated in this study. Table I outlines their demographic data and previous experience with hand exoskeleton and/or FES. All participants gave informed consent before their participation.

TABLE I
PARTICIPANT DEMOGRAPHICS

| Participant | Age (years) | exoglove† | FES† |
|---|---|---|---|
| 1 | 28 | Yes | Yes |
| 2 | 23 | No | Yes |
| 3 | 30 | No | Yes |
| 4 | 28 | No | No |

† Previous experience with an exoglove and FES

All participants were right-handed but wore the hybrid soft exoglove on their left hand, as the soft exoglove is


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specifically designed for the left hand (Figure 1). Note that participants are passive in this study, and furthermore, the objective is not to assess the effectiveness of the system in dominant versus non-dominant hands.

*2) Experimental design and analyses:* This study evaluates the advantage of integrating a soft exoglove into FES system to enhance grasping motion. Therefore, we compare the performance of the hybrid soft exoglove and solo FES in providing functional hand movements for passive participants. As the soft exoglove assistance is intended to be proportional to the user's residual movement or FES-induced movements, it does not provide any assistance without voluntary or FES-induced functional movement. Thus, the solo soft exoglove is not considered in our evaluation. The administration of the two conditions was counterbalanced across the participants (Table I) and interleaved with the rest period aiming for recovering from fatigue. Each condition consists of 10 trials, each lasting 10 seconds of active assistance interleaved with 10 seconds of a resting period (Figure 5). In both conditions, the participants are instructed to relax and allow the assistive devices to perform the full movement.

*3) Calibration:* The soft exoglove calibration determines the maximum flexion in the motor encoder-flexion map for each participant, which is later used in soft exoglove control. For this purpose, the participants are asked to flex their fingers as much as possible. In FES calibration, after manually determining the electrode set producing the desired motion most selectively (**g** in Eq. 3), the FES intensity is gradually increased, and participants report when it becomes uncomfortable. This value is set as the maximum stimulation strength ($u^F_{max}$). Then, the FES-flexion map ($f$) is generated by administering six different FES intensities (equally spaced between the minimum (0.1 mA) and maximum ($u^F_{max}$) intensities). Each FES stimulation lasts 5 seconds, interleaved with 5 seconds of a resting period (Figure 5). Given FES and the flexion profiles, the nonlinear FES-flexion map is modeled by the cubic spline.

*4) Protocol:* The experimental protocol is outlined in Figure 5. At the start of the experiment, multi-array FES, EMG sensors, and Soft exoglove are fitted to each participant (Figure 1). Then, the calibration of exoglove/FES and FES-flexion map learning are performed (Section III-A.3). After the calibration, the solo FES and hybrid system are tested. During the task, the participants are instructed to relax during the active phase and bring their hands back to the rest position during the rest phase interval.

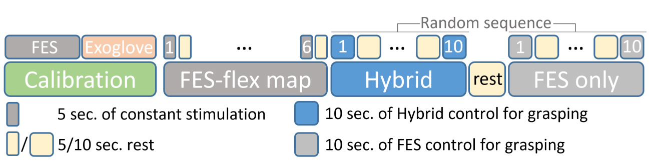


Fig. 5. Overview of the experimental protocol including the FES and exoglove calibration, FES-flexion map learning, and two assistive methods presented randomly to each participant: hybrid soft exoglove and solo FES.

### *B. Control apparatus*

*1) Functional electrical stimulation:* A 32-electrode array FES (Tecnalia Research & Innovation, Spain) allows real-time control over stimulation parameters, including the pulse amplitude, width, and frequency of stimulation. In this study, the 25 Hz biphasic electrical pulse featuring a fixed pulse width of 300 $\mu s$ and varying intensity with a precision of 100 $\mu A$ is considered as a control variable in FES control. After placing the 32-electrode array on the skin of the lower arm, a garment is used to maintain the correct position of the electrodes and to ensure that the electrodes are well adhered to the skin.

*2) Soft exoglove:* Soft exoglove developed by ARIES lab (Heidelberg, Germany) and described in detail in Section II-B.1 is integrated into the system to complement the limitation of FES in functional movement assistance. The flexion angle measured by the flex sensor of the soft exoglove is sent to FES and soft exoglove systems for the purpose of online control.

### *C. Other apparatus and data processing*

For a thorough analysis of the result, EMG and hand motion-capturing systems are employed to measure muscle activities and hand movements, respectively. These two measurements are not directly integrated into the control system and will be utilized for offline data analysis.

*1) EMG measurements and adaptive filtering:* The Trigno Wireless Biofeedback System (Delsys, USA) records the EMG biofeedback signals from the skin's surface. The setup consists of two Trigno EMG sensors with dry electrodes (silver bar contacts), which are affixed to the anterior and posterior of the forearm using the adhesive sensor interface, and operate at a sampling rate of 4370 Hz.

This study aims to investigate the performance of the FES-alone and hybrid systems in assisting passive users, therefore, despite the instruction for the participants to remain passive throughout the trial, we need to consider the effect of unintentional voluntary muscle contraction, which can affect our evaluation. To estimate the level of voluntary contribution in these two systems, we measured the EMG signals to monitor the volitional activity of participants. The volitional EMG (vEMG), showing the volitional activity of participants, is estimated using recorded raw EMG signals. First, the EMG, corrupted by FES artifacts and M-wave contributions [16], is filtered out using an adaptive filter [17]. Then, the average of the filtered signal envelope is used as an estimate of the voluntary muscle activity.

*2) Hand motion capturing:* The Qualisys motion capture system (Qualysis AB, Sweden), as a standard marker-based motion capture system, is used in this study. The data is recorded with a sampling frequency of 150 Hz, and as illustrated in Figure 1, markers are attached to the subject's thumb, index/middle finger, and ring/little finger to measure the movement of the three hand groups (Figure 4a), and four additional markers are used as the reference for the general forearm movement. The position of the markers is recorded during the whole experiment for offline analysis


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of the kinematics of finger movements with the help of wrist and hand model. Note that marker-less motion capture methods, such as MediaPipe Hands framework [18], offer an alternative approach for hand motion tracking.

The OpenSim musculoskeletal model of the hand and wrist [19] is employed for inverse kinematics of finger movements using marker-based motion tracking. This model consists of 21 degrees of freedom (DOF) for the fingers/thumb and two DOFs for the wrist. The exemplar result of the inverse kinematics for two postures of the left hand (rest and maximum flexion) is illustrated in Figure 6.

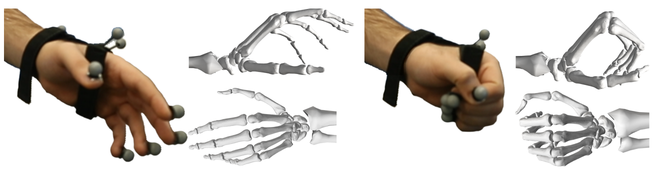

Fig. 6. OpenSim wrist and hand model [19] is utilized for inverse kinematics evaluation of finger movements using marker-tracking data. Two hand postures, rest (left) and maximum flexion (right), are shown. For a clearer representation of the finger's flexion, the hybrid soft exoglove illustrated in Figure 1 is excluded in this specific experiment and figure.

## IV. Results and Discussions

The result of the hand flexion in both scenarios, solo FES and hybrid soft exoglove systems, are depicted in Figure 7. The joint angles of the three hand groups, acquired from the hand inverse kinematics analysis, show higher flexion in the hybrid case, meaning that the soft exoglove assists and complements FES-alone flexion. Table II presents the average result of FES intensity, flex sensor, fingers/thumb joint angle, and vEMG across all participants and trials in both systems. The average stimulation intensity in both scenarios is near the maximum tolerable stimulation intensity (83.7% and 81.6% in FES-only and hybrid, respectively), showing that for reaching the maximum flexion, FES induces almost the maximum possible torque inside its comfort zone, while the flex sensor and hand group join angles results show the higher flexion in the hybrid system. In other words, the control goal, reaching maximum flexion inside the comfort/safe zone of stimulation, is partly accomplished in FES-alone control, while in the hybrid case, thanks to the extra torque generated by soft exoglove, we reach the higher flexion inside FES comfort/safe zone. Therefore, not only do we benefit from FES active muscle contraction inside the participant's comfort zone, but we also further accomplish our control goal of having higher hand flexion.

Close inspection of the achieved index/middle group flexion in both FES-only and hybrid systems for all trials and participants (Figure 8) highlights larger hand flexion in the hybrid system than that in FES alone. Given Figure 7 and Figure 8, although we note an overall increased finger flexion in the hybrid system, both in average performance and across the majority of individual trials, the consistent and similar behavior of the system in each trial cannot clearly be observed. Integrating a comprehensive neuromuscular model and advanced control method that accounts for intricate and time-varying factors such as fatigue and hand reflexes, which are not considered in this study, can help gain deeper insights into the system's behavior and achieve more accurate control performance in each trial.

Moreover, the Wilcoxon signed-rank test is employed due to the study's small sample size (four participants) to investigate the significance of the hand flexion differences between hybrid and FES-only systems. The analysis indicates a statistically significant increase in hand flexion in the hybrid case ($Z = 1.64, p = 0.05, one - tailed$).

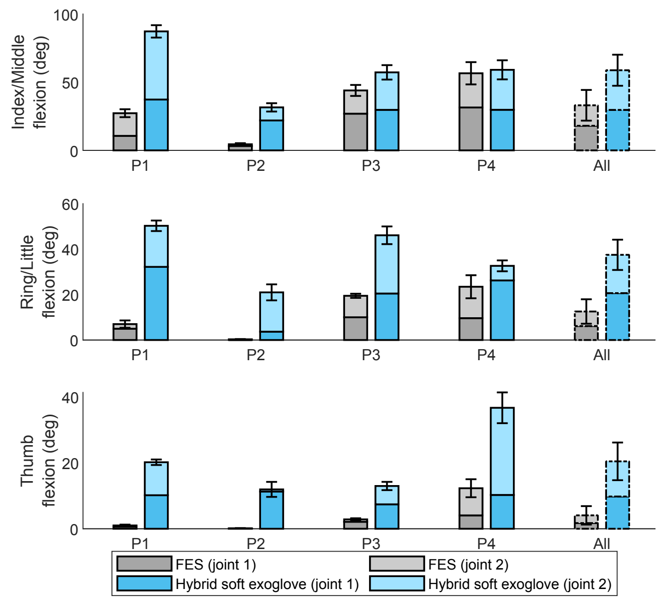


Fig. 7. Hand flexion, represented by joint angles of three hand groups, in FES and hybrid exoglove system. The figure shows the average flexion values of ten trials across all participants for three distinct hand groups (index/middle, ring/little, and thumb) by two joint angles (index/middle and ring/little: MCP and PIP, thumb: CMC and MCP). The standard deviation represents the standard deviation in the sum of two joint angles ($\theta_{j_1} + \theta_{j_2}$) within each group. The solo soft exoglove is not considered in this study as its assistive control is based on residual or induced FES movement, meaning that without voluntary or FES-induced functional movement, exoglove will not assist.

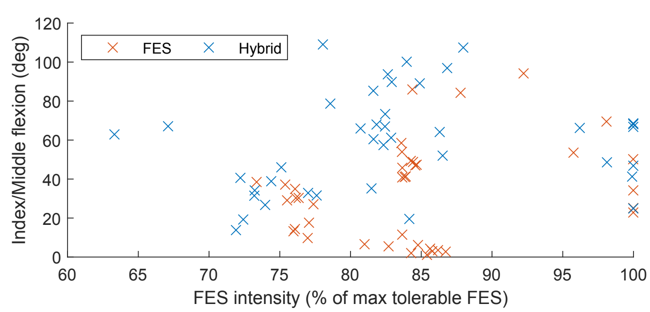


Fig. 8. Flexion of the index/middle group, $\theta_{j_1} + \theta_{j_2}$, achieved in different FES intensities (percentage of the user-specific maximum FES intensity) in both hybrid and FES systems and for all trials and participants.

Evaluation of the result of each participant illustrates that in three participants (P1, P2, P3), we observe a considerable increase in targeted hand group flexion, while for Participant


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TABLE II

AVERAGE RESULT ACROSS ALL PARTICIPANTS AND TRIALS IN FES AND HYBRID SOFT EXOGLOVE SYSTEMS

| Variable | FES<br>Mean (std) | Hybrid<br>Mean (std) |
|---|---|---|
| **FES intensity (% of max tolerable FES)** | 83.7 (3.74) | 81.6 (4.90) |
| **Glove sensor flexion (deg)** | 28.2 (8.86) | 58.2 (6.96) |
| **Index/Middle flexion (deg)** | 33.1 (11.3) | 58.8 (11.4) |
| **Ring/Little flexion (deg)** | 12.6 (5.38) | 37.5 (6.67) |
| **Thumb flexion (deg)** | 4.10 (2.80) | 20.5 (5.72) |
| **vEMG* envelop (flexor, $\mu V$)** | 3.28 (0.44) | 3.61 (0.36) |

*Extracted from raw EMG with adaptive filter [17]

4, the flexion on the index/middle group an only merginal improvement was observed (56.55° and 59.07° degrees in FES and hybrid case, respectively). On the other hand, all participants showed higher flexion of the other hand groups (ring/little and thumb) with the hybrid case.

The average of the filtered vEMG of the flexor across all participants and trials (Table II) does not show a significant difference between the vEMG in FES and hybrid systems (3.28 $\mu V$ and 3.61 $\mu V$, respectively), which suggests that the volitional contraction during both tasks does not have a considerable difference.

## V. CONCLUSION

This study presents and evaluates the performance of a novel lightweight wearable hybrid soft exoglove system, comprising multi-array FES and soft exoskeleton glove, with user-specific control architecture designed to provide the desired hand flexion in passive users. Our control architecture would allow the assistive technology to benefit from FES as a primary source of the actuation supplemented by soft exoglove as a complementary assistive device. This combination enhances assistance for hand functional movements, allowing for increased finger flexion and compensating for the incomplete induced FES torque within the FES comfort zone. Evaluation of the experimental results demonstrates the improvements of the hybrid system compared to the FES-only system in enabling hand flexion.

## ACKNOWLEDGMENT

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