Soft Robotics to enhance endurance in individuals with Multiple Sclerosis

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Abstract

Multiple Sclerosis (MS) is a chronic autoimmune disorder that affects the central nervous system and can result in various symptoms, including muscle weakness, spasticity, and fatigue, ultimately leading to the deterioration of the musculoskeletal system. However, in recent years, exosuits have emerged as a game-changing solution to assist individuals with MS during their daily activities. These lightweight and affordable wearable robotic devices have gained immense popularity. In our study, we assessed the performance of an elbow motion exosuit on eight individuals with MS using high-density electromyography to measure biceps muscle activity. The results demonstrated that our prototype significantly reduced muscle effort during both dynamic and isometric tasks while increasing the elbow range of motion. In addition, the exosuit effectively delayed the onset of muscle fatigue, enhancing endurance for people with MS and enabling them to participate in longer and more extensive rehabilitation protocols.

Keywords: Multiple Sclerosis, Exosuits, Wearable Robotics, High-density Electromyography

1. Introduction

Multiple sclerosis (MS) is a common neurodegenerative chronic disease affecting approximately 3 million people globally.[1] Individuals with MS suffer from motor and cognitive impairments, including muscle weakness, fatigue, spasticity, and attention deficit.[2] Upper limb impairments in people with MS affect finger movements, bilateral coordination, and muscle synergies activation, which significantly impact their activities of daily living and quality of life.[3–6]

Robotic devices show promise in improving motor function for individuals with MS.[7] However, despite the rapid growth in technology for assistance and rehabilitation, there are only few studies focused on treating upper limb-related MS disorders.[5,8–11] For example, Pierella et al.[12] developed a body-machine interface for a planar robot manipulandum that reduces biceps/triceps co-contraction in reaching tasks, and Jakob et al.[13] tested the efficacy of commercially available robotic platforms in reducing kinematic impairments. There is evidence suggesting that long-term rehabilitation programs involving upper limb robotics can provide functional benefits for people with MS.[14]

Due to the high cost of rehabilitation robots, only a limited number of private customers are

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able to afford them. Thus, these devices have been primarily used in specialized markets such as hospitals, clinics, and rehabilitation centers. The development of low-cost untethered lightweight exoskeletons and exosuits[15] presents an alternative to traditional rigid robotic platforms, which can increase the accessibility of wearable robots for people affected by MS to assist with activities of daily living.

The goal of this approach is to provide devices that can be worn and operated independently, without the need for expert or medical supervision, both in the home and outdoor environments. These devices can improve working conditions,[16] restore walking,[17] upper-limb movements,[18,19] and grasping functions.[20]

In the last few years, we demonstrated how exosuits are able to reduce muscular effort[21] without hindering the wearer's kinematics,[22] both in industrial applications[23] and in high dynamic tasks.[24] We refined our architecture to match three main points: lightness, portability, and usability.

In this study, we aimed to assess the effect of using an exosuit on individuals with MS by having eight of them undergo two different tasks while wearing a soft device for elbow assistance. Our goal was to determine if the exosuit improved endurance while preserving natural motion. The first task required dynamic arm movements through elbow flexion, while the second task required participants to hold a weight isometrically for a time of $180\mathrm{s}$. We monitored performance using a combination of kinematic and physiological metrics through high-density surface electromyography. The results indicated that the exosuit did not hinder natural movements during the dynamic task and effectively reduced muscle effort. Moreover, the robotic assistance delayed the onset of muscular fatigue and enabled individuals with MS to exercise with higher intensity, a more number of repetitions, and for a longer duration. These findings align with those of a previous study on people with Bethlem muscular dystrophy and cervical spinal cord injury.[25]

This paper aims to demonstrate the potential of wearable devices to revolutionize the support provided to individuals with Multiple Sclerosis in rehabilitation practice and daily activities. This can lead to an improvement in their quality of life and increased independence.

2. Exosuit Design and Control

[Figure 1 about here.]

The exosuit, which is depicted in Fig.1a, is an untethered system that assists in elbow flexion movements: it consists of an actuation unit, which is the central component of the active support system, and a custom-made textile harness to transfer the force to the user's joint via an external artificial tendon.

This last element, made of kevlar fiber (Black Braided, KT5703-06, 2:2kN max load, Loma Linda CA, USA), is connected to the subject's forearm through a 3D printed distal anchor point sewed onto the orthosis. The resistive forces of the tendon, such as friction and backlash, are absorbed by a Bowden cable (Shimano SLR, $\varnothing 5\mathrm{mm}$, Sakai, Ōsaka, Japan) and transferred to the textile harness via a second anchor point located at the shoulder. The actuation stage is designed to be lightweight and portable, weighing only $2\mathrm{kg}$ and powered by a battery pack, allowing the user to receive active support for around 8 hours.

The actuation stage comprises a flat brushless motor (T-Motor, AK60-6, 24V, 6:1 planetary gearhead reduction, Cube Mars actuator, T-MOTOR, Nanchang, Jiangxi, China), and two microcontrollers. The first microcontroller manages communication with the sensors through Bluetooth Low Energy (BLE), while the second microcontroller is responsible for real-time control. The sensing network, which detects the user's motion and measures the interaction force between the wearer and exosuit, includes two Inertial Measurement Units (IMUs, Bosch, BNO055, Gerlingen, Germany) for detecting 3D arm kinematics and a force sensor (ZNLBM-1, $20\mathrm{kg}$ max load, Bengbu Zhongnuo Sensor, China) to measure the interaction force applied to the user. The communication protocol between the sensing systems and the control stage has been implemented via BLE, as described in Burchielli et al.[26]

The control framework operates in real-time (as shown in Fig. 1b) and is built on the "Dynamic Arm Module" approach previously proposed in Lotti et al.,[24] which exploits the electromechanical assistance using a 3D biomechanical model of the human arm, customized to the participant's body measurements. The force sensor measures the interaction torque, and an admittance controller uses the difference between this value and the reference torque to determine the motor velocity command.

3. Experiments

The study involved eight right-handed individuals diagnosed with Multiple Sclerosis according to the McDonald criteria.[27] These participants were selected from the group of outpatients treated at the AISM (Italian Association of Multiple Sclerosis) Rehabilitation Service of Genoa, Italy. The inclusion criteria were:

- $>$ 18 years old;
- all diseases courses;[28]
- stable disease course in the last 3 months;
- Expanded Disability Status Scale (EDSS) $\leq$ 7.5;[29]
- Mini-Mental Status Examination (MMSE) $>$ 24;[30]
- Evaluation of upper limb disability through Rasch methodology (ABILH) $\geq$20.[31]

Participants' demographic and clinical data are reported in Table 1 (two females, 62.1 ± 8.0 years old, height 1.71 ± 0.09 m, body weight 67.4 ± 8.5 kg, ABILH 38.9 ± 9.0, EDSS 4.81 ± 1.16, mean ± sd).

[Table 1 about here.]

The local Ethics Committee approved the study (CER Liguria: 197/2022 - DB id 12304). It conformed to the ethical standards Declaration of Helsinki as revised in 2013, and each participant signed a consent form to participate in the study.

3.1. Experimental Apparatus and Protocol

We evaluated the exosuit performance in individuals with MS using a high-density electromyography system (HDsEMG), a sixty-four channels probe (Muovi+Pro, OT Bioelettronica s.r.l., Torino, Italy), placed on the participant's arm, to measure the biceps activity.

The experiment included two distinct tasks, referred to as *Pick and Place* (dynamic) and *Endurance* (isometric), described in subsequent sections, with the objective of evaluating various outcomes.

[Figure 2 about here.]

1. *Pick and Place* (Fig. 2a). The participants were required to move a $500\mathrm{mL}$ bottle of water, weighing $0.5\mathrm{kg}$, between two positions placed in front of them that differed in height by approximately $30\mathrm{cm}$. An audio cue from an external source initiated the movement to the appropriate target location, and no constraints on movement or timing were imposed for completing the task. The *Pick and Place* task was performed in three different random conditions: (1) without the device (*No Suit*), (2) wearing the device while it was turned off (*Unpowered*), and (3) with the assistance of the device (*Powered*). For each condition, 12 back-and-forth movements were performed. A $5\mathrm{min}$ break was scheduled between the conditions to prevent muscle fatigue.
2. *Endurance* (Fig. 2b) Test in which participants held a dumbbell with a mass corresponding to approximately $\approx 5\%$ of their total body weight at a 90° angle of the elbow, avoiding involving the shoulder muscles. The maximum time limit for this task was set to 180s but was terminated at the subject's request when exhaustion was reached. The *Endurance* task was performed in two different conditions presented randomly: (1) *Unpowered*, and (2) *Powered.* A $15\mathrm{min}$ rest period was given to the participants between conditions to allow them to recover from muscle fatigue.

3.2. Data Analysis

To evaluate the performance of the exosuit in individuals with Multiple Sclerosis, we examined kinematic and physiological measures. For the *Pick and Place* task, we utilized Inertial Measurement Units (IMUs) to obtain data at a sampling rate of 100Hz and determine the elbow flexion and extension phases. To calculate the speed of the joint, a 4th-order Savitzky-Golay filter with a 10Hz cutoff was employed. The onset of movement was identified as the point when the speed surpassed 10% of its maximum value, and the endpoint was identified as the time when the speed fell below the same threshold.[32] The range of motion, mean velocity and peak velocity of the elbow joint were analyzed during these phases. In order to assess the smoothness of the kinematics, we utilized the SPectral ARC length (SPARC) technique, which assigns lower values to movements that are less smooth.[33]

The HDsEMG signals were recorded at a rate of 2kHz and underwent further processing to clean the data. A fourth-order Butterworth bandpass filter was applied, with a frequency range of 20-400Hz, to extract the relevant signal. Any power line interference was removed using a notch filter (50Hz), and any remaining noisy channels were interpolated using the data from neighboring channels. Each channel was normalized based on the 95^{th} percentile of all signals calculated from multiple recordings of the same participant.[34] The biceps activity was measured in terms of activation volume, which was calculated as the volume of the distribution of root mean square (RMS) amplitudes for each electrode in a monopolar configuration. The activation volume was calculated using 500ms epochs and was compared across conditions to assess changes in activity.[34]

In addition, the HDsEMG data collected during the *Endurance* task was used to analyze the onset of fatigue. The muscle fiber conduction velocity (CV) was used as an indicator of fatigue.[35] Longitudinal double-differentials were calculated by subtracting signals from consecutive rows in the single-differential configuration. CV was estimated by dividing the distance between two consecutive detection points along the muscle fibers by the delay between the detected signals.[35] The delay was calculated from the maximum of their cross-correlation. Fatigue was quantified as the slope of a first-order model fitting the CV data during the first minute of the *Endurance* task, with epochs of 500ms. A steeper negative slope indicated a faster onset of fatigue.[36] Finally, the duration of the *Endurance* task was also taken into account as a muscle fatigue metric.

3.3. Statistical Analysis

We assessed the normal distribution of the measurements via a Shapiro-Wilk test with a significance level set at $\alpha = 0.05$. Repeated measures analysis of variance (rANOVA) was adopted to examine the effects of the biceps activities in the *Pick and Place* task. We considered the *'Assistance'* as within-subjects factor: (*No Suit*, *Unpowered*, *Powered*). Statistical significance was considered for p-values lower than 0.05; we reported the notation $F_{df1,df2}$ to indicate the degrees of freedom. Post-hoc analysis on significant main effects and interaction was performed using Bonferroni-corrected paired t-tests. Statistical analysis was conducted using Minitab (Minitab, State College, PA, USA). Reported values and measurements are presented as mean ± standard error (SE). We highlighted significant differences in the results with the symbol * in all the figures.

4. Results

4.1. The exosuit increases elbow range of motion

Fig.3 shows the kinematic data extracted from IMUs signal during the *Pick and Place* task. The flexion and extension phases of elbow kinematics, normalized with respect to execution time, are presented in Fig.3a-b, displaying the average data from all participants. While assisted by the device, the elbow angle achieved higher amplitude peaks, resulting in a significantly higher range of motion in the *Powered*(46.38±3.57°) with respect to the *Unpowered*(41.07±3.06°) condition (Fig.3c, $p < 0.001$).

Fig.3b shows higher velocities during flexion in the *Unpowered* condition, whereas similar profiles were found during extension between conditions. As a consequence, a significantly higher peak velocity was found in the *Unpowered* condition (59.00±4.11°/s) with respect to *Powered* (43.65±3.57°/s) condition (Fig.3d, $p < 0.001$).

However, no significant difference resulted in the elbow mean velocity (*Unpowered*: 22.07±1.61°/s, *Powered*: 22.12±1.90°/s, $p = 0.96$, Fig.3f).

At last, movement smoothness (Fig.3e) was significantly higher ($p < 0.001$) in the *Unpowered* condition (SPARC: -1.44±0.06) with respect to the *Powered* condition (SPARC: -1.47±0.03).

[Figure 3 about here.]

4.2. The exosuit reduces muscular effort in both dynamic and isometric tasks

A repeated measures ANOVA showed significant differences between the conditions regarding the normalized activity volume ($F_{2,7} = 17.61$, $p < 0.001$). As shown in Fig.4a, a representative participant's HDsEMG activation matrix during the *Pick and Place* task was similar in *No Suit* and *Unpowered* conditions in both the flexion and extension phases, whereas biceps activity was lower in the *Powered* condition. Post-hoc analysis confirmed this finding (Fig.4b), revealing a significant difference in the normalized biceps activation volume ($p < 0.001$) between the *Powered* (0.30 ± 0.13) and the *No Suit* (0.53 ± 0.14) conditions and a significant difference ($p = 0.003$) between the *Powered* and the *Unpowered* (0.43 ± 0.14) conditions. No significant difference was observed between the *No Suit* and *Unpowered* conditions ($p = 0.030$).

The reduction in biceps activity during the *Powered* condition was observed also in the *Endurance* task, as shown in Fig.4c by the activation volume of a representative participant holding the dumbbell in isometric flexion. This was confirmed for all participants by the highlighting of a significant difference ($p = 0.0325$) between the *Unpowered* (0.36 ± 0.01) and the *Powered* (0.32 ± 0.01) conditions.

[Figure 4 about here.]

4.3. The exosuit increases biceps endurance

HDsEMG allows assessing how the command from motor neurons spreads through muscle fibers, as depicted in Fig.5a: a decrease in conduction velocity was associated with higher levels of fatigue. A significant difference ($p = 0.0325$) was found between the *Unpowered* ($-0.04 \pm 0.02\%$/s) and *Powered* ($0.15 \pm 0.14\%/\mathrm{s}$) conditions, indicating that the exosuit improved endurance (Fig.5b). Moreover, we noticed that most participants terminated the *Endurance* task prematurely when they performed it without assistance from the exosuit. However, during the *Powered* condition, they were able to hold the dumbbell for the entire duration of the task. This pivotal finding becomes more evident when examining the time spent on the Endurance task (Fig.5c), which showed a significant difference ($p = 0.0026$) between the *Unpowered* (114.6 ± 14.7s) and the *Powered*(165.5 ± 11.6s) condition.

[Figure 5 about here.]

5. Discussion

Individuals with Multiple Sclerosis experience a gradual and consistent decline in neuromuscular abilities, resulting in reduced muscle strength and endurance.[37,38] This reduces their ability to perform everyday activities related to personal care, leading to a decreased quality of life and making it difficult to lift or carry objects independently.[39] Our goal was to investigate the efficacy of an exosuit designed to assist the biceps muscle in reducing the burden on the musculoskeletal system of people with MS. The prototype we developed is compact, lightweight, and can be easily worn by those with neuromuscular disabilities.[24] Our control method does not require calibration or medical assistance but instead incorporates the user's anthropometric measurements into the control process.

5.1. Higher mobility without hindering wearer's motion

The use of the exosuit led to an increased range of motion for all the participants (see Fig.3c), and it enabled them to carry out the *Pick and Place* task by keeping a consistent mean velocity during elbow movements (see Fig.3f).

A lower peak velocity (Fig.3d) in the *Powered* condition can be attributed to the novelty of using the exosuit for the participants. Indeed, it is reasonable to assume that with a longer familiarization, the kinematics would improve and match the values recorded during the *Unpowered* condition. Our results indicated that the movements were smoother without the exosuit's assistance (see Fig.3e), which is consistent with prior research on unimpaired individuals who used the same control strategy.[22]

5.2. Reduction in muscular effort

By utilizing the HDsEMG system for biceps activity acquisition, we were able to conduct a deep analysis of biceps muscle activation during both dynamic (*Pick and Place*) and isometric (*Endurance*) tasks. We assessed biceps activity in terms of activation volume, which considered not only the amplitude of the channels but also the distribution of muscle activity across the electrode matrix.

Our results demonstrated that individuals with MS had lower biceps activity when using the exosuit, regardless of the type of movement required. This pattern has been extensively studied in unimpaired people, where our elbow exosuit has been proven to reduce biceps effort in most elbow flexion tasks.[21–24,40] The results of our present study further emphasize the advantages of using an exosuit, particularly for individuals who have experienced partial muscle strength and endurance loss.

5.3. Higher endurance and less fatigue

The analysis of conduction velocity using the HDsEMG exhibited a noticeable enhancement in muscular endurance while lifting loads, as demonstrated by the delayed onset of fatigue (Fig.5b). This significant finding was further corroborated by the fact that most of the participants were unable to complete the *Endurance* task unaided, stopping before the maximum time of 180s. On the other hand, in the *Powered* condition, the average stop time was nearly 60s longer.

5.4. Limitations and future steps

Our study's findings provide evidence for the potential benefits of exosuits in assisting people affected by Multiple Sclerosis. However, it is worth noting that our study has limitations as the exosuit was tested in a controlled setting (i.e. laboratory) for a limited number of participants and a restricted amount of time (i.e. 1h). To better understand the practical applications of the exosuit for people with MS, further research is required to examine its use over extended periods of time in more ecological settings (e.g. at home and work), with a larger population that includes different types of MS and stages of the disease. Additionally, the ergonomic properties of the exosuit could be evaluated through ad-hoc and validated questionnaires. In this way, we will be able to enhance the quality of life for people with Multiple Sclerosis and other neuromuscular conditions.

6. Conclusions

The use of wearable and lightweight devices to assist individuals with neuromuscular diseases has been restricted to a few specific situations. However, in this study, we showed the potential of using an exosuit to support individuals in completing easy tasks but important for completing daily living activities. Our findings indicated that the exosuit effectively reduced musculoskeletal strain, delayed the onset of biceps fatigue, and improved endurance. In summary, our approach has the potential to assist people with Multiple Sclerosis in their daily activities, and we believe that widespread adoption of such devices can greatly enhance their quality of life.

Author Disclosure Statement

No competing financial interests exist.

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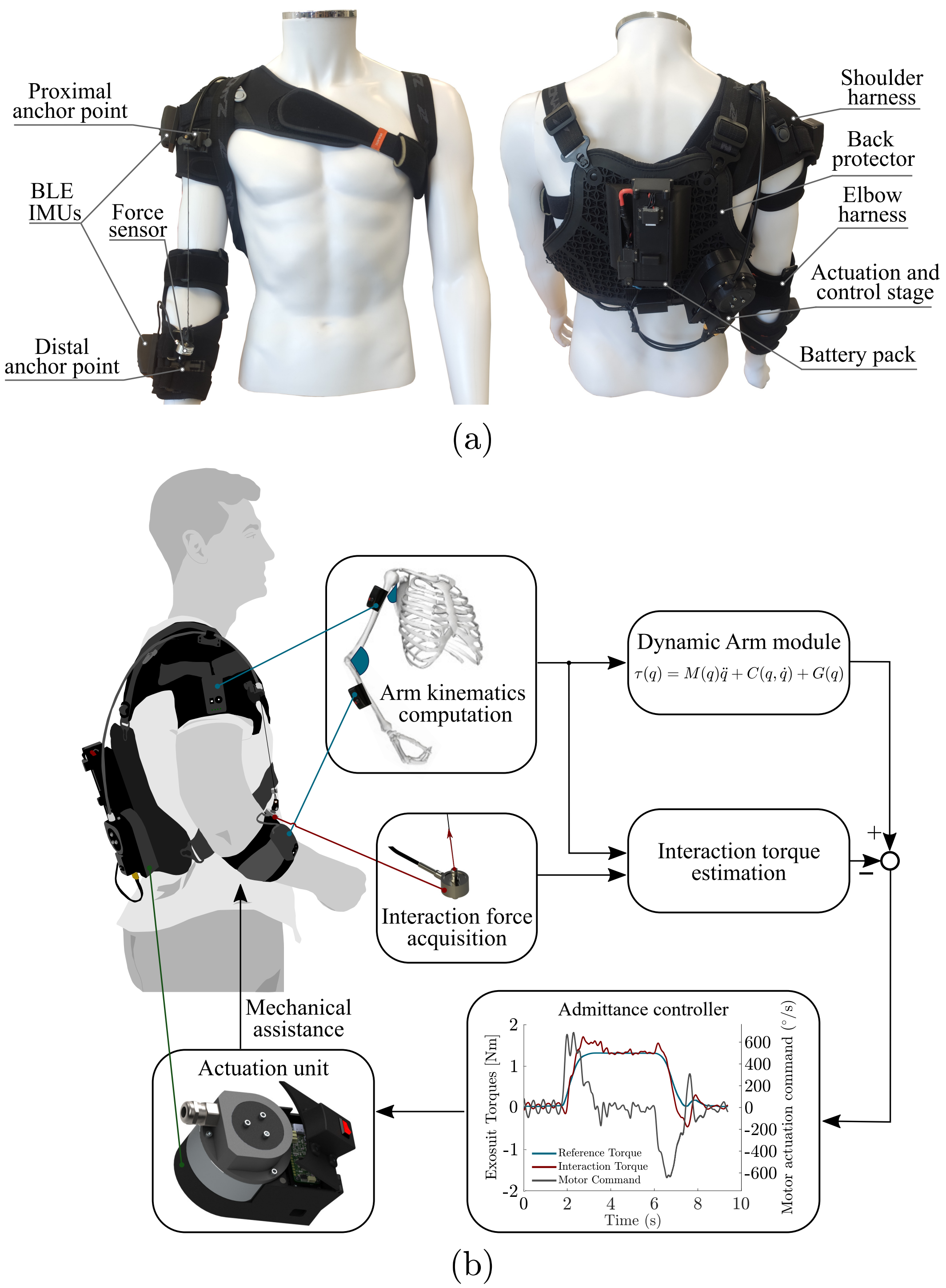


Figure 1. *Elbow exosuit design and real-time control framework* The design and control framework of the elbow exosuit can be described as follows. (a) The exosuit is a system that supports elbow flexion through fully-actuated tendon-driven mechanisms. It consists of two main components: a lightweight orthosis and a back protector that houses the actuation stages, control unit, and power unit. The exosuit is equipped with two IMUs that capture the 3D arm orientation and a force sensor that measures the interaction force between the user and the suit. (b) The exosuit is capable of assisting the wearer through the dynamic arm module by compensating for the effort required to lift the forearm against gravity. The control framework includes a biomechanical model that is customized to the user's anthropometry. The reference torque is estimated and then compared to the interaction torque that is extracted from the force sensor. The torque tracking error is then converted into a motor velocity command through an admittance controller and sent to the actuation stage to provide the necessary assistance .

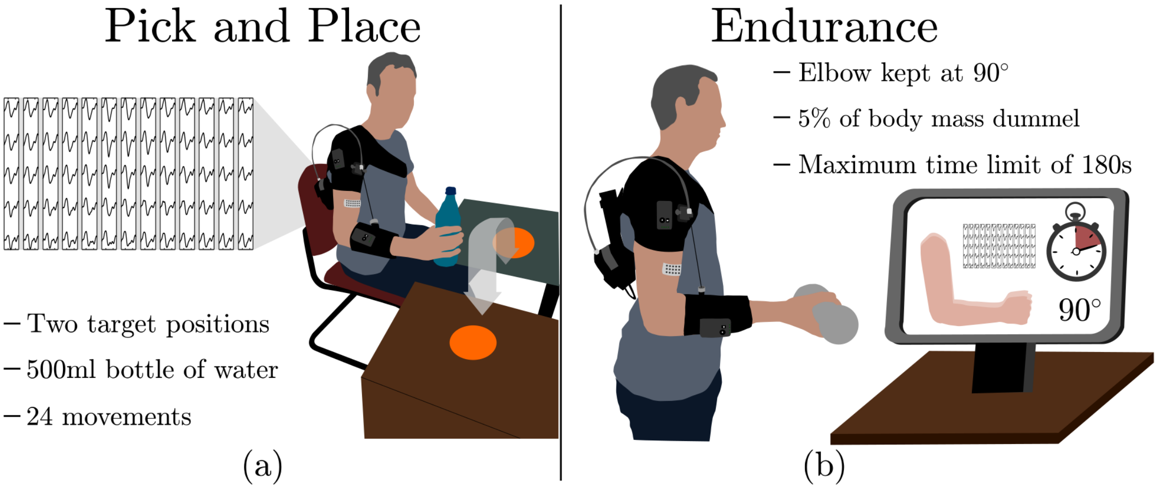


Figure 2. *Functional tasks.* (a) The *Pick and Place* task involved participants grasping and moving a 500mL bottle filled with water between two designated locations (i.e. the orange circles). (b) In the *Endurance* task, participants were required to hold a dumbbell equivalent to ≈5% of their overall body mass while keeping their elbow at a 90° angle.

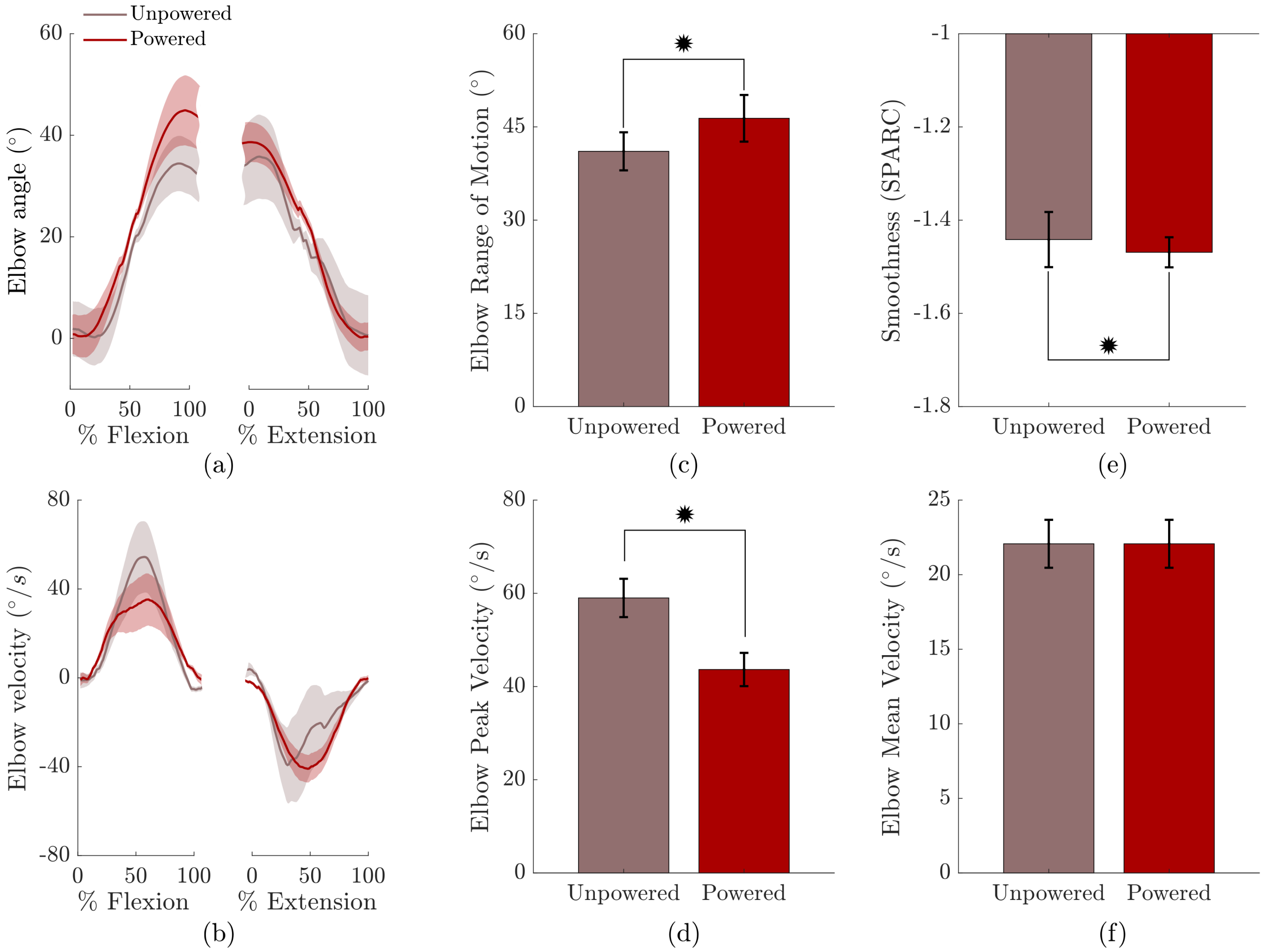


Figure 3. *Pick and Place, kinematic results.* Data related to the *Unpowered* condition are depicted in grey, while *Powered* condition is represented in red. (a) IMU signals used to extract elbow kinematics for all participants are shown and normalized with respect to execution time. (b) Elbow velocity averaged across all participants is presented, The solid lines represent the mean value, while the shaded area is the standard deviation. Panels (c), (d), (e), and (f), respectively, display the elbow range of motion, peak velocity module, SPARC index, and mean velocity module for both the flexion and extension phases. The error bar depicts the standard error. The symbol $*$ denotes a statistically significant difference ($p < 0.05$).

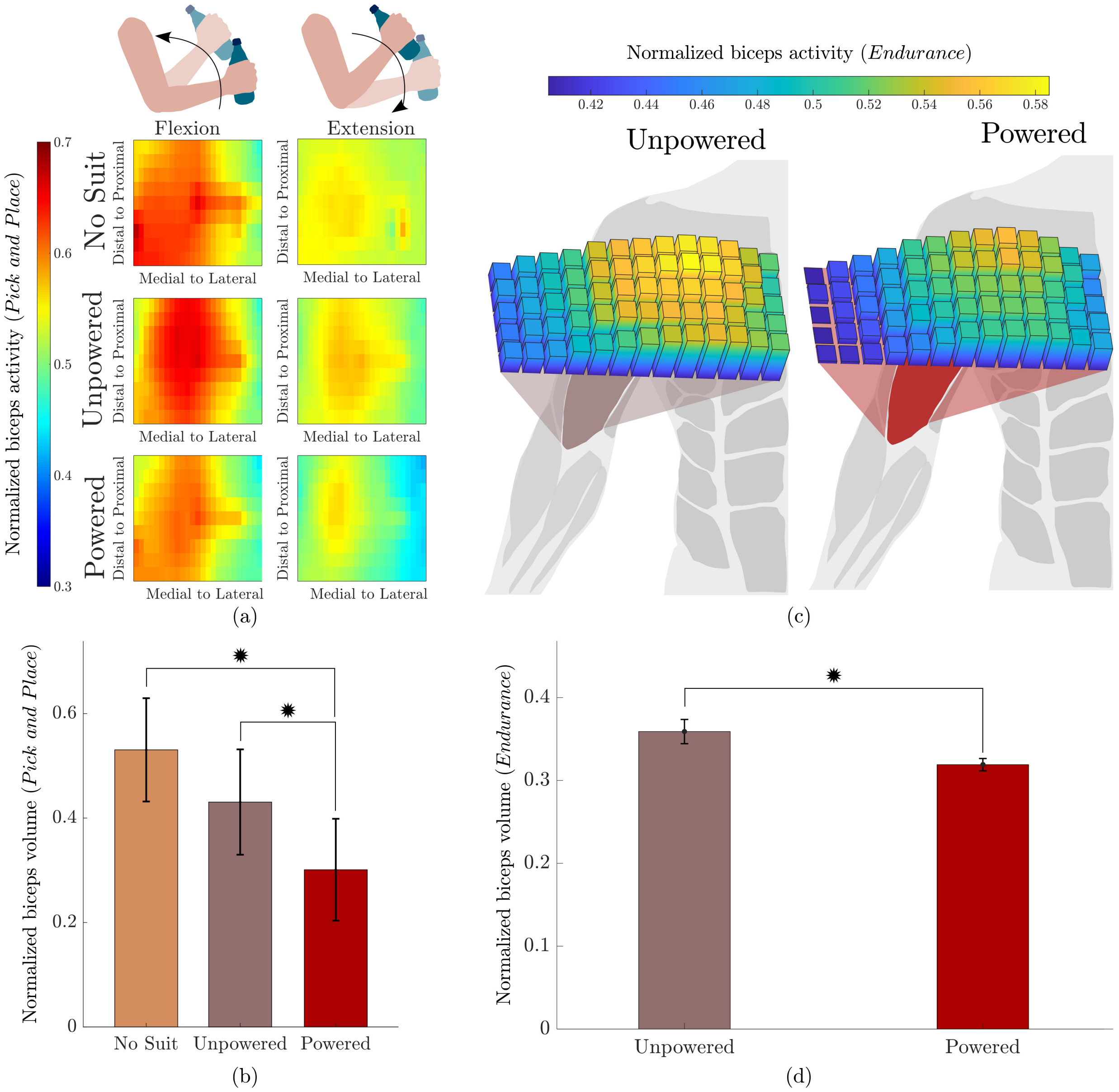
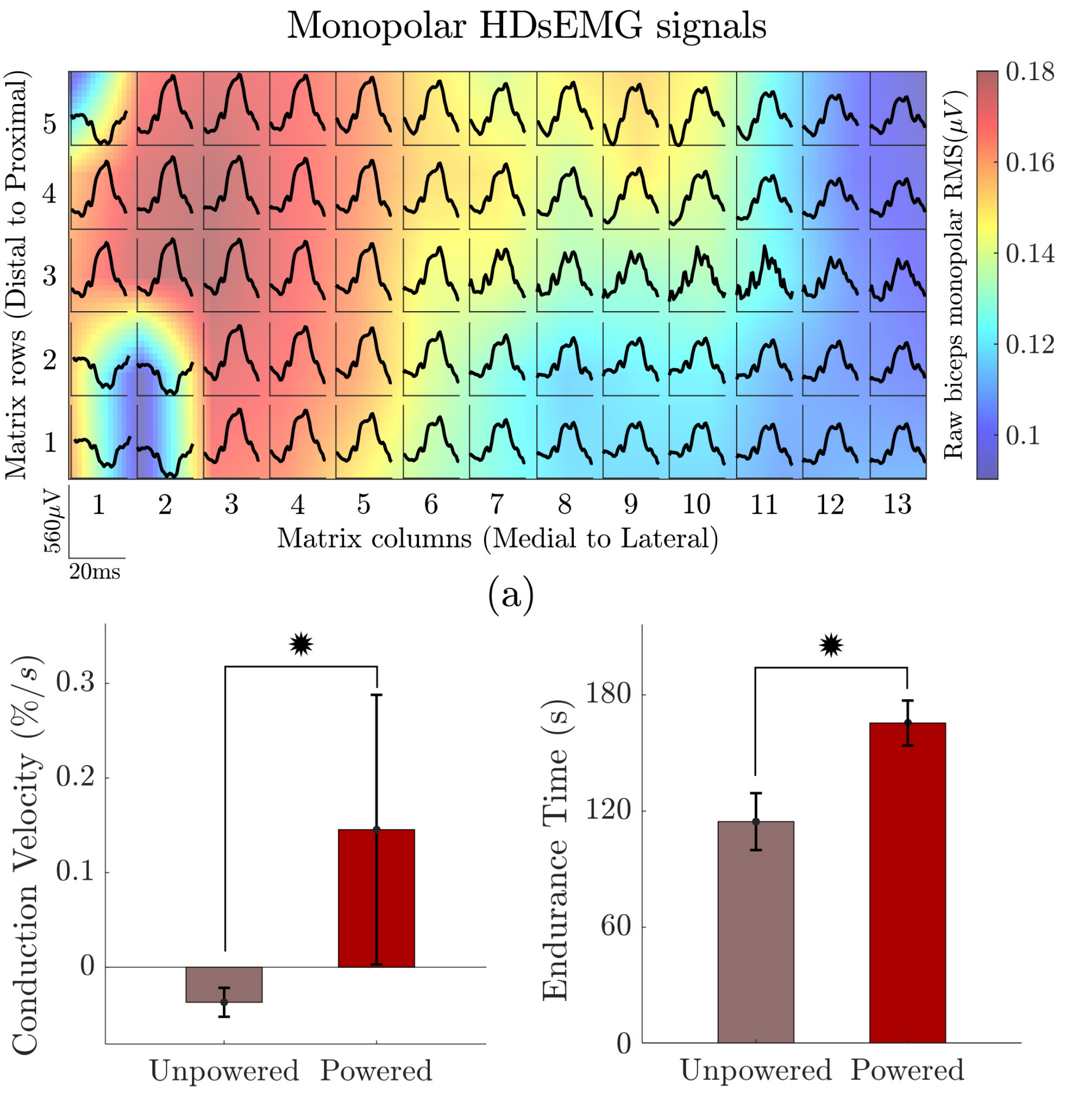


Figure 4. *Biceps activation.* (a) Matrix showing the muscle activation of a representative MS subject during the *Pick and Place* task in the three different conditions (*No Suit*, *Unpowered*, and *Powered*). (b) Volume of biceps muscle activation normalized across all participants during the flexion and extension phases of the *Pick and Place* task. (c) Biceps muscle volume of a representative participant during the *Endurance* task with and without exosuit assistance (*Powered* and *Unpowered* conditions, respectively). (d) Volume of biceps muscle activation normalized across all participants during the *Endurance* task. The error bar depicts the standard error. The symbol $*$ denotes a statistically significant difference ($p < 0.016$ in panel b, $p < 0.05$ in panel d).



(a)

(b)

(c)

Figure 5. *Biceps fatigue and participants' endurance.* (a) Raw HDsEMG signals in a monopolar configuration of a typical subject during the *Endurance* task. The black lines represent the channels in a time window of 20ms, and the colormap indicates the RMS. (b) Conduction velocity and (c) endurance times averaged across all the participants. The error bar depicts the standard error. The symbol $*$ denotes a statistically significant difference ($p < 0.05$).

List of Tables

Table 1. *Demographic and clinical table.*

Subject	Gender	Age (yrs)	Height (m)	Weight (kg)	ABILH	EDSS
1	M	49	1.83	84	44	3.5
2	M	61	1.80	71	46	6.0
3	M	68	1.65	72	35	4.0
4	F	62	1.60	60	24	6.0
5	F	75	1.63	60	29	7.0
6	M	67	1.80	66	38	4.5
7	M	60	1.70	68	46	4.0
8	M	55	1.70	58	49	4.5