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Comfort, consistency, and efficiency of garments with textile electrodes versus hydrogel electrodes for neuromuscular electrical stimulation in a randomized crossover trial

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The efficacy and comfort of neuromuscular electrical stimulation (NMES) largely depend on the type of electrodes used. Traditional self-adhesive hydrogel electrodes, while effective, pose limitations in terms of wearability, skin compatibility, and reusability. This randomized crossover trial investigates the performance of a specific textile electrode integrated into garments for NMES of lower extremities, focusing on their potential rehabilitative applications for patients with neurological disorders such as stroke, multiple sclerosis (MS), and spinal cord injury (SCI). In this randomized crossover design, ten healthy subjects participated in the study. Each subject performed isometric knee extension exercises using both textile and hydrogel electrodes in random order. The electrodes were compared in terms of comfort, temporal consistency, stimulation efficiency, and electrical impedance under isometric conditions. Our findings revealed no significant difference between the two types of electrodes across all evaluated parameters. Textile electrodes, used after applying moisturizing lotion to enhance the electrode-skin interface, demonstrated comparable levels of comfort, consistency, and efficiency to hydrogel electrodes. The equivalence of textile and hydrogel electrodes, coupled with the advantages of washability and reusability, positions textile electrodes as a promising alternative for NMES applications, particularly in rehabilitation settings.

E-textiles, derived from "electronic textiles," merge electrical and electronic functionalities with traditional textile products, such as garments, enhancing their utility and versatility[1,2]. Wearable healthcare devices emerge as a prominent application in the e-textile domain, serving dual pivotal roles: diagnostic and therapeutic[3]. On the diagnostic front, these devices harness the human body's inherent electrical signals which can be precisely captured using electrodes embedded in textile substrates. Consequently, they enable continuous monitoring of vital signs and facilitate key medical assessments such as electrocardiography (ECG)[4,5], electromyography (EMG)[6,7], and electroencephalography (EEG)[8]. Therapeutic e-textile applications encompass electrotherapy, which applies regulated electrical currents to manage various medical conditions[3,9]. This modality demonstrated efficacy in analgesia, notably through transcutaneous electrical nerve stimulation (TENS)[10,11], and is instrumental in the neuromuscular rehabilitation process[12].

Neuromuscular electrical stimulation (NMES) is a well-established electrotherapy technique that involves the controlled application of low-charge electrical pulse trains to superficial nerve trunks or muscle motor points using surface electrodes to elicit muscle contractions[13]. NMES can induce physiological and psychological benefits, such as increased muscle strength[13] and improved cerebrovascular and cognitive functions[14,15]. In addition, NMES can be integrated into functional regimens, targeting different muscle groups in a rhythmic pattern, allowing individuals affected by neurological disorders (e.g., stroke, spinal cord injury (SCI), multiple

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sclerosis (MS)) to perform tasks such as cycling[16–18], walking[19], and grasping[20–22]. This particular application is known as functional electrical stimulation (FES)[23].

NMES is typically applied on the skin surface using disposable self-adhesive hydrogel electrodes[24]. However, practicality and patient compliance with self-adhesive hydrogel electrodes are limited by several disadvantages. These electrodes, not being embeddable into garments, demand careful storage and handling to maintain their effectiveness, yet they are still prone to drying out and losing conductivity over several months of storing or weeks of use. This degradation leads to reduced stimulation efficacy and comfort[25–27]. Their lack of flexibility and conformity to body contours often causes peeling and wrinkling during movement[28,29]. This necessitates individual, manual positioning by trained personnel, complicating their application. Moreover, their disposability contributes to environmental concerns and increases costs, as they require frequent replacement[30]. Additionally, these electrodes pose hygienic challenges, as they are neither washable nor easily sanitized[31].

These drawbacks highlight the necessity for improved electrode designs, such as customizable and washable textile electrodes, which offer integration with garments, enhanced patient comfort, and mass-production viability at reduced costs. Prior research has concentrated on diverse aspects of textile electrode production and subsequent evaluation metrics[30].

Textile electrodes are fabricated using various textile production techniques such as embroidery[30,32], printing[33–36], coating[29,37], knitting[28,38,39], and weaving[40]. Adding-on techniques such as embroidery usually require cutting and sewing the fabric to form electrodes, a process that can lead to material waste, particularly depending on the specific shape and size of the electrodes[30]. On the other hand, methods like knitting and weaving, while widely used, have their limitations. They can be expensive and may restrict design flexibility due to their one-step fabrication process[30].

Regarding the conductive materials, textile electrodes are predominantly fabricated using silver due to good conductivity and antibacterial properties, typically in the form of metal-coated polyamide threads, occasionally combined with elastane to enhance flexibility[30]. When initially worn, textile electrodes that utilize polymer coatings infused with silver demonstrate favorable impedance levels and a comfortable stimulation experience. Nevertheless, these positive attributes tend to diminish significantly after the electrodes undergo washing (silver oxidizes) and extended wear. Similarly, fabrics and embroidery based on silver and steel are unsuitable for high-quality e-textiles, as they tend to lose their quality following washing and regular use[41].

Textile electrodes are available as dry and/or wet variants. Dry electrodes benefit from higher fabric densities to enhance skin hydration through sweat retention[30]. For wet applications, utilized electrolytes are water[26,28,39], saline[42], and hydrogel[26,30]. The choice of electrolyte can modulate the impedance at the skin-electrode interface, subsequently influencing the level of comfort experienced by the user and stimulation efficiency. Zhou et al.[26] explored the comfort associated with electrical stimulation using textile electrodes in relation to conventional hydrogel electrodes. Spectral analysis of electrical impedance revealed suboptimal skin contact with the dry textile electrode, which improved when the textile electrode was moistened. Nevertheless, wetting the electrodes poses its own challenges. It does not offer any significant advantage in placement efficiency over hydrogel electrodes, as the wetting process can be as time-consuming as the placement of traditional electrodes[42]. Moineau et al.[28] developed textile electrodes that had to be moistened with water to have high conductivity, making the stimulation unpleasant when the electrodes dried off, within approximately 9 to 18 min. These studies underscore the necessity for a skin-friendly moisturizing solution capable of sustaining its conductive properties throughout a training session, without needing recurrent application.

Stimulation comfort plays a crucial role in the effectiveness of stimulation electrodes since it is vital that the intensity remains within the patient's tolerance threshold. Previous studies demonstrated that electrolyte type[26,39], electrode dimension[21,24], and contact pressure[39,43] are the most effective parameters to reduce the perceived discomfort level[30]. Smaller electrodes may intensify pain at certain stimulation amplitudes, potentially compromising the efficacy of NMES by necessitating lower intensities[24]. Euler et al.[39] showed that applying pressure enhances the performance of the textile electrodes. These studies highlight the necessity of consistent pressure application and the use of electrodes with identical dimensions in comparative studies, such as those evaluating textile (dry or wet condition) versus hydrogel electrodes.

In the current study, a multi-layer textile electrode with a biocompatible silicone surface from Nanoleq AG (Zurich, Switzerland) were integrated into pants using a hot-pressing technique. These electrodes were selected for their potential suitability in wearable applications, as they allow for simple integration into garments via a thermo-adhesive backing, requiring a processing time of 20–30 s. Additionally, they are designed to maintain stable impedance behavior over multiple uses and washing cycles, an important consideration for durability in real-world scenarios. In this study, garments with textile electrodes were used at least five times and underwent one washing cycle prior to testing. The ElectroSkin electrodes also meet international standards for biocompatibility, including cytotoxicity, skin sensitization, and irritation, ensuring their appropriateness for human use. These electrodes were compared to commercially available self-adhesive hydrogel electrodes of the same dimensions, focusing on perceived discomfort, temporal consistency, and stimulation efficiency during isometric knee extension tasks in ten healthy subjects, with controlled pressure applied to the electrodes. For the textile electrode, a moisturizing lotion was applied to hydrate and smoothen the skin surface, leading to lower impedance and more uniform current distribution over the skin surface. Impedance spectroscopy was used to assess the electrical properties of the textile electrodes, both with and without lotion, as well as hydrogel electrodes, before and after a single session of NMES involving three subjects. This study aims to advance the understanding and potential future applications of textile electrodes in motor rehabilitation, with a focus on comfort, reliability, and effectiveness under controlled experimental conditions.

Methods

Participants

Ten healthy subjects, consisting of seven males and three females, with a mean age of 28.9 years (standard deviation σ = 5.80), a mean height of 176.3 cm (σ = 8.51), and a mean weight of 71.3 kg (σ = 14.65), volunteered to participate in this study. Except for three of them, all participants had prior experience with FES (Table 1). Participants were excluded if they had any known neuromuscular or skeletal disorders, or if they presented with open wounds or rashes at the sites where electrodes were to be placed. Before participating in the experiments, the participants were provided with a detailed description of the purpose and testing procedures. Each participant provided written informed consent. This study followed the Consolidated Standards of Reporting Trials 2010 statement with extension to randomized crossover trials. The project was conducted in accordance with the Declaration of Helsinki, all experimental protocols were approved by Northwest II Ethics Committee for the Protection of Persons, and Registered at ClinicalTrials.gov (NCT06421753, 20/05/2024).

Instrumentation

The ElectroSkin STIM textile electrode (Nanoleq AG, Zurich, Switzerland) was utilized in this study. This electrode is composed of the following layers: a biocompatible silicone rubber surface that interfaces with the skin, a conductive core layer, and an insulating thermally adhesive layer on the back, featuring a designated contact spot for electrical connections. The textile electrode size was 5 × 9 cm^2 and the thermo-adhesive backing was hot-pressed onto stretchable pants (74% Polyamide, 26% Elastane), available in four sizes for males and females (S, M, L, XL), in a single step using a lamination temperature of 130–150 °C and a lamination time of 20–30 s. The positions of these electrodes were carefully determined based on the pants sizes and anatomical landmarks to ensure comprehensive coverage of the quadriceps femoris (QF) motor points[44]. The electrical connection was established with snap buttons via the PhantomLink connection patch (Nanoleq AG, Zurich, Switzerland). A side zipper was added to the pants to make it easier to put on and take off. In addition to the QF, the developed pants have the capability to stimulate various lower limb muscles on both sides including the gluteus maximus, hamstrings group, tibialis anterior, fibularis longus, and gastrocnemius (Fig. 1a). However, it's important to note that our primary focus in this study was on the QF muscle groups. In sessions involving textile electrodes, a minimum amount of moisturizing lotion (CeraVe Moisturizing Lotion for dry to very dry skin), enough for epidermal hydration beneath the position of the electrodes, was applied to the participant's skin before they donned the garments to improve electrode-skin adhesion.

Self-adhesive hydrogel electrodes (Compex Dura-Stick plus, 5 × 9 cm[2]) were utilized as a benchmark to assess the performance of the textile electrodes in this study.

Compensated asymmetric biphasic electrical pulses were applied to the QF of the participants using an 8-channel programmable current-controlled MotiMove stimulator (3 F-Fit Fabricando Faber, Belgrade, Serbia) which was connected to a laptop via a USB-RS485 converter[45]. The stimulation pulse characteristics, including frequency, pulse width (PW), and pulse amplitude (PA), were controlled by a custom-made program developed in LabVIEW 2019 (National Instruments, Austin, TX, USA).

A universal membrane force sensor (EMSYS, EMS30-500 N, Slovakia) was incorporated into a custom metal structure to measure the isometric force generated during electrical stimulation tests. For maximum voluntary isometric contraction (MVIC) tests, a Chronojump force sensor kit (Chronojump-Boscosystem, Barcelona, Spain) with a maximum capacity of 500 kg was employed. The force samples were recorded at a frequency of 80 Hz and recorded in a text file for subsequent data analysis (Fig. 1b).

To conduct the impedance spectroscopy analysis of the electrodes, a Keysight (Agilent/HP) 4284 A Precision LCR Meter, which has a frequency range of 20 Hz to 1 MHz, in conjunction with a Keysight (Agilent/HP) 16,047 C test fixture was used. A custom LabVIEW program was developed to allow the selection of measurement parameters and frequencies. This program was set to RX mode to measure the resistance (R) and reactance (X)

Participants	Gender	Age (years)	Height (cm)	Weight (kg)	FES Naive	Dominant Leg
P1	F	23	164	46	No	R
P2	M	27	184	85	No	R
P3	M	39	175	65	No	R
P4	M	37	192	102	Yes	R
P5	M	32	183	75	No	R
P6	M	33	175	75	No	R
P7	F	23	165	55	No	R
P8	F	27	168	65	No	L
P9	M	27	176	72	Yes	R
P10	M	21	181	73	Yes	R
P11	M	31	175	82	No	R
P12	M	29	180	76	No	R
P13	M	36	174	78	Yes	R

Table 1. Demographic characteristics of the participants. The last three rows (P11, P12, and P13) correspond to participants in the electrical impedance spectroscopy test.

(a) (b)

Fig. 1. (**a**) Stretchable pants embedded with textile electrodes to stimulate various lower limb muscles on both sides, including the gluteus maximus, quadriceps femoris group, hamstrings group, tibialis anterior, fibularis longus, and gastrocnemius. (**b**) Illustration of the experimental setup for the isometric knee extension task using pants embedded with textile electrodes, a current-controlled stimulator, a force sensor, and a PC with a custom-made LabVIEW program. The image was created using Adobe Photoshop 2021 (Version 22.0, https://www.adobe.com/products/photoshop.html).

of the load at specified frequencies. The data collected were automatically saved to a text file for subsequent impedance analysis.

Trial design

This study was initially designed to compare self-adhesive hydrogel electrodes, textile electrodes without lotion, and textile electrodes with lotion in terms of comfort, consistency, and efficiency. However, due to the occurrence of painful contractions with textile electrodes without lotion during preliminary trials and the findings from impedance analysis, the primary protocol was refined to focus exclusively on comparing textile electrodes with lotion and hydrogel electrodes.

This study was conducted as a randomized crossover trial with a 1:1 allocation ratio at the physical therapy clinic of SMR Val Rosay (UGECAM Rhône-Alpes) between 20/05/2024 and 22/06/2024. The allocation of electrode types was randomized such that at the end, five participants started with hydrogel electrodes and the other five started with textile electrodes. Each participant was randomly assigned to start with either the textile electrode with lotion condition or the hydrogel electrode condition. A computer-based random number generator was used to create a random allocation sequence, ensuring equal distribution of the starting electrode type among participants. To conceal the allocation, the random sequence was placed in sequentially numbered, opaque, sealed envelopes, each containing a card indicating the starting electrode type (hydrogel or textile). These envelopes were prepared and shuffled by an independent researcher who was not involved in the recruitment or intervention processes. At the beginning of each participant's involvement in the study, an envelope was opened to reveal the allocation, ensuring that the sequence was concealed until the interventions were assigned. After a washout period of at least 48 h to minimize carryover effects of muscle fatigue, participants crossed over to the other condition. The randomization ensured that each participant received both interventions in random order, allowing for a direct comparison between the two types of electrodes. Blinding of participants and assessors was not possible due to the visible nature of the electrode types. Both the textile and hydrogel electrodes were clearly distinguishable when applied to the participants' legs, making it impossible to conceal the type of electrode being used from either the participants or the assessors (Fig. 2).

Experimental protocol: comfort, consistency, and efficiency tests

Participants were positioned on an adjustable-height bed, ensuring that their popliteal fossa (the area behind the knee) was in contact with the edge of the bed, their thigh was parallel to the ground, and their feet were suspended in the air, lacking contact with the ground. The knee joint angle was fixed at 90°, and a cushioned backrest was used to achieve a posterior inclination of 115° (Fig. 1b).

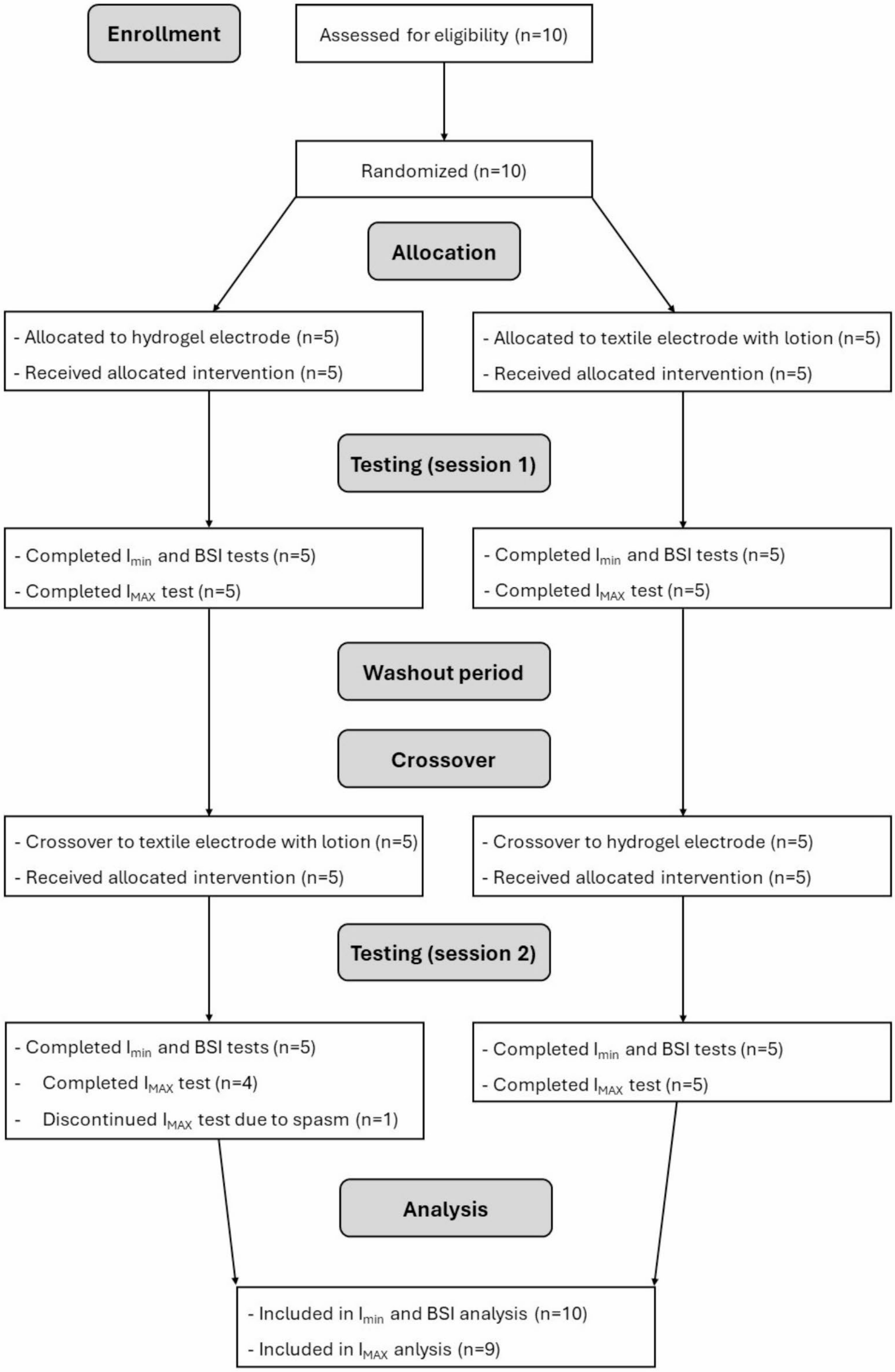


Fig. 2. CONSORT (Consolidated Standards of Reporting Trials) flow diagram of randomized crossover design.

At the beginning of each session, participants were introduced to the testing procedure. This included familiarizing them with the perceptions of burning sensation and maximum tolerable intensity induced by electrical stimulation. To avoid muscle fatigue in the dominant leg, this familiarization was conducted on the non-dominant leg using the corresponding type of electrode. The garments embedded with textile electrodes were used at least five times and washed once before the tests, whereas hydrogel electrodes were used for the first time in each trial to ensure that their hydrogel layer was in the freshest possible condition. In sessions involving textile electrodes, moisturizing lotion was applied to the participant's skin before they donned the garments. During the test, a train of pulses was initiated at a pulse amplitude (PA) of 15 mA, with a frequency of 40 Hz and a PW of 400 μsec. These values were chosen based on previous studies[36,46] and preliminary results with participants. Then PA was manually increased by the experimenter until the participant reached burning sensation intensity (BSI) and subsequently, maximum tolerable intensity. BSI (mA) was defined as the minimum intensity at which the participant felt an uncomfortable heat or burning sensation on the skin beneath the electrode. The I_{MAX} (mA) was defined as the maximum tolerable stimulation intensity for the subject, indicating the point beyond which the pain becomes intolerable. This test was repeated at least twice to ensure the participant could confidently identify both burning sensation and maximum tolerable intensities.

After transitioning to the dominant leg for the main test, the MVIC test began. Participants performed three consecutive 5-second MVIC trials of knee extension using the dominant leg, with a 55-second rest interval between each trial. The average value of these three tests was calculated as the MVIC (Nm). Participants were not permitted to view the measurements, were instructed to keep their arms crossed over their chest, and received verbal encouragement during the test. Following a 5-minute rest, the corresponding electrodes were set up. In the case of textile electrodes, moisturizing lotion was applied. A sequence of electrical pulses, consisting of 5-second stimulation and 5-second rest periods, was then administered. The parameters were as follows: PW = 400 μsec, frequency = 40 Hz, and an initial PA of 15 mA. The pulse amplitude automatically increased by 3 mA after each 5-second rest period for the subsequent train of pulses until the participant reached the BSI, at which point the stimulation stopped. This procedure was repeated at 10, 20, 30, and 40-minute intervals. However, for the final trial, the stimulation continued until the I_{MAX} was achieved. The I_{min} was defined as the minimum intensity needed to generate torque exceeding the average baseline torque by more than three standard deviations. The I_{min} values were extracted later during data analysis. Thus, at the end of each session, five I_{min} values, five BSI values, and one I_{MAX} value were obtained (Fig. 3). Throughout the electrical stimulation tests, participants were instructed to remain relaxed and passive to minimize the impact of volitional torque.

Both types of electrodes were identical in size and were consistently positioned on the same skin area for each subject. To ensure accurate replication of their placement with the other set of electrodes, pictures, and measurements of the electrode positions relative to body landmarks were taken. To maintain matched electrode pressure across both sessions for each subject, the following methodology was adopted: For sessions involving hydrogel electrodes, the electrodes were first placed on the subject's skin. The garments were then worn to simulate the condition of the textile electrode. Straps equipped with Velcro tapes (8×100 cm^2) were subsequently wrapped around both proximal and distal electrodes (visible from the outer surface of the garment) to secure them. The tightness of the straps was adjusted to ensure comfort and to avoid excessive pressure on the muscles. This tightness was matched between the two sessions for each subject based on the starting and ending positions of the strap around the leg. These measurements and strap sizes were documented to replicate the electrode pressure from the first session to the second session.

Electrical impedance spectroscopy test

Electrical impedance spectroscopy was used to evaluate the conductivity behavior of the textile electrode, both with and without lotion, and to compare these results with those from self-adhesive hydrogel electrode. Three healthy male subjects participated in this study (Table 1). The measurements were carried out at frequencies of 20, 40, 60, 80, 100, and 1000 Hz, using sinusoidal alternating current (AC) input signals of 1 V (RMS). To ensure accuracy and consistency, the measurement was repeated five times at each frequency. The setup for electrode placement and the stimulation procedure were identical to those used in the previous section tests, but with a key difference: all three tests (textile electrode without lotion, textile electrode with lotion, and self-adhesive-hydrogel electrode) were performed on the same day. The primary objective of these tests was to characterize the impedance behavior of the electrodes under controlled conditions. Parameters related to stimulation comfort, consistency and efficiency (e.g., I_{min}, BSI, and I_{MAX}) were not used for evaluation in this part of the study. To eliminate potential interference in subsequent tests, the skin was cleansed with 75% isopropyl alcohol and dried with tissue before each test. Additionally, a two-hour break was scheduled between each test. Impedance spectroscopy was conducted twice for each electrode test: once before the test began and again approximately

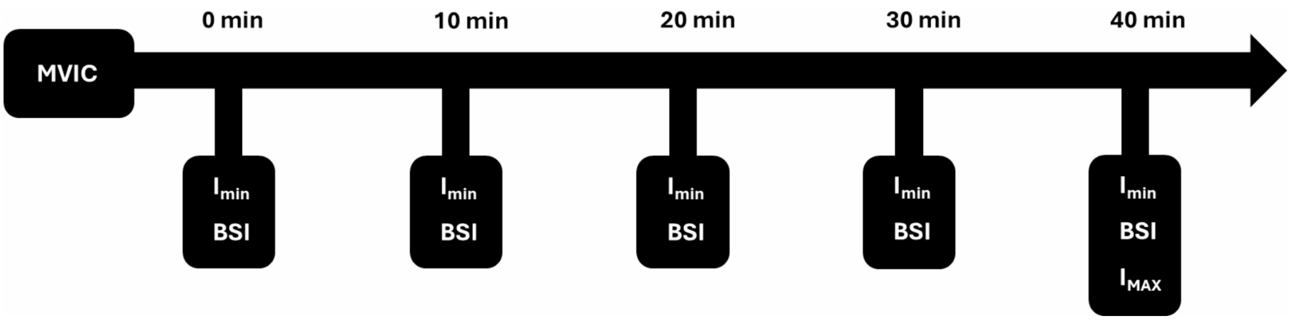


Fig. 3. Experimental protocol followed for both sessions using hydrogel electrodes and textile electrodes with lotion.

40 min later, immediately after the test was completed. The ambient temperature was maintained at approximately 22 °C during the tests to eliminate any potential bias related to sweating conditions.

Data analysis and statistics

The recorded data were analyzed using Microsoft Excel (Microsoft Corporation, USA) and MATLAB R2023a (MathWorks, Natick, USA) to assess comfort, temporal consistency, stimulation efficiency, and impedance for textile and hydrogel electrodes.

To evaluate comfort, the I_{MAX} and average BSI values for each participant were compared across the two types of electrodes. For assessing temporal consistency, the slope of a linear regression model was calculated using BSI values as the dependent variable and repetitions (minutes) as the independent variable during each participant's sessions, with 5 data points per session. Consequently, each participant had two slopes representing temporal consistency: one for the session using textile electrodes with lotion and another for the session using hydrogel electrodes.

To assess stimulation efficiency, the average I_{min} values for each participant were compared across the two types of electrodes. Moreover, the average active torque values were calculated for each 5-second period of stimulation during the last trial (after 40 min). To provide the same number of data points between the tests with different electrode types for each participant, the average active torque values were calculated for intensities from 21 (mA) up to the smaller I_{MAX} value. The average active torque values for each participant were normalized by the corresponding MVIC to be comparable between different participants.

For electrical impedance spectroscopy, at first the absolute impedance (kΩ) was calculated from resistance and reactance at the specified frequencies using $|Z| = \sqrt{R^2 + X^2}$.

For comparative analysis, the mean and standard deviation of absolute impedances were calculated for each frequency across the three subjects. Subsequently, these average values at different frequencies were compared across three electrode types: textile without lotion, textile with lotion, and hydrogel electrodes, both before and after the tests.

To confirm the assumption of normality, the Shapiro-Wilk test was applied to the distribution of the difference vectors for corresponding parameters in the tests performed with different electrode types. If the p-value was greater than 0.05 (normality was confirmed), the two-tailed paired t-test (parametric test) was employed to identify any differences. Otherwise, the Wilcoxon signed-ranked test (non-parametric test) was applied. The p-values and d-values (Cohen's d) were used to indicate the significance and effect size of parametric tests. The p-values and r-values (Z-score divided by the square root of sample size) were used for the same purpose in non-parametric tests. In this study, a p-value lower than 0.05 indicates statistical significance.

In the box-and-whisker plots, the lower and upper edges of the box represent the first quartile (Q1), and third quartile (Q3), respectively. The center line of the box indicates the median value (Q2). An outlier is characterized as a data point that deviates by more than 1.5 times the interquartile range (IQR = Q3 – Q1) from either the lower or upper edge of the box. The whiskers extend to the most extreme data points not considered outliers. The outliers are included in the statistical tests.

Results

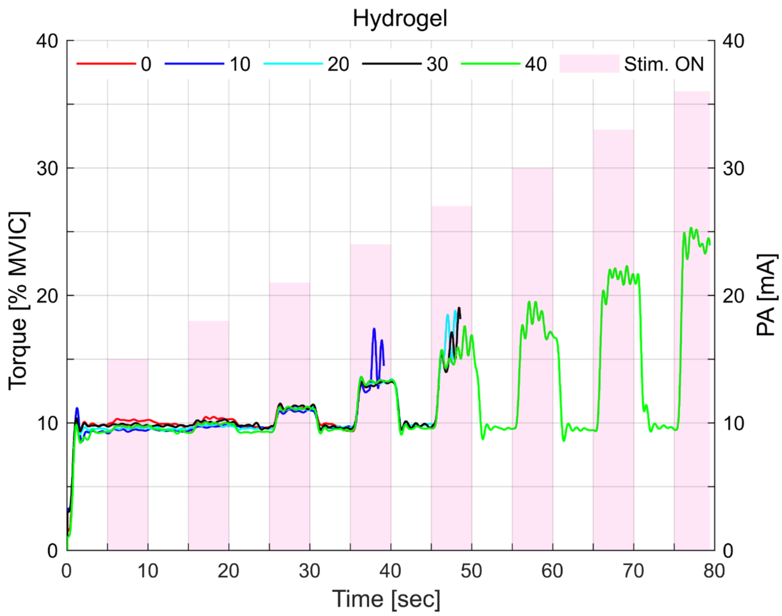
Figure 4a and b showcase the generated torque as a percentage of MVIC for all repetitions (after 0, 10, 20, 30, and 40 min) with respect to time (seconds) and PA (mA) for P1 in hydrogel and textile electrode with lotion sessions, respectively.

Comfort

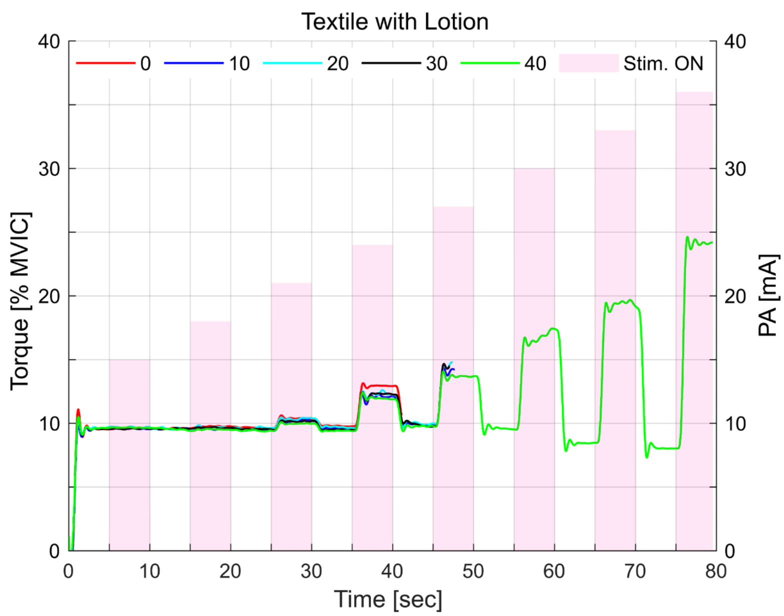
In Fig. 5a, two box-and-whisker plots illustrate the average BSI values for all participants and their variation between the two electrode types. During hydrogel electrode sessions, the average BSI had a mean value of 42.6 ± 15.6 mA, a median of 38.40 mA, Q1 of 31.8 mA, Q3 of 48 mA, and ranging from 23.4 mA to 73.2 mA. In textile electrode sessions, the average BSI showed a median of 40.5 mA, Q1 of 28.8 mA, Q3 of 46.8 mA, and a range from 25.2 mA to 77.4 mA. Statistical analysis using a Wilcoxon signed-rank test indicated no statistically significant difference between the hydrogel and textile electrodes concerning average BSI (p-value = 0.557, r = 0.186). Moving to Fig. 5b presents two box-and-whiskers plots illustrating the I_{MAX} values for nine participants and their variations between the two electrode types. I_{MAX} values were analyzed for nine participants as P10 requested to discontinue the final repetition with textile electrodes due to a painful muscular spasm before reaching the I_{MAX} threshold. During hydrogel electrode sessions, the I_{MAX} had a mean value of 66 ± 23.4 mA, a median of 60 mA, Q1 of 51 mA, Q3 of 76.5 mA, and ranged from 36 mA to 117 mA. In textile electrode sessions, it had a mean value of 67.3 ± 28.6 mA, with a median of 63 mA, Q1 of 45.8 mA, Q3 of 77.3 mA, and ranged from 36 mA to 129 mA. A paired t-test found no significant difference between the hydrogel and textile electrodes with respect to I_{MAX} values (p-value = 0.586, d = 0.189). Table 2 provides a summary of the statistical analysis performed on the average BSI and I_{MAX} values for both types of electrodes.

Temporal consistency

Figure 6a and b display the linear regression models between BSI values for each participant during hydrogel and textile electrode sessions, respectively. In these figures, each subject is represented by a color. In Fig. 6c, two box-and-whiskers plots illustrate the slope of BSI values (mA/min) for all participants and their variation between the two electrode types. The slope of the linear regression model for the hydrogel electrode had a median of 0.075, Q1 of -0.03, Q3 of 0.6, and ranging from – 0.03 to 0.6, while for the textile electrode, the slope of the regression line had a median of 0.09, Q1 of -0.06, Q3 of 0.15, with a range from – 0.09 to 0.78. Conducting a Wilcoxon-signed rank test, no significant difference was found between the slopes of subjects across the two



(a)



(b)

Fig. 4. Torque as a percentage of maximum voluntary isometric contraction (%MVIC) across multiple repetitions at time intervals of 0, 10, 20, 30, and 40 min from the commencement of the test. Different colors distinguish these repetitions. The data is presented concerning time (seconds) on the x-axis, utilizing (**a**) hydrogel electrodes and (**b**) textile electrodes with lotion for one participant (P1). The right axis of each figure illustrates pulse amplitude (PA) during 5-second active stimulation intervals (Stim. ON) denoted by pink-shaded columns.

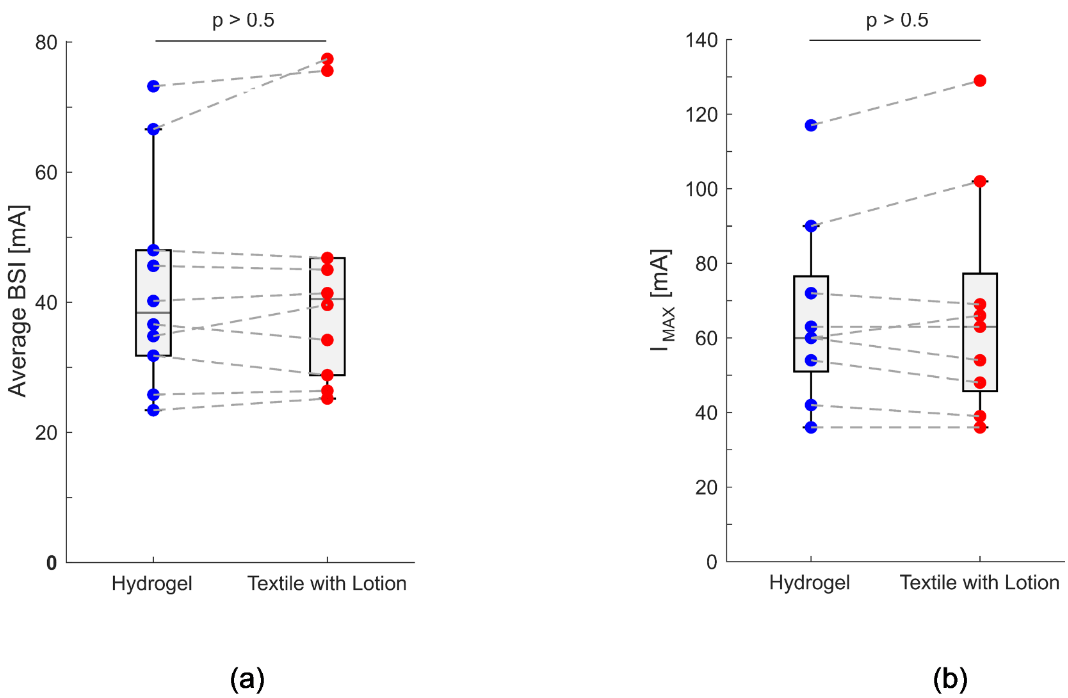


Fig. 5. Box-and-whisker plots of (**a**) average burning sensation intensity (BSI) for each participant ($n = 10$) and (**b**) maximum tolerated intensity (I_{MAX}) ($n = 9$) using both hydrogel electrodes (blue) and textile electrodes with lotion (red). One participant was excluded from the analysis on I_{MAX} due to muscular spasms.

	I_{min} (mA)		Average BSI (mA)		Slope of BSI (mA/minute)		I_{MAX} (mA)	
	Hydrogel	Textile	Hydrogel	Textile	Hydrogel	Textile	Hydrogel	Textile
min	17.4	19.8	23.4	25.2	−0.03	-0.09	36	36
Q1	19.2	20.4	31.8	28.8	−0.03	-0.06	51	45.75
Median	24	23	38.40	40.5	0.075	0.09	60	63
Q3	25.2	26.4	48	46.8	0.15	0.15	76.5	77.3
MAX	26.4	30	73.2	77.4	0.6	0.78	117	129
Mean	–	23.58	42.6	–	–	-	66	67.3
STD	–	3.56	15.56	–	–	-	23.4	28.6
p-value	**0.500 (n.s.)**		**0.557 (n.s.)**		**0.919 (n.s.)**		**0.586 (n.s.)**	
Effect size	d = 0.222		$r = 0.186$		$r = 0.032$		d = 0.189	

Table 2. Summary of statistical analysis for comfort (Average BSI and I_{max} values), consistency (Slope of BSI values), and efficiency (I_{min} values) metrics comparing hydrogel and textile electrodes with lotion. A significance threshold of p-value < 0.05 was used. The mean and STD values are empty for metrics that do not follow a normal distribution. 'n.s.' indicates 'not significant'.

electrode types (p-value = 0.919, $r = 0.032$). Table 2 provides a summary of the statistical analysis performed on the slope of BSI values (mA/min) for both types of electrodes.

Efficiency

In Fig. 7, two box-and-whisker plots illustrate the average I_{min} values for all participants and their variation between the two electrode types. During hydrogel electrode sessions, the average I_{min} had a median of 24 mA, Q1 of 19.2 mA, Q3 of 25.2 mA, and ranged from 17.4 mA to 26.4 mA. In textile electrode sessions, it had a mean value of 23.6 ± 3.6 mA, median of 23 mA, Q1 of 20.4 mA, Q3 of 26.4 mA, and ranged from 19.8 mA to 30 mA. A paired t-test found no significant difference between the hydrogel and textile electrodes with respect to average I_{min} (p-value = 0.500, d = 0.222). Table 2 provides a summary of the statistical analysis performed on the average I_{min} values for both types of electrodes.

To investigate the effects of electrode type and stimulation intensity (mA) on average active torque (%MVIC), a linear mixed-effects model (LMM) was employed. LMM is well-suited for this analysis as it accounts for both fixed effects, representing population-level effects of predictors (electrode type and stimulation intensity), and

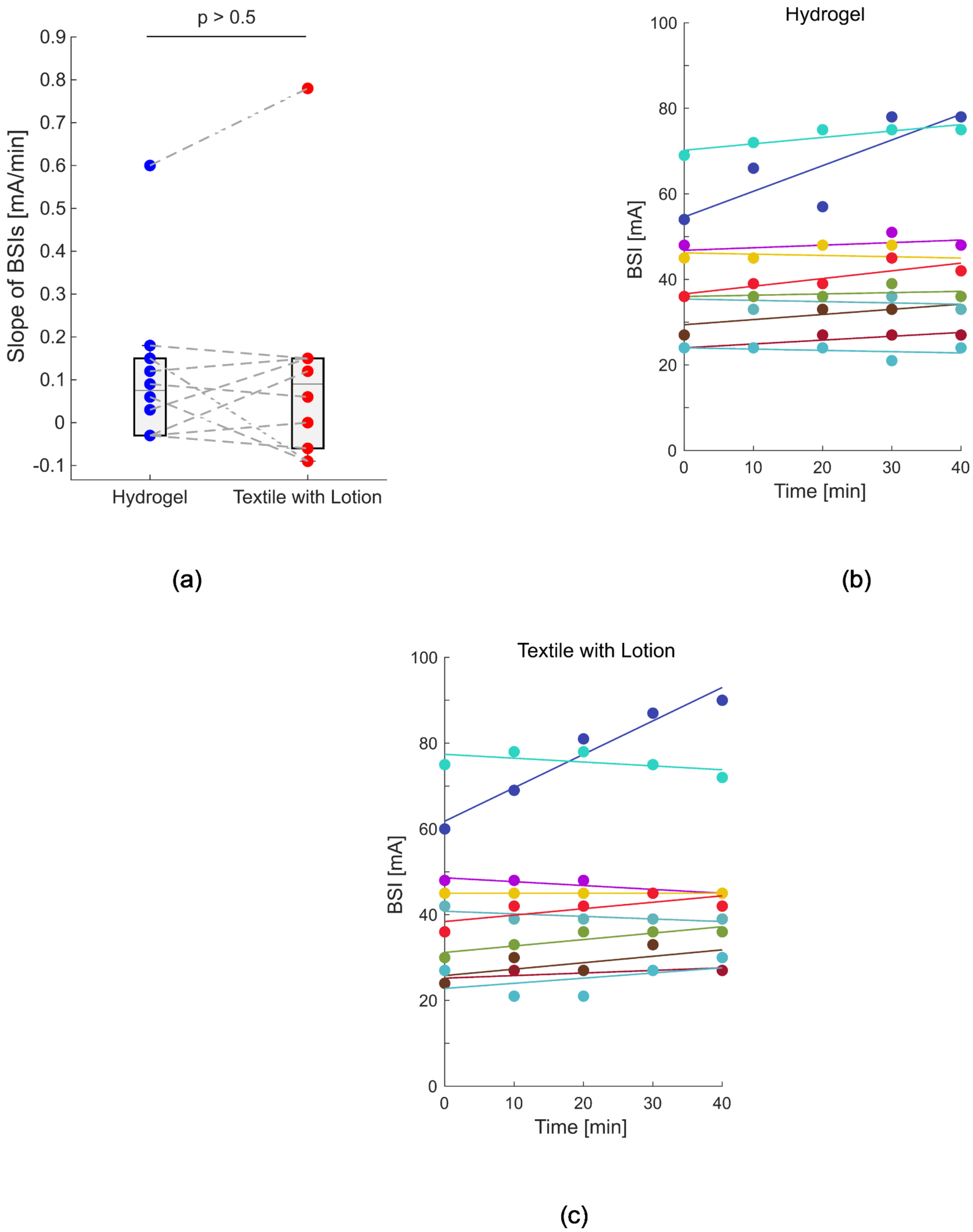


Fig. 6. Linear regression models of burning sensation intensity (BSI) points ($n = 5$) for each participant ($n = 10$) across multiple repetitions at time intervals of 0, 10, 20, 30, and 40 min from the commencement of the test. Each participant is presented with a specific color. The data is presented concerning repetition time intervals (min) on the x-axis, utilizing (**a**) hydrogel electrodes and (**b**) textile electrodes with lotion. (**c**) Presents the box-and-whiskers plots of the slope of BSI values for hydrogel electrodes (blue) and textile electrodes with lotion (red).

random effects, which capture subject-specific variability. Data from all participants, except P10, were included ($n = 82$ observations per electrode type).

Stimulation intensity was standardized (mean-centered and scaled by its standard deviation) to enhance numerical stability during model fitting. The dependent variable was average active torque (%MVIC), while the predictors included electrode type, standardized stimulation intensity ($Intensity_S$), and their interaction. The electrode type was coded as a binary variable (0 for hydrogel electrodes and 1 for textile electrodes with lotion).

The random-effects structure accounted for subject-specific variability by including random intercepts (allowing each subject to have their own baseline torque), random slopes for $Intensity_S$ (allowing the effect of stimulation intensity to vary across subjects), and random slopes for electrode type (capturing individual

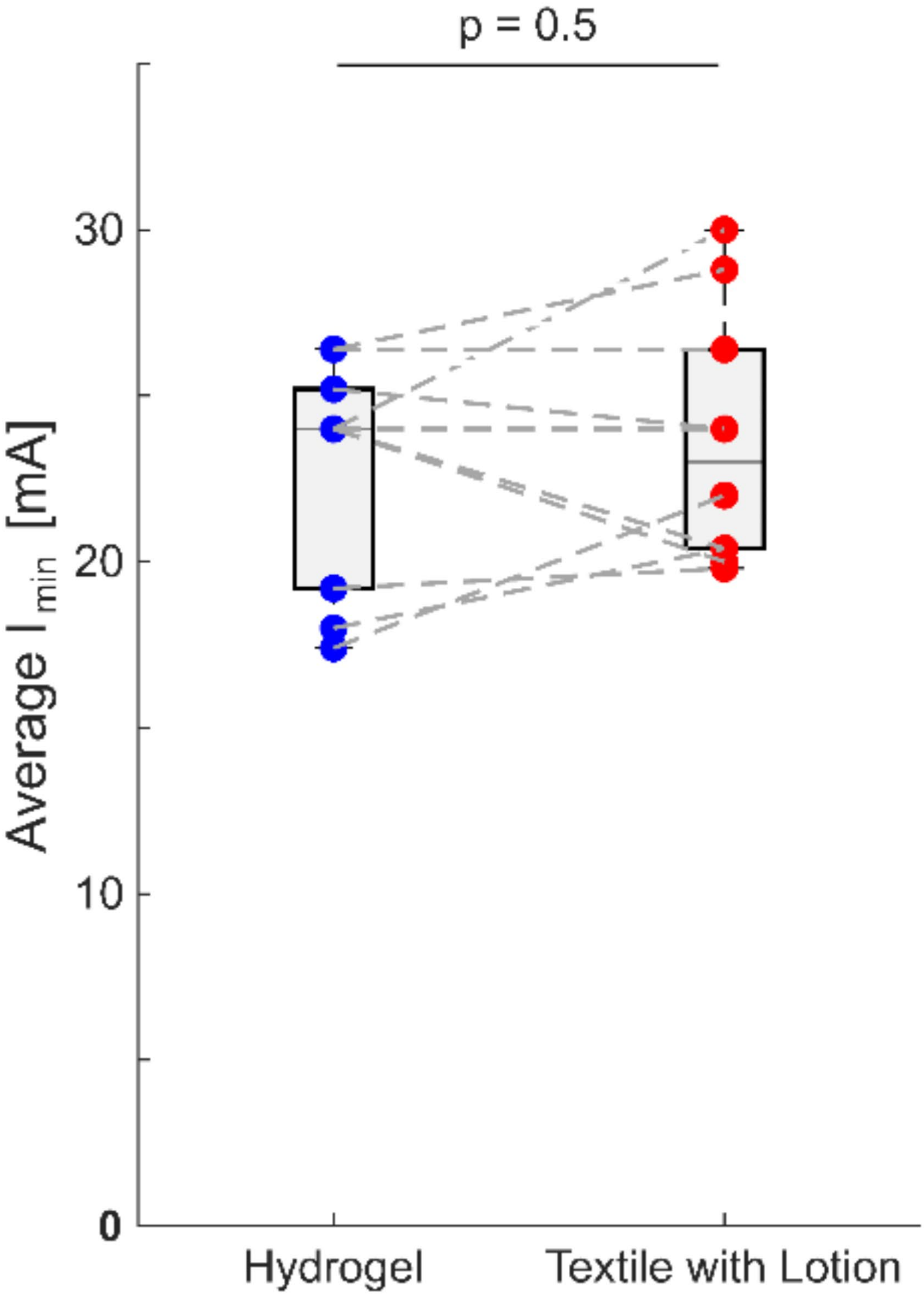


Fig. 7. Box-and-whisker plots of average minimum intensity required to evoke torque (I_{min}) for each participant ($n = 10$) using hydrogel electrodes (blue) and textile electrodes with lotion (red).

differences in response to electrode type). The model was fitted using maximum likelihood estimation. The statistical significance of fixed effects was assessed using marginal F-tests, and confidence intervals were computed for all estimates.

The results of the fixed-effects analysis are summarized in Table 3. $Intensity_S$ had a highly significant positive effect on torque ($F(1, 160) = 189.58$, p-value < 0.001), indicating that average active torque increased with higher stimulation intensities. Electrode type ($F(1, 160) = 0.040$, p-value $= 0.842$) did not show a significant main effect,

Fixed Effect	Estimate	SE	tStat	DF	*p*-value	95% CI (Lower, Upper)
Intercept	8.25	1.45	5.68	160	< 0.001	(5.38, 11.12)
Electrode Type	0.14	0.71	0.20	160	0.842	(−1.26, 1.54)
Intensity_S	7.48	0.54	13.77	160	< 0.001	(6.41, 8.55)
Electrode Type* Intensity_S	0.16	0.28	0.55	160	0.581	(−0.40, 0.71)

Table 3. Fixed-effects estimates from the linear mixed-effects model examining average active torque (%MVIC) as a function of electrode type and standardized stimulation intensity (Intensity_S). Electrode type was coded as 0 for hydrogel electrodes and 1 for textile electrodes with lotion. The fixed effects included electrode type, Intensity_S, and their interaction. Random intercepts and slopes for Intensity_S were included for each subject, along with random slopes for electrode type. (Model formula: Torque ~ 1 + Electrode * Intensity_S + (1 + Intensity_S | Subject) + (Electrode | Subject)). The table presents the fixed-effects estimates, standard errors (SE), t-statistics, degrees of freedom (DF), p-values, and 95% confidence intervals (CI) based on 82 observations per electrode type. Significant fixed effects (p-value < 0.05) indicate factors or interactions that significantly affect average active torque.

suggesting no overall difference in torque production between electrodes. The interaction between electrode type and stimulation intensity ($F(1, 160) = 0.306$, p-value = 0.581) was also not significant, indicating that the effect of stimulation intensity on torque was consistent across both electrode types.

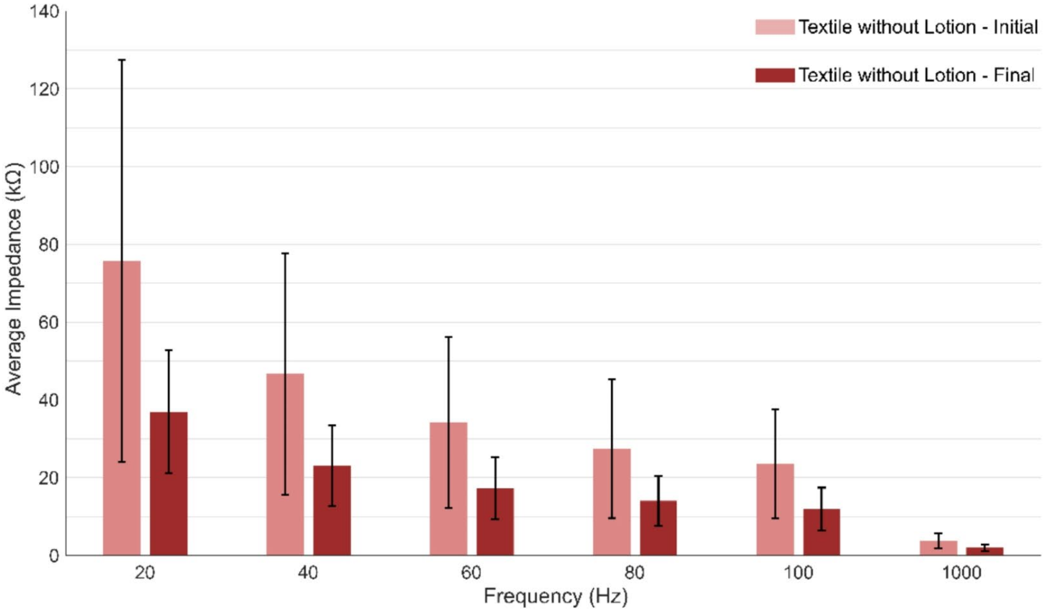
The random-effects structure captured significant variability in torque production among subjects. The standard deviation of random intercepts was 4.26, indicating substantial variation in baseline torque levels across subjects. The random slope for Intensity_S had a standard deviation of 1.32, with a strong positive Pearson correlation coefficient of 0.94 between the random intercepts and slopes. This suggests that subjects with higher baseline torque tended to have steeper torque-intensity relationships. The random slope for electrode type had a standard deviation of 1.94, reflecting subject-specific differences in torque responses to hydrogel electrodes compared to textile electrodes with lotion.

Electrical impedance spectroscopy test
Figure 8 depicts the mean and standard deviation of absolute impedance values (kΩ) across three subjects for tests conducted using textile electrode without lotion (Fig. 8a), as well as hydrogel electrode and textile electrode with lotion (Fig. 8b), at various frequencies (20, 40, 60, 80, 100, and 1000 Hz). Measurements were taken both before and after the tests, with approximately 40 min in between, without removing electrodes between the tests.

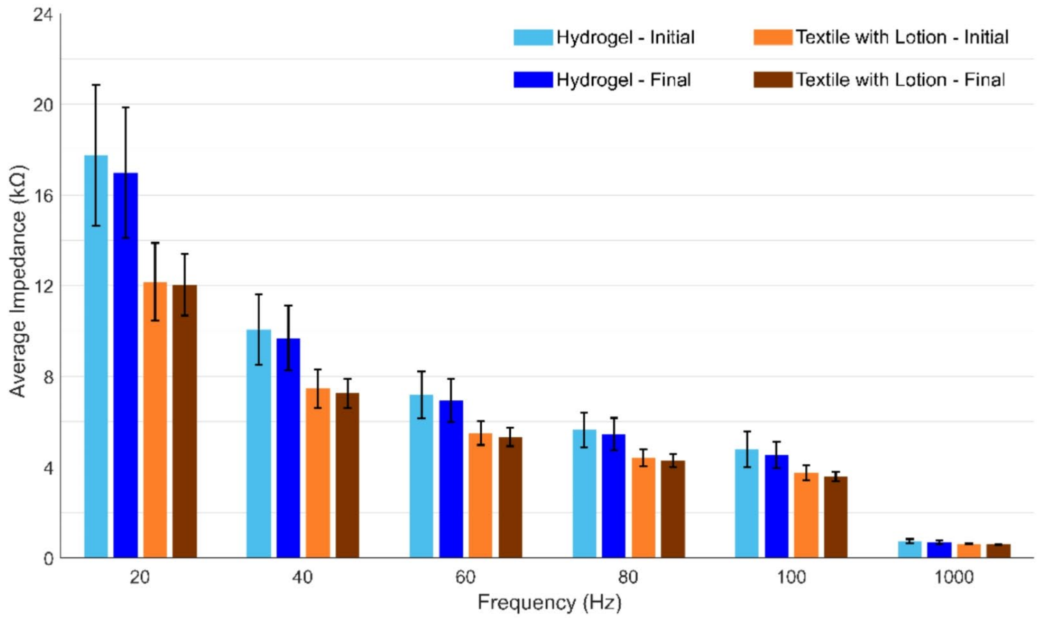
Discussion
This study explored the performance of a novel garment embedded with textile electrodes for neuromuscular electrical stimulation regarding comfort, temporal consistency, efficiency, and electrical impedance. For comparative analysis, a self-adhesive hydrogel electrode, commonly used in clinical settings served as a benchmark. Our garment, in combination with moisturizing lotion, enough for epidermal hydration, showed no statistically significant difference compared to self-adhesive hydrogel electrodes of similar shape and size under identical pressure regarding the proposed metrics during isometric knee extension exercise. One of the primary limitations associated with hydrogel electrodes is their disposability, non-washability, and hygienic challenges. The hydrogel layer of these electrodes is prone to degradation after use due to drying, loss of adhesiveness, or contamination. In this study, new hydrogel electrodes were employed to ensure that their hydrogel layer was in the freshest possible condition. In contrast, the garments embedded with textile electrodes were used at least five times and washed once prior to the tests. This distinction underscores the significant importance of the developed garments with textile electrodes, as they not only retain the benefits of hydrogel electrodes regarding comfort and efficiency but also overcome their limitations.

In this study, electrical impedance spectroscopy was utilized to analyze the electrode-skin interface, with a specific focus on the impact of time (before and after 40 min) and electrode type (textile without lotion, textile with lotion, and hydrogel) on conductivity changes. Across all types of electrodes, a general trend of decreasing absolute impedance values was observed with increasing frequency (from 20 to 1000 Hz), consistent with the capacitive characteristics of the skin-electrode interface[26]. The textile electrode with lotion and hydrogel electrode exhibited lower mean absolute impedance values compared to the textile electrode without lotion both before and after 40 min for all frequencies. This analysis is pivotal particularly for patients with preserved sensation, as the impedance of the electrode-skin interface is a key determinant of stimulation comfort[26]. Excessive impedance levels can lead to discomfort, such as a burning sensation beneath the electrodes at lower intensities, potentially limiting the electrode's effectiveness in achieving the desired level of muscle contraction.

The average absolute impedance values were lower after 40 min compared to those recorded before the tests, which can be attributed to sweating induced by the garments and straps[47]. For instance, at 40 Hz, a commonly used stimulation frequency[13], the average absolute impedance for the hydrogel electrode decreased from 10.07 ± 1.54 kΩ before the test to 9.68 ± 1.43 kΩ after the test, corresponding to a 3.87% decrease. For the textile electrode with lotion, the average absolute impedance decreased from 7.46 ± 0.84 kΩ before the test to 7.25 ± 0.65 kΩ after the test, a 2.82% decrease. In contrast, the textile electrode without lotion showed a substantial decrease in impedance, from 46.69 ± 31.08 kΩ before the test to 23.03 ± 10.35 kΩ after the test, representing a 50.67% decrease. These findings suggest superior impedance consistency in hydrogel electrodes and textile electrodes



(a)



(b)

Fig. 8. Average absolute impedance values (kΩ) for tests conducted on three participants: (**a**) textile electrodes without lotion and (**b**) hydrogel electrodes and textile electrodes with lotion, at various frequencies (20, 40, 60, 80, 100, and 1000 Hz). Measurements were taken both before (initial) and after 40 min (final) of stimulation tests. Electrodes were not removed between the initial and final measurements.

with lotion compared to those without lotion. This observation is particularly noteworthy, as previous research[28] found that using water to moisten textile electrodes led to an increase in impedance over time, causing discomfort after 16 min of stimulation.

Both the initial and final standard deviations of impedance values for textile electrodes without lotion were notably larger than those of the other electrode types. We attribute this inter-subject variability in the textile electrode without lotion to differences in the electrode-skin interface, which can be influenced by factors such as skin characteristics (e.g., perspiration), contact pressure, and individual thigh morphology. These findings suggest that the textile without lotion configuration is more sensitive to environmental and user-specific conditions, making it less consistent and predictable compared to the other electrode types (i.e., hydrogel electrodes and textile electrodes with lotion). On the other hand, the application of moisturizing lotion enhances the conductivity of the textile electrode-skin interface, improving consistency both over time and across subjects. Unlike water, lotion does not require frequent reapplication; a single application per session suffices. Given the amount needed for each application, it avoids creating a sensation of wetness both during and after the test.

This study was initially planned to compare all three types of electrodes regarding comfort, consistency, and efficiency. However, due to painful contractions experienced when using textile electrodes without lotion, and based on the results of spectroscopy analysis, our primary protocol was adjusted. We focused on a cohort of ten subjects to assess comfort, consistency, and efficiency, limiting the comparison to textile electrodes with lotion and hydrogel electrodes. The comparative results indicated no significant difference between the textile electrode with lotion and the hydrogel electrode in terms of motor threshold intensity, the intensity at which subjects experienced a burning sensation and maximum tolerable intensity. These results hold significant importance, as an effective electrode should facilitate strong contractions while minimizing discomfort. The burning sensation experienced during electrode use primarily stems from uneven contacts at the electrode-skin interface. This unevenness leads to an inhomogeneous flux of current across small areas of the skin, resulting in the early activation of pain-sensing Aδ fibers[26,48].

While previous studies[26] have employed various subjective sensations such as tingling, aching, and stinging as evaluative metrics, the ambiguity inherent in defining and distinguishing these sensations at the same time poses challenges for participants. Although this ambiguity also applies to the detection of burning sensation intensity in our protocol, our approach minimizes bias by focusing solely on each participant's interpretation of the burning sensation across the two electrode types. Thus, even if different participants have varying definitions of "burning sensation," the within-subject comparisons remain valid. Furthermore, we believe that determining the maximum tolerable intensity is more straightforward, as its definition is clear to all participants. Recent advances in sensory feedback calibration[49], such as Demofonti et al.[50], who identified pulse amplitude modulation in TENS as a key parameter of intensity discrimination, and Bucciarelli et al.[51], who developed multiparametric TENS paradigms (e.g., co-modulating pulse width and frequency) to enhance intuitiveness of artificial sensations, highlight the importance of standardized protocols for reducing variability in sensory reporting.

In this study, we aimed to streamline the evaluation process by minimizing the reliance on subjective sensations, thereby simplifying and clarifying the testing procedure. This approach is particularly relevant considering the intended application of the final product for patients with neurological disorders, who may experience verbal and cognitive difficulties. The use of simpler and more straightforward protocols is especially advantageous in such contexts, ensuring more accessible and reliable assessment methods.

In this study, we meticulously ensured uniform testing conditions across different electrode types to obtain comparable results. These standardized conditions included the size, shape, and placement of the electrodes, as well as the ambient temperature and the pressure applied to each electrode's surface for every subject. Previous studies have demonstrated that applying pressure using compression stockings[39] or manual compression[43] can reduce discomfort during neuromuscular electrical stimulation. Similarly, sweating, which is more likely with garments, can reduce the impedance of the electrode-skin interface[47]. To ensure fairness and minimize potential biases in favor of textile electrodes, these factors were standardized across both electrode types. Garments and Velcro straps of identical lengths were used to apply consistent pressure and simulate comparable sweating conditions for both hydrogel and textile electrodes. While using Velcro straps of identical lengths does not guarantee equal pressure between subjects, it ensures within-subject consistency, which is critical in crossover studies. It should be noted, however, that the elasticity of the straps may change over time, potentially leading to variations in their size and tension with extended use.

To minimize external influences on the data, subjects were instructed to remain silent and focused during testing. It was observed during initial tests that engaging in concurrent activities, such as using mobile phones or talking, could impact the results. Another critical aspect of our methodology was the protocol familiarization on the non-dominant side, which was intended to ensure that all participants, regardless of prior FES experience, were introduced to the burning sensation and maximum tolerable intensity induced by electrical stimulation. This process ensured that the measurements were taken on non-fatigued muscles, thereby enhancing the accuracy of our findings and standardizing the participants' exposure to the testing procedure.

The principal limitation of this study is its exclusive reliance on healthy subjects, rather than including individuals with neurological conditions. This selection has significant implications, particularly in the measurement of force output and impedance analysis. Healthy subjects are capable of providing volitional torque, especially at higher stimulation intensities (due to pain), which may not be representative of responses in individuals with neurological impairments. Consequently, our analysis included the motor threshold intensity, occurring at low intensities, as a measure of stimulation efficiency. Moreover, the impedance analysis to compare the three types of electrodes was confined to three subjects due to painful contractions with textile electrodes without lotion. This issue resulted in the exclusion of textile electrode without lotion from the comfort, consistency, and efficiency tests. Future research should address these gaps by incorporating a diverse participant group, including those with neurological conditions such as stroke and SCI, to fully understand the range of responses to neuromuscular electrical stimulation and to enhance the generalizability of our findings.

Another consideration in this study is the use of moisturizing lotion to enhance the electrode-skin interface of textile electrodes. The lotion was applied and spread evenly to hydrate the skin without inducing a sensation of wetness. This approach was intended to ensure hydration across the electrode placement area, mimicking typical use of lotion. However, the exact amount of lotion applied may vary between operators, making this an operator-dependent procedure. While this variability was not quantified in our experiments, future studies could explore standardized methods for lotion application to reduce potential inconsistencies. Additionally, our experiments were conducted in a controlled clinical environment with temperatures between 22 and 26 °C. Environmental factors such as temperature, humidity, and season could potentially influence the lotion's effectiveness and the electrode-skin interface. Investigating these factors in varying environmental conditions would be valuable to enhance the robustness and applicability of textile electrodes in diverse settings.

A notable limitation of the study protocol was the inability to blind participants to the types of electrodes used. This aspect could introduce a form of bias, particularly if subjects had pre-existing preferences or perceptions about the different electrode types. Such biases might influence their subjective experience and feedback during the study, potentially affecting the reliability of the results in terms of perceived comfort. Future studies could benefit from incorporating a double-blind design, where neither the participants nor the researchers know which electrode type is being used, to minimize this potential source of bias and enhance the validity of the findings.

This study specifically targeted the quadriceps femoris muscle group, which, due to its large size, necessitates the use of relatively large electrodes. However, it is important to note that prior research has indicated that smaller electrodes induce greater discomfort due to higher current density[24]. This is a critical consideration as smaller electrodes are essential for achieving selective muscle stimulation and eventually reducing muscle fatigue[22]. Consequently, these findings underscore the need for further experiments involving smaller electrodes. Such studies would not only address the aspect of comfort with different electrode sizes but also evaluate the effectiveness of stimulation in smaller muscle groups, thereby contributing to a more comprehensive understanding of neuromuscular electrical stimulation using textile electrodes.

It is important to acknowledge that the scope of this study was confined to isometric conditions, where the electrodes remained static and stable throughout the tests. Consequently, this study does not provide insights into the comparative performance of textile electrodes versus hydrogel electrodes during dynamic activities, such as cycling or walking. In dynamic scenarios, positional changes of the electrodes due to body movement and the shifting of motor points during muscle contraction and relaxation could affect stimulation performance. These challenges may include reduced stimulation efficiency or altered comfort levels. Recognizing these limitations, future research will specifically focus on evaluating the performance of textile electrodes in dynamic tasks. This will include exploring new design solutions, such as broader electrode coverage or enhanced fixation methods, to ensure stable and effective stimulation during movement.

While this study demonstrates the feasibility of textile electrodes for neuromuscular electrical stimulation in healthy participants, several factors may limit their applicability in patients with neurological conditions such as stroke, MS, and SCI. Patients with these conditions often have altered skin properties, such as impaired sweating[52], which could impact the electrode-skin interface and the overall effectiveness of stimulation. Additionally, variations in muscle tone, spasticity, and reduced motor control may require adjustments in electrode placement, and garment fit to achieve consistent results. Furthermore, the dependence on moisturizing lotion for optimal impedance may present challenges in clinical settings. Future studies are essential to evaluate these factors and to optimize the design and usability of textile electrodes in populations with CNS conditions.

Conclusion

This study presents a detailed analysis of the performance and potential application of textile electrodes embedded in garments for neuromuscular electrical stimulation, based on experiments conducted with healthy participants. By juxtaposing these textile electrodes against conventional self-adhesive hydrogel electrodes, the study delves into key aspects such as stimulation comfort, temporal consistency, efficiency, and electrical impedance behavior under isometric conditions. The research demonstrates that textile electrodes, when used with a moisturizing lotion, exhibit similar levels of comfort, consistency, and efficiency to hydrogel electrodes, evident in parameters like motor threshold intensity, burning sensation intensity, and maximum tolerable intensity. The research methodology ensured standardized testing conditions, bolstering the reliability of the findings. The study's findings are promising for the application of textile electrodes in motor rehabilitation. Future studies should include individuals with neurological conditions to understand the full spectrum of responses and enhance the generalizability of findings.

Data availability

The data are available from the corresponding author (E.J.) on reasonable request.

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Author contributions
All authors contributed to the conception and design of the study. E.J. acquired the data and performed the data analysis. E.J., L.P.M. and A.M. interpreted the results. E.J. drafted the manuscript. All authors edited and revised the manuscript and approved the final version.

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Declarations

Competing interests
The authors declare no competing interests.

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