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Fabric Sensing of Intrinsic Hand Muscle Activity

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***Abstract*—Wearable robotics has the capacity to assist and rehabilitate hand function in stroke survivors. Many devices that use surface electromyography (sEMG) for control rely on extrinsic hand muscle signals, since sEMG sensors are relatively easy to place on the forearm without interfering with hand function. In this work, we target the intrinsic muscles of the thumb, which are superficial to the skin and thus potentially more accessible via sEMG sensing. Traditional, rigid electrodes can not be placed on the hand without adding bulk and affecting hand functionality. We thus present a novel sensing sleeve that uses textile electrodes to measure sEMG activity of intrinsic thumb muscles. We evaluate the sleeve's performance on detecting thumb movements and muscle activity during both isolated and isometric muscle contractions of the thumb and fingers. This work highlights the potential of textile-based sensors as a low-cost, lightweight, and non-obtrusive alternative to conventional sEMG sensors for wearable robotics.**

I. Introduction

Stroke-induced hemiparesis can cause chronic upper limb weakness and reduced hand dexterity [1][2], which can hinder a stroke survivor's mobility and independence. Wearable robotic devices can aid stroke survivors by assisting hand function and providing rehabilitation therapy. Because continued, active use of the paretic hand is a key element of effective robotic rehabilitation [3], there is great interest in developing devices that promote this active engagement.

Surface electromyography (sEMG) sensors can measure residual muscle activity during active use of the paretic hand, enabling ipsilateral, robotic orthosis control. These robotic orthoses commonly place sEMG sensors on the forearm to capture activity from extrinsic hand extensor and flexor muscles, which are responsible for many gross hand movements. This data is then processed by machine learning models to infer user intent [4][5]. While these methods work well on healthy participants, stroke complications like muscle spasticity, abnormal muscle co-activation, and neurological disorders [6], introduce challenges for sEMG-based intent inferral on stroke survivors.

Beyond the forearm, the intrinsic muscles in the hand offer an alternate sEMG sensing region for intent inferral. Muscles in the thenar eminence (TE) are responsible for some thumb movements during grasping and fine motor movements [7].

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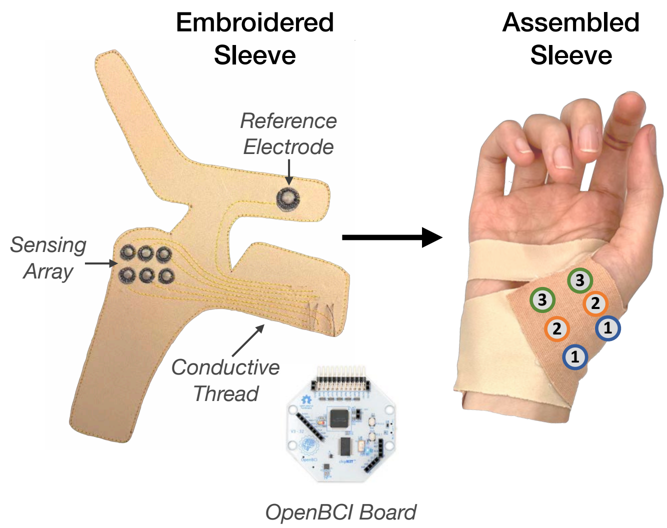

Fig. 1. The fabric sensing sleeve. After embroidering the fabric electrodes and conductive thread, which act as wires to connect the sleeve to the OpenBCI board, the sleeve is assembled into a wearable form. The sensor array is positioned on the thenar eminence of the thumb to detect when the thumb moves into abduction.

Research has suggested that in stroke survivors, the *abductor pollicis brevis* (APB) in the TE has reduced spasticity compared to other muscles in the hand [8], which highlights the TE's potential as a sensing region for stroke survivors.

Despite its advantage as a localized, grasping-specific muscle sensing region, the TE is underexplored due to its small size on a curved contour of the palm. Conventional sEMG sensors are often bulky and use stiff, adhesive pads that, when placed on the TE, can interfere with grasping and restrict thumb movement.

Textile sensors, made from conductive fabrics and threads, are an alternative sensing platform that is low-profile, non-adhesive, and comfortable for extended wear. Unlike conventional sEMG sensors, fabric electrodes are flexible and can conform to curved surfaces without adhesives on the skin.

In this pilot study, we introduce a novel, textile sensing array embroidered in a fabric sleeve to measure sEMG activity of the intrinsic thumb muscles. Our main contributions are:

- To the best of our knowledge, we are the first to use fabric sensors to measure surface EMG activity of intrinsic hand muscles. The fabric sensors are built with off-the-shelf fabrics and are optimized to mitigate motion artifacts and improve skin-contact quality without adhesive pads.
- We demonstrate that the textile sensors can distinguish

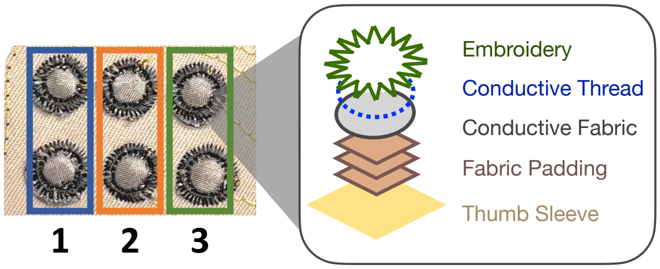

Fig. 2. The 3-channel textile sensing array, labeled by color and channel number. Each textile electrode is made of conductive fabric embroidered to a fabric substrate with internal padding to improve skin-electrode contact. Conductive thread is stitched around the perimeter of the electrode to connect the electrode to the bioamplifier board.

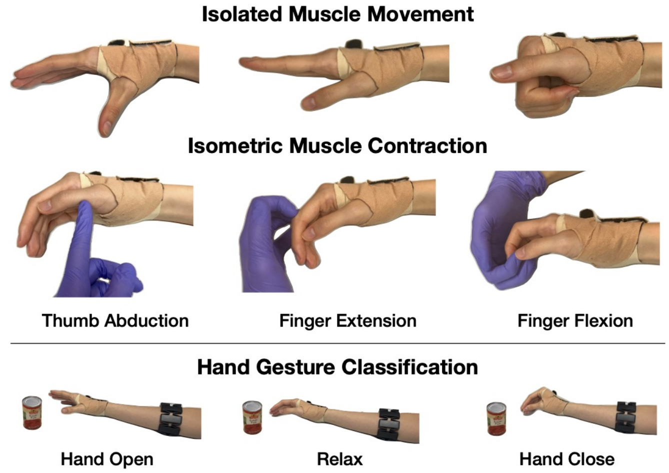

Fig. 3. Schematic of experimental protocol. During the Isolated Muscle Movement task, participants moved their thumb or fingers from rest to an engaged position as shown. The Isometric Muscle Contraction task required participants to resist external force from the experimenter's hand to engage the relevant muscles for the movement. Hand Gesture Classification data collection involved participants opening and closing their hands into a lumbrical grasp, as shown.

thumb muscle activity from finger movements. In addition, training a classifier with only the 3-channel sensing array achieves promising classification accuracy for detecting hand opening and closing.

- Our results demonstrate the fabric sensing sleeve's potential as an effective sEMG sensor for intent inferral, highlighting the value of intrinsic muscle sensing modalities for improving model classification performance in future work.

II. Related Work

Surface EMG sensing for intent inferral has been explored with various sensor configurations. Tacca et al. combined forearm sEMG sensing with a non-EMG data glove in a multi-modal system for hand gesture recognition [9]. Previous works with conventional sEMG sensors combined extrinsic and intrinsic hand muscle sensing for post-stroke rehabilitation exercises [10] and hand gesture recognition [11]. Multiple groups built fabric sleeves with textile electrodes for the forearm to measure extrinsic muscle activity for hand gesture recognition [12][13]. Lara et al. developed a PCB sEMG electrode array with a flexible polyamide substrate for intrinsic hand muscle sensing, though this system requires custom adhesive pads for use [14]. Across these works, however, intrinsic hand muscle sensing in a soft, wearable system remains underexplored.

To our knowledge, the only works related to fabric sensing of intrinsic hand muscles are a piezoresistive strain fabric sensor that measures muscle strain of the APB [15] and a graphite composite sEMG sensor extruded on a fabric substrate that measures APB muscle activity [16]. However, [15] measures muscle strain rather than sEMG activity, and [16] uses fabric as a substrate, rather than a sensing modality. This distinction highlights how fabric sEMG sensors for intrinsic hand muscles have not yet been directly explored, which our work aims to address.

III. Fabric Sensing Sleeve Design

The fabric sleeve presented in this work is a prototype 3-channel, fabric sEMG sensing sleeve that measures the intrinsic muscle activity of the thumb. The materials for fabricating the sleeve are off-the-shelf and low-cost (<$5 per sleeve) and takes about 2 hours to assemble, which enables modular design for project-specific sensing array customization and scalability.

The biopotential sensing electrode is made of a layer of conductive fabric [17] embroidered to an elastic fabric substrate. Three layers of fabric padding are placed between the conductive fabric and fabric substrate to increase electrode concavity and improve skin-electrode contact (Fig. 2). The reference electrode is 8 mm in diameter, and each sensing electrode is 6 mm in diameter, with a center-to-center electrode distance per channel of 9 mm. The electrodes were sized to fit comfortably on the TE and reduce motion noise during thumb movement.

We designed the fabric sleeve to place the 3-channel sensing array over the TE of the palm, with the reference electrode placed on the back of the hand (Fig. 1). The 3-channels array wraps around the curved TE to maintain skin contact and, similar to high-density electromyography methods, enable simultaneous sEMG measurements of one muscle for increased spatial resolution [14]. Each fabric electrode routes to a bioamplifier board (Cyton, OpenBCI) [18] via machine-sewn conductive thread [19], which is positioned on the outside of the sleeve and insulated with sports kinesiology tape to reduce noise reduce impedance and cross talk between wires and prevent off-target skin contact. Previous work using this conductive fabric as a biosensor found the material is robust to changes in signal strength after 50 wash cycles [20]. We confirmed the connectivity between the fabric electrode and the wiring adapter with a multimeter and measured an average resistance of $46.3\ \Omega \pm 3.3\ \Omega$ across all electrodes and conductive thread wires.

IV. Methods

We designed two experiments to evaluate the fabric sleeve's performance on nine healthy participants and one stroke participant. Our first objective was to determine whether the sleeve could distinguish thumb-specific movements from overall finger movements and movement noise. The tasks chosen to evaluate this aspect included both dynamic and static thumb and finger movement conditions to isolate intrinsic thumb muscle activity. Our second objective was to explore whether signals measured by the fabric sleeve could be used for intent inferral. To test this, we trained a machine learning classifier to detect hand opening and hand closing from sEMG signals measured by the fabric sleeve.

A. Isolated Muscle Movement Task

The Isolated Muscle Movement Task distinguished between dynamic, thumb-only movement and coordinated finger movement. Participants moved either their thumb or all four fingers from rest into an engaged position with moderate effort for about 5 seconds (Fig. 3). To assess thumb-specific muscle activity, participants moved their thumb from rest into abduction. For finger-specific muscle activity, participants simultaneously moved all four fingers from a resting position into either extension or flexion.

B. Isometric Muscle Contraction Task

The Isometric Muscle Contraction Task targeted thumb-specific muscle activity in a static position. Participants performed the same actions as the Isolated Muscle Movement task with added resistance from the experimenter (Fig. 3). To minimize movement artifacts, participants resisted the external force for 5 seconds, without moving their thumb or fingers. For the thumb, the experimenter applied pressure with their finger to the lateral side of the participant's thumb MCP joint. For finger extension, the experimenter applied resistance on the dorsal side of their fingers at the head of the proximal phalanx. For finger flexion, the experimenter applied resistance on the palmar side of the participant's fingertips.

C. Hand Gesture Classification

To test whether signals from the fabric sleeve could be used for intent inferral, we collected data while participants performed a series of hand gestures. We instructed participants to open and close their hand as if they were to grasp a metal can, which we provided as a visual aid to encourage thumb abduction in a lumbrical grasp (Fig. 3). We collected two datasets for training and testing, during which the participant opened and closed their hand 8 times, each for 5 seconds, with 5 seconds of rest between each movement. The stroke participant performed an abbreviated set of 3 hand movements instead of 8.

D. Data Collection and Analysis

During data collection, participants were seated with their forearms resting on the table and elbows bent at a 90 degree angle. Participants donned both the fabric sensing sleeve and the commercial, 8-channel forearm sEMG armband (Myo, Thalmic Labs). Before donning the fabric sensing sleeve, we prepped the participant's hand by wiping their skin with a moist towelette and adjusted the position of the sensing array to lie over the TE of the thumb.

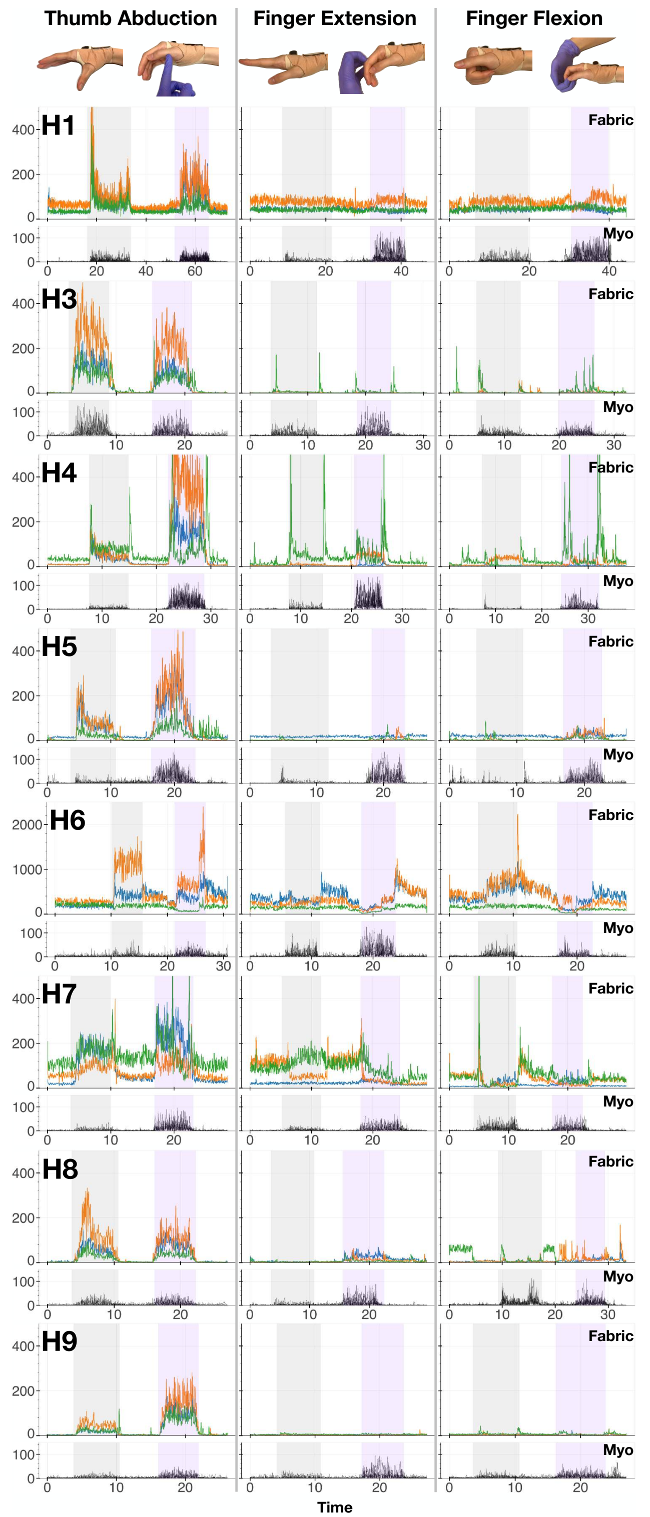

Fig. 4. (best seen in color) Data from our fabric sensing sleeve and commercial armband (Myo) during the Isolated Muscle Movement and Isometric Muscle Contraction tasks over time (s). Grey bars denote isolated movement, and purple bars denote isometric contraction. Each row depicts data from one healthy participant, and each column corresponds to a hand movement (Fig. 3). For each figure, the top plot shows the fabric sensor activity in μV_{rms} (blue = Channel 1, orange = Ch. 2, green = Ch. 3). Y-axis limit is 500 μV except for H6 (2,500 μV), and all cut-off peaks are below 1,000 μV. Bottom plot depicts corresponding Myo sensor activity in proprietary values (a.u.), with all 8 channels plotted in black.

Using the OpenBCI software, we measured the skin-electrode impedance to ensure sufficient contact and monitored the contact throughout the session. We collected raw voltage sEMG data from the fabric sleeve at 250 Hz and 1x amplification and used a 4th order Butterworth bandpass filter from 50 Hz to 115 Hz with a notch filter at 50 Hz and 60 Hz to eliminate environmental powerline noise. We collected sEMG data from the Myo armband at 200 Hz and did not perform any additional filtering of the output signal.

For the Isolated Muscle Movement and Isometric Muscle Contraction Tasks, we needed to to quantify changes in muscle activity between rest and active phases. To achieve this, we first rectified the raw EMG signal and passed it through a 40 Hz low-pass filter. Next, we found the average signal amplitude per sensing channel (3 channels in the fabric sensing sleeve and 8 channels in the commercial armband) to calculate the ratio of signal amplitude between the resting phase and the active phase of each of the two tasks.

For hand gesture classification, we processed the raw output from the OpenBCI board by extracting overlapping sliding windows of size 250 (1 second) with an offset of 10 samples. Each window was labeled with the ground truth at the end of the window, indicating the intent. From each window, we extracted both time-domain and frequency-domain features from each channel in each window, including Mean Absolute Value, Root Mean Square, Variance, Waveform Length, Zero Crossing Rate, Mean Frequency, Median Frequency, and Total Power. After feature extraction, we standardized features by removing the mean and scaling to unit variance using the training set.

We then trained three machine learning models to classify the extracted features: Linear Discriminant Analysis (LDA), Random Forest (RF), and a Multi-layer Perceptron (MLP). LDA was chosen for its simplicity and effectiveness with lower-dimensional data, RF for its ability to capture nonlinear relationships, and MLP for its capability to model more complex patterns. Each model was trained using subject-specific data, with distinct training and test sets.

E. Participants

We recruited nine healthy participants (five male, four female, ages 22-27)[1]. We also recruited a single stroke participant with chronic hemiparesis (male, right-hand impaired, scores of 1+ elbow flexors and 1 finger flexor on the Modified Ashworth Scale) for feasibility testing in a clinical setting under the supervision of an occupational therapist. Testing with all participants was approved by the Columbia University Institutional Review Board (IRB-AAAS8104).

V. Results & Discussion

We evaluated the sensor performance by finding the ratio between the average signal amplitude during the resting phase and the active phases. The raw data is visualized in Fig. 4[2], and Table I shows the average ratio values across all sensing channels measured by the fabric sleeve. In Table I, the hand movement labels are abbreviated: Thumb for thumb abduction, FE for finger extension, and FF for finger flexion.

TABLE I
Average Change in Signal Amplitude of Fabric Sensing Sleeve Relative to Relaxed State

Participant	Isolated Finger Movement			Isometric Muscle Contraction		
	Thumb	**FE**	**FF**	**Thumb**	**FE**	**FF**
H1	**2.2**	1.0	1.1	**2.4**	0.9	1.2
H3	**88.5**	4.1	2.1	**66.6**	2.9	2.6
H4	**4.9**	2.5	2.4	**18.9**	5.7	2.5
H5	**13.2**	1.2	1.1	**30.9**	3.5	4.8
H6	**2.4**	1.0	1.5	**1.9**	0.7	0.5
H7	**3.7**	1.0	1.4	**5.2**	0.8	1.6
H8	**20.5**	0.8	0.9	**22.0**	4.3	2.1
H9	**11.6**	1.2	1.4	**39.3**	1.2	1.2
Avg	**18.4**	1.6	1.5	**23.4**	2.5	2.1

We did not control for uniform force output exerted by each participant during the movement, so we posit that individual strength differences may have contributed to the varying sEMG signal amplitudes. Other factors that can be explored in future work include measurements of skin conditions and overall engagement with the task.

A notable outlier in signal quality from Fig. 4 was H6, whose baseline signal and overall signal amplitude was larger than all other participants. As a simple proxy for TE size, we measured the depth of the TE for each healthy participant between the palmar and dorsal sides of the hand. H6 had a TE depth of 25 mm, compared to the average TE depth of 34 ± 3.9 mm among all other healthy participants. Furthermore, we observed that H6 had drier skin compared to other participants. Thus, H6's hand size and skin condition could have affected skin-electrode contact with the fabric sleeve for reduced performance.

A. Isolated Muscle Movement Results

During the Isolated Muscle Movement Task, we observed the largest increase in signal amplitude during thumb abduction. For the thumb abduction condition, we report an average increase in signal amplitude by a factor of 18.4 from the relaxed position across all healthy participants. In contrast, the average signal amplitude change for the finger conditions were much smaller, with a factor of 1.6 for finger extension and 1.5 for finger flexion.

The difference in average signal magnitude between the thumb condition and the finger conditions demonstrated that the fabric sensing sleeve measured high activity during thumb activity and low activity when thumb movement was absent. Even during finger movement, the fabric sensors detected low activity as long as the thumb was not engaged.

To confirm the low activity detected by the fabric sensors during finger movement was not due to a lack of effort, we recorded the commercial sEMG armband values of concurrent extrinsic muscle activity in the forearm during finger extension and flexion (Fig. 4). The sustained peaks in signal activity measured by the commercial sEMG armband suggested greater activation of the extrinsic muscles than the

[1]H2 was later excluded from the study due to insufficient sEMG activity measured by the commercial armband.

[2]H1 performed a slightly extended active period of about 10 seconds for all tasks.

intrinsic muscles. During the finger movement conditions of the Isolated Muscle Movement task, the fabric sensor did not detect sustained activation during the 5 second period, indicating that the sensor was more sensitive to TE muscle activity than to finger movements.

We observed that three healthy participants had transient peaks at the start and end of each movement. However, the lack of sustained activation as observed in the thumb movement tasks supported the conclusion that the sensor primarily detected thumb muscle activity. These transient peaks could also be attributed to the participant's ability to maintain a relaxed thumb position during both the isolated finger movements.

B. Isometric Muscle Contraction Results

The Isometric Muscle Contraction Task focused on measuring TE muscle activity without finger movement to mitigate potential motion noise. With isometric muscle contraction alone, the results aligned with those of the Isolated Muscle Movement Task–the thumb abduction condition exhibited the largest change in average signal amplitude from the relaxed phase. Across the healthy participants, we report an average increase in signal amplitude by a factor of 23.4 for the thumb abduction condition, compared to a factor of 2.5 and 2.1 increase from relaxed during the finger extension and flexion conditions, respectively.

During the thumb abduction condition, a visible and sustained peak in signal during both Isolated Muscle Movement and Isometric Muscle Contraction indicated its sensitivity to thumb activity, whether from movement or muscle engagement (Fig 4). While muscle shape changes during contraction could affect the contact surface with the sensors, the sustained peak during isometric muscle contraction—where no thumb movement occurred—indicated that the signal was likely due to muscle activation rather than motion artifacts.

C. Classification Performance

Using the simultaneously collected fabric sensor and commercial sEMG armband data, we trained three machine learning models (LDA, RF, MLP) with the fabric sensor and the commercial armband separately to assess their classification accuracy. The results are shown in Table II, with the highest classification accuracy per sensing modality marked in bold. For the fabric sensor, the highest classification accuracy of 92.6% was achieved with the LDA model. The commercial sEMG armband achieved a maximum classification accuracy of 91.1% with the RF model.

The classification accuracy of the fabric sensing sleeve highlighted its potential as a viable sensor for intent inferral. For half of the participants, the 3-channel fabric sensing sleeve achieved a maximum classification accuracy within 5% of the commercial armband. This comparison is not intended to suggest the fabric sensing sleeve could replace the commercial forearm sEMG sensor. Rather, this suggests that sEMG signals from TE activity alone captured sufficient signal information for intent inferral. These results suggest the fabric sensing sleeve could augment a forearm sEMG sensing setup to improve intent inferral in future work.

TABLE II
CLASSIFICATION ACCURACY OF FABRIC SENSING SLEEVE AND MYO ARMBAND ACROSS 3 CANDIDATE MODELS

Hx	**Fabric Sensor**			**Myo Armband**		
	LDA	**RF**	**MLP**	**LDA**	**RF**	**MLP**
H1	**70.1%**	68.6%	65.1%	84.6%	**84.7%**	80.4%
H3	**84.7%**	83.8%	79.4%	**84.1%**	83.1%	82.1%
H4	**84.4%**	80.8%	83.0%	**86.6%**	86.3%	81.5%
H5	**81.9%**	69.6%	66.7%	78.7%	**84.8%**	79.0%
H6	13.0%	**67.5%**	42.0%	77.3%	**81.3%**	74.6%
H7	70.1%	46.5%	**70.6%**	88.2%	**91.1%**	89.9%
H8	**92.6%**	91.1%	87.7%	89.3%	**90.7%**	90.0%
H9	77.5%	78.6%	**80.3%**	86.8%	**87.4%**	83.3%
Avg	71.8%	73.3%	71.9%	84.4%	86.2%	82.6%
Std	24.9%	13.6%	14.5%	4.3%	3.4%	5.2%

D. Preliminary Testing with Stroke Participant

We performed a modified version of this protocol with one stroke survivor who had limited active thumb movement. We performed only the thumb movement of the Isolated Muscle Movement and the Isometric Muscle Contraction Tasks and an abbreviated Hand Gesture Classification data collection set due to stroke participant fatigue.

For the thumb-only Isolated Muscle Movement and Isometric Muscle Contractions, we observed a 0.8 change in signal amplitude from resting for both tasks. Unlike the healthy participants, we did not observe increased signal amplitude with the fabric sleeve during thumb engagement. However, the participant had a 3.9 factor increase in signal amplitude measured by the commercial sEMG armband during isolated thumb movement, and a 2.6 factor increase in signal amplitude during isometric thumb muscle contraction. The lack of signal activity measured by the fabric sleeve could be because the stroke survivor had difficulty isolating fine-motor movement of the thumb from overall hand engagement.

During overall hand engagement, however, the fabric sleeve captured some signals from the stroke participant. The fabric sensor had a maximum classification accuracy of 74.5% with the RF model, and the commercial sEMG armband had a maximum classification accuracy of 86.7% with the MLP model. While the fabric sleeve may not distinguish isolated thumb movement in stroke survivors, this result shows potential for its use with a commercial armband for intent inferral.

E. Future Work & Limitations

The modularity of the textile sensor design presents an opportunity to integrate additional, targeted sEMG sensors on the body for improved intent inferral. A future direction of this work would be integrating additional textile sensors to create an entirely fabric-based sensing sleeve to measure intrinsic and extrinsic muscle activity. Developing a multimodal machine learning model to leverage both intrinsic and extrinsic muscles would be a logical next step toward improving classification accuracy for intent inferral.

Limitations of this work include the small sample size of stroke participants. For the stroke participant, we could not rule out that the activation may have been from *flexor pollicis brevis* rather than APB, as stroke survivors may have difficulty distinguishing between these motions. Expanding the number of stroke participants in the work would allow us to draw more conclusions on using intrinsic hand muscle activity for intent inferral and the use of textile sensors to detect abnormal muscle signals from impaired individuals.

Further research will focus on characterizing the textile sensors, including a comparison of its performance to commercial sEMG systems on the TE, evaluating the sensors' dynamic response, and skin-electrode contact quality. As seen with participant H6, two factors—hand size and skin condition—motivates multiple fabric sleeve sizes and testing sEMG preparation gel to improve skin-electrode contact. Exploring different skin conditions and methods could help address the fluctuations in signal quality observed among healthy participants to ensure better sensor performance.

VI. Conclusion

In this work, we present a textile sEMG sensing array to measure muscle activity of intrinsic hand muscles in the TE. To the best of our knowledge, this is the first fabric sensing sleeve that uses textile sensors to measure intrinsic hand muscle sEMG activity. With a 3-channel sensing array on the thenar eminence, we demonstrate that the textile sensors can effectively discriminate intrinsic thumb movements from extrinsic finger movements during both Isolated Muscle Movement and Isometric Muscle Contraction Tasks. Furthermore, we show that the fabric sleeve alone can achieve promising classification accuracy in classifying hand poses for intent inferral. For assistive robotics, where wearability and comfort are key aspects of device design, textile sensors offer a non-obtrusive interface for muscle sensing.

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