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Myoelectric performance of the reconstructed elbow flexor in patients with brachial plexus injuries

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ABSTRACT

Traumatic adult brachial plexus injury is a debilitating injury. Myoelectric exoskeletons are functional tools for restoring elbow flexion. Electromyography signals are used for exoskeleton control, but a characterization specific to the traumatic adult brachial plexus injury population has yet to be performed. This study evaluated if adult patients with traumatic brachial plexus injury and a reconstructed elbow flexor can control a myoelectric exoskeleton. Adult patients who underwent surgical intervention to restore elbow flexion with traumatic brachial plexus injury were recruited for this cross-sectional study. The processed elbow flexor muscle signal and activation thresholds were used to evaluate criteria for exoskeleton control algorithm development. A single activation threshold can be utilized for exoskeleton control, but the calibration routine should consider the resting signal for both extended and flexed elbow positions. The data indicated a 'settle-time' following contraction is needed to prevent unintentional movement of the exoskeleton. All patients activated their elbow flexor above the activation threshold in the supported, flexed position. However, there were different abilities to generate multiple, discrete signals. These results were not specific to surgery, nerve implemented for reconstruction, or post-operative recovery time. Patients with a brachial plexus injury and a reconstructed elbow flexor demonstrated subject-specific capabilities for exoskeleton control.

1. Introduction

Traumatic adult brachial plexus injury (BPI) is a debilitating life-altering injury (Shin et al, 2022). The brachial plexus consists of cervical nerve roots C5-C8 and the thoracic nerve root T1 (Shin et al, 2005). Injury occurs when the head and neck are vigorously displaced from the ipsilateral shoulder causing a stretching, rupture, or avulsion from the spinal cord of the brachial plexus nerves (Shin et al., 2005). Brachial plexus injuries impact the use of the shoulder, arm and/or hand and range from varying levels of muscle weakness to a complete inability to use any of the muscles in the shoulder, arm or hand (Shin et al., 2005). Reconstructive surgeries are common in the treatment of BPI to restore elbow flexion. Despite surgical reconstruction, some patients remain unable to generate and sustain functional elbow flexion for activities of daily living (ADL) (Anderson et al., 2021). Diminished elbow flexion decreases an individual's ability to perform activities of daily living and live independently (Webber et al, 2021). Upper limb exoskeletons activated by muscle signals have successfully been used as rehabilitation tools in a clinical setting and under appropriate supervision to operate in parallel with the human upper limb and improve elbow flexion in this population [Doi et al., 2022, Gull et al, 2020, Kubota et al, 2017, Kubota et al, 2018, ÖGCE and ÖZYALÇIN, 2000, Shigeki Kubota et al, 2019, Webber et al., 2021). In addition to devices for controlled medical rehabilitation, upper limb exoskeletons are being introduced as functional tools for independent use in the free-living environment. These functional exoskeletons are designed for assistance and motion amplification for elbow flexion for during ADLs (Anderson et al., 2021, Gull et al., 2020; Pulos et al, 2021, Webber et al., 2021). However, the functional commercial myoelectric exoskeleton currently utilized in the adult traumatic BPI population, MyoPro (Myomo Inc., Boston, MA, USA), was initially designed for stroke patients and is a cross-over application that was not specifically designed for patients with a BPI (Anderson et al., 2021) and does not specifically consider the needs of patients with elbow-flexor reconstruction due to a traumatic BPI (Webber et al., 2021). Specifically, the MyoPro (Myomo Inc., Boston, MA, USA) requires users to produce a sustained elbow flexor contraction to maintain a flexed elbow position and extension occurs when the elbow flexor stops contracting (Webber et al., 2021). This design

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requirement causes fatigue for patients with elbow flexor reconstruction due to a traumatic BPI and cannot successfully be achieved (Webber et al., 2021). Myoelectric exoskeletons must be tailored to the specific needs of the patient and be adapted to the patient's specific injury (Gandolfi et al, 2021).

Electromyography (EMG) signals have been used to control exoskeletons, either using binary control or a more sophisticated control strategy (Gull et al., 2020, Lobo-Prat et al, 2017, Lucas et al, 2004, Singh and Chatterji, 2012, Stein et al, 2007). It has been suggested that future exoskeleton research and development should focus on the control strategy (Gull et al., 2020, Herr, 2009, Proietti et al, 2016). Developing a successful control strategy requires knowing the user's needs, abilities, and preferences. Nam et al. conducted an extensive investigation, based on patient perspectives, to classify user need for upper extremity exoskeletons but limited the study to stroke patients (Nam et al, 2019). Webber et al. collected feedback from a small cohort of patients with a BPI regarding exoskeleton device usage, hardware performance, and device design (Webber et al., 2021) and Pulos et al. evaluated the functional outcomes of patients with a BPI after using a myoelectric exoskeleton and reported the patients' strength, function, and pain (Pulos et al., 2021). However, these studies lacked details regarding BPI elbow flexor exoskeleton control strategy. Characterization and myoelectric performance of the reconstructed elbow flexor for the BPI population has yet to be established.

An exoskeleton's design parameters are dictated by the target population (Gull et al., 2020). Therefore, to develop a subject and injury-specific control strategy for patients with a BPI, it is essential first to characterize the signal used to activate the device. The purpose of this study was to determine if patients with a BPI and a reconstructed elbow flexor can control an EMG-activated exoskeleton. Once the capability of the condition-specific signal is clearly defined, it is possible for research teams to design an appropriate BPI condition-specific control strategy. We hypothesize that specific muscle activation strategies for exoskeleton control are dependent on post-surgery recovery time.

2. Methods

2.1. Participants

Patients who underwent surgical intervention to restore elbow flexion with traumatic BPI were recruited. These patients had surgical procedures to restore elbow flexion with a gracilis free functioning muscle transfer (gFFMT) innervated by the spinal accessory nerve (SPA) or the intercostal nerves (ICN), nerve grafting from the upper trunk, or nerve transfer (from the SPA, ICN or ulnar nerve fascicle to the musculocutaneous nerve or its biceps motor branch). This study was approved by our Institutional Review Board and all patients provided informed consent before participation. Data collection occurred during post-surgical clinical appointments at a multidisciplinary Brachial Plexus clinic. A potential selection bias was eliminated by considering every post-surgical patient on the clinic schedule. Potential adult patients in good neuromuscular health were screened during their appointment by the surgeon (AYS) according to the inclusion and exclusion criteria for study participation (Table 1). The minimum sample size for this study was 12 patients (Julious, 2005). Twenty-seven patients (3 female, age: 26 ± 30 yr., BMI: 28 ± 5 kg/m^2, post-Op: 26 ± 29 mo.) consented and participated in this study. Demographics, surgical details, and qualitative elbow flexor muscle strength graded using the modified version of the British Medical Research Council (BMRC) system (Dyck et al, 2005) were collected (Table 2).

2.2. Experimental Setup

Patients stood for the data collection. The skin surrounding the elbow flexor was wiped with an alcohol wipe and a surface EMG electrode (EMG500, Motion Lab Systems, Inc., Baton Rouge, LA) was secured to the muscle belly of the reconstructed elbow flexor muscle (gracilis vs. biceps), along the muscle's long axis. Each EMG electrode pre-amplifier (Input Impedance= >100MΩ, CMRR at 65 Hz = 100 dB, SNR= <2μV RMS, Gain = x500 ± 5 % @100 Hz) had two medical grade stainless steel disk-shaped contacts (12 mm diameter, 17 mm inter-electrode distance) separated by a reference contact (13 x 3 mm bar) for differential input. The patients followed a calibration routine to establish the signal activation threshold, which was consistent with the daily calibration routine required for the commercially available exoskeleton currently prescribed for patients with a BPI. The EMG signal was acquired (f_s = 1000 Hz; A/D card = 16 bits, NI6361, National Instruments, Austin, TX), bandpass filtered (65 Hz to 550 Hz) and displayed using linear envelope detection (lowpass 4th order Butterworth filter, f_c = 4 Hz) with custom software (LabVIEW 20.0.1, NI, Austin, TX). The elbow flexor's baseline level was observed while the elbow was placed in a relaxed, uncontracted, extended position. The activation threshold was then adjusted slightly above the baseline level and verified or modified using a series of elbow flexions and extensions prior to the data collection trials. The elbow flexor EMG linear envelope and the activation threshold were displayed on a screen using custom software (LabVIEW 20.0.1, NI, Austin, TX) for visual feedback during the entire data collection.

Table 1
Study inclusion and exclusion criteria.

Inclusion Criteria	Exclusion Criteria
• 18–65 years of age	• Non-functional passive range of motion (screened by AYS)
• Patients with injuries resulting in loss of elbow flexion, in particular a traumatic BPI	• Soft tissue or skeletal injuries which preclude use of an orthosis
• Functional passive range of motion of the involved upper extremity (screened by AYS)	• Closed head injury with resultant inability to follow commands
• Able to follow simple directions	• Neuropathic pain which prevents use of a powered exoskeleton
• No restriction will be placed on gender, race, or ethnicity	

2.3. Data collection protocol

The patients were verbally instructed to perform a series of sequential tasks relevant to exoskeleton control, where each task sequence was considered one trial. Before each trial, a study team member reviewed the task sequence. During the trial, the study team member prompted each task and did not move on to the next section until the patient fully executed the requested task and the activation threshold was set appropriately. The research team adjusted the activation threshold for each task on a subject-by-subject basis. The verbal instructions and task sequence for each trial were as follows: (1) Do not contract your elbow flexor. Allow your elbow flexor to relax and position your arm in an extended position (Fig. 1A). During this section, a study team member verified that the EMG signal was below the activation threshold and adjusted accordingly, if necessary. (2) Contract your elbow flexor to flex your elbow to approximately 90-degrees. When your arm reaches the flexed position, a study team member will fully support your forearm. (3) Stop contracting your elbow flexor and allow the elbow flexor to relax in the supported, flexed position (Fig. 1B). During this section, a study team member verified that the EMG signal was below the activation threshold and adjusted accordingly, if necessary. (4) While your arm is in the supported, flexed position, you will be instructed to execute, either a constant contraction to indicate increased flexion or two distinct, rapid contractions to indicate extension. These tasks replicate potential bidirectional exoskeleton control strategies. (5) After you execute the commanded tasks in the flexed position, the trial will be complete. The study team member will stop supporting your forearm and you may extend your arm. The activation control sequence

Table 2
Subject Demographics.

Surgery Type	Nerve Used	Post-Op (mo.)	mBMRC	Gender	Age (yr.)	BMI (kg/m^2)	Affected Side
gFFMT	Anterior Upper Trunk	16.8	3	M	53	29.8	Left
	ICN	6.9	2	M	19	27.0	Right
	ICN	24	3+	M	27	32.1	Right
	ICN	32	2	M	59	27.9	Left
	ICN	63.9	3	M	41	31.3	Left
	ICN	155.1	3	M	37	29.1	Left
	SPA	7	2-	M	21	20.7	Left
	SPA	8.2	2-	F	26	35.4	Right
	SPA	8.2	2	M	28	30.5	Left
	SPA	8.6	2	M	22	21.2	Right
	SPA	9.8	NA	M	21	22.5	Right
	SPA	13.8	NA	M	38	31.2	Left
	SPA	15.8	3	M	60	23.2	Right
	SPA	26.8	3	M	29	25.4	Left
	SPA	34.1	2	M	29	25.2	Left
Nerve Transfer	SPA†	23.1	3+	M	23	36.6	Right
	SPA†	26.1	3+	M	23	36.6	Right
	Ulnar	6.3	3	M	23	23.0	Left
	Ulnar	12.1	NA	F	65	28.3	Left
	Ulnar	12.4	4+	M	23	23.0	Left
	Ulnar	12.6	2+/3-	M	31	27.6	Right
	Ulnar	14.7	4	M	29	25.4	Right
	Ulnar	17.2	3	M	59	28.7	Right
	Ulnar	25.2	2+/3-	F	41	25.7	Left
	Ulnar	46	2+	M	36	35.0	Right
Nerve Graft	Musculocutaneous	41.5	4+	M	24	33.8	Right
	SPA, Upper Trunk	21.1	4-	M	65	32.5	Right

†Same patient, separate test dates.
Abbreviations: ICN = intercostal nerves, SPA = spinal accessory nerve, Ulnar = ulnar nerve to biceps motor branch.

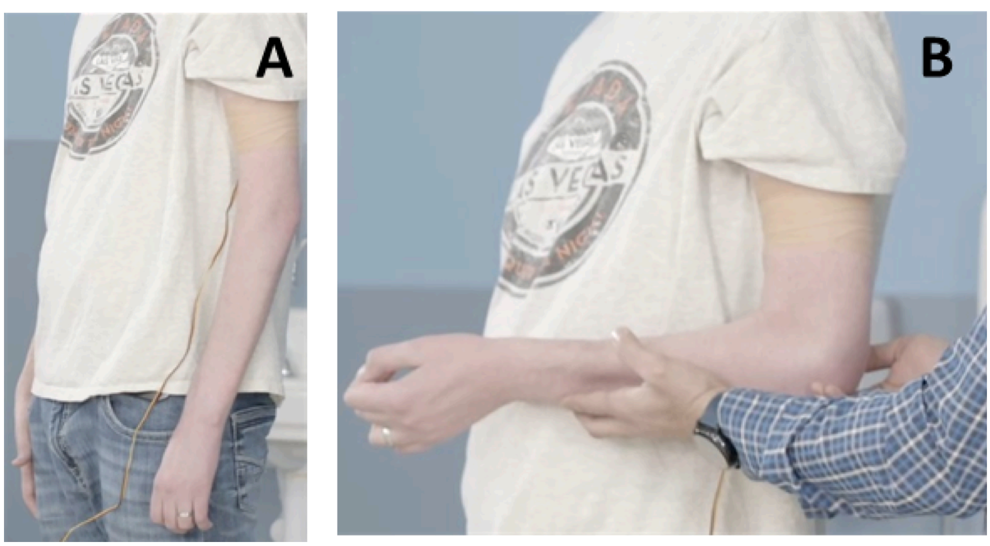

Fig. 1. Patient positions during a data collection trial: (A) Relaxed elbow flexor with elbow in extended position (B) Relaxed elbow flexor with elbow in flexed position and forearm fully supported by a study team member.

(Steps 1–3) utilized in this study was consistent with the control strategy implemented in the current functional commercial exoskeleton, MyoPro (Myomo Inc., Boston, MA, USA). The tasks to indicate extension (Step 4), were a novel control strategy compared to the commercial exoskeleton, MyoPro (Myomo, Inc. Boston, MA, USA).

2.4. Outcome Measures for exoskeleton design criteria

The processed EMG signal, activation thresholds for the extension and flexion positions, and subject performance (i.e., yes/no subject successfully executed each requested task) were recorded for each trial. This data was used to evaluate specific criteria for exoskeleton control algorithm development. The design criteria were: (1) activation threshold, (2) time required for muscle relaxation following muscle activation, and (3) bi-directional control. This study will investigate if an activation threshold can be established for patients with a BPI that differentiates the EMG signal between a resting muscle and an active muscle and determine the EMG value (i.e., activation threshold) required to initiate exoskeleton movement. It will also determine if the same activation threshold level was appropriate for an extended and flexed elbow position or if the activation threshold level was position specific. Additionally, the activation threshold will be monitored to determine if the activation threshold changed over the course of the data collection. This study will also determine how much time is required for patients with a BPI to stop contracting their elbow flexor and return to an EMG level below the activation threshold (i.e., ‘settle-time’) in a flexed, supported position. The time between peak contraction and a stable signal below the established activation threshold in the flexed position was calculated for each trial (i.e., ‘settle-time’). The median ‘settle-time’ and interquartile range were calculated for each patient. Finally, this study will determine if patients with a BPI can generate multiple distinct, commanded signals (i.e., a constant contraction or two distinct quick contractions) in a supported, flexed position necessary for bidirectional exoskeleton control.

3. Results

Prior to patient data collection, the activation threshold was quantitatively established as the average quiescent baseline value plus three standard deviations (Hodges and Bui, 1996). This value was too high to sufficiently capture the entire range of activation as the elbow flexor contracted from initial contraction to terminal contraction to move the elbow from extension to flexion. Thus, the calibration routine was adjusted to the protocol described in the Methods section.

The duration of the data collections (9 ± 3 min) and the number of trials collected (8 ± 4) for each patient were dependent on the patient’s elbow flexor fatigue and clinical appointment schedule. Twenty-five out of the twenty-seven patients enrolled in this study were able to complete some or all the instructed tasks during the data collection (Table 3). One patient was unable to generate a detectable elbow flexor contraction and instrumentation problems prohibited data collection for one patient.

3.1. Activation threshold

A single subject-specific activation threshold was appropriate for all the patients evaluated in this study, but the position used to establish the activation threshold varied across subjects. The activation threshold established in the extended relaxed position was appropriate for nineteen out of twenty-five patients enrolled in this study. These patients were able to relax their elbow flexor below the activation threshold level established in the extended relaxed position, while their arm was in the flexed, supported position (Fig. 2). For the patients with a different resting elbow flexor signal in the flexed position compared to the extended position, the baseline signal for the flexed position was greater than the extended position. For these patients, the activation threshold was increased to the minimum level required to accommodate the resting signals for both the extended and the flexed, supported positions. These results were not specific to the surgery and the nerve implemented for reconstruction or the post-operative recovery time. Fourteen out of twenty-five patients required adjustments to the activation threshold at the beginning of the trial in the extended, relaxed position from trial to trial across the entire data collection.

3.2. Settle-time

The ‘settle time’ varied across all trials (median (IQR): 1.4 (2.5) sec), however it decreased during the data collections from the first trial (median (IQR): 2 (5) sec) to the last trial (median (IQR): 1 (1.6) sec) (Fig. 3). This ‘settle time’ decreased as post-operative recovery time increased across both surgery types and all nerves implemented for reconstruction.

3.3. Execution of commanded tasks for bidirectional control

All the patients were able to activate their elbow flexor above the activation threshold in the supported, flexed position. However, there were variations in their abilities to generate the specific commanded tasks successfully. In the supported flexed position, twenty out of twenty-five patients were able to execute two quick rapid pulses (Fig. 4) and sixteen out of twenty-five patients were able to execute a prolonged constant contraction (Fig. 5). The patients who were not able to execute two quick pulses or execute a prolonged contraction were not limited to a specific type of surgery or nerve involved for the reconstruction or post-operative recovery time and there was a representative patient (i.e., surgery, nerve, post-op) who was able to execute the commanded tasks.

4. Discussion

The current study demonstrated that following reconstruction for traumatic BPI, patients can achieve specific muscle activation strategies to control an exoskeleton successfully. Previous studies have demonstrated that stroke survivors can successfully utilize an myoelectrically controlled powered exoskeleton (Desplenter et al, 2020, Marchal-Crespo and Reinkensmeyer, 2009, Stein et al., 2007). However, for the BPI population EMG activation has only been used to evaluate muscle activity and has not been extended to characterizing the control strategies specific to exoskeleton control. For example, electromyographic evaluation with EMG needle electrodes was used to study reinnervation of the elbow flexor muscle following gFFMT in patients with traumatic BPI (Kazamel and Sorenson, 2016). These findings established a timeline for reinnervation for this specific patient population and established EMG as a beneficial tool for evaluating postoperative performance, but these findings did not provide information regarding functional reconstructed elbow flexor control. In another study, muscle activity of the reconstructed biceps and the triceps during repetitive elbow flexions and exercises using an exoskeleton designed for rehabilitation was described in a single case study (Kubota et al., 2018). This case study demonstrated biceps muscle activity during the rehabilitation elbow flexion exercises, but it did not provide information for specific muscle activation control strategies. Additionally, EMG measurements have been presented in post-operative assessments to demonstrate activation and to compare the clinical results of different reconstructive surgeries (Chia et al, 2020). However, these evaluations only considered concentric and eccentric contractions of the elbow flexors with the patient in a seated position and did not extend to the strategies specific to myoelectric exoskeleton control. In a previous study, our lab compared EMG signals from healthy, unimpaired controls to patients with a BPI (Bhat et al, 2023). This study demonstrated that patients with a BPI had reduced control of the elbow flexor EMG and were not able to modulate their muscle activation as well as control subjects. These findings further emphasized the need to characterize BPI elbow flexor control for exoskeleton control. The specific activation characteristics for a reconstructed elbow flexor presented in this study can be used to guide algorithm development for patients with BPI. For example, a single activation threshold can be utilized for exoskeleton control, but the calibration routine should consider the resting signal for both the extended and flexed positions. Additionally, the results showed that a ‘settle-time’ following contraction is needed in the control logic to prevent unintentional movement of the exoskeleton.

Despite the short duration for the data collection session, the metrics improved as the subjects became more familiar with the strategy. Each data collection trial was an opportunity to practice, implement and gain confidence with the control strategy. This demonstrated that the patients could achieve the required criteria for exoskeleton control. This was further reinforced by a single patient who, based on the clinical schedule, participated in this study on two separate occasions. For this patient, the second visit yielded more trials in less time, less adjustments to the activation threshold and the ability to perform both the two quick pulses and a prolonged contraction in the relaxed flexed position. The results do show that with a properly designed rehabilitation program and ample training time a viable EMG signal pattern can be achieved for exoskeleton control. This was consistent with previous exoskeleton rehabilitation programs, which have demonstrated improved elbow flexion due to the training program (Doi et al., 2022; Kubota et al., 2017, Kubota et al., 2018, Shigeki Kubota et al., 2019).

These findings suggest that each patient should complete a subject-specific evaluation for muscle activation and control, in addition to conventional musculoskeletal outcomes for traumatic BPI, which

Table 3
Patient Elbow Flexor Performance.

Surgery Type	Nerve Used	Post-Op (Mo)	Test Length (min)	Number of Trials	Activate Above Threshold in Extended Position	Median (IQR) Time for Signal to Fall Below Threshold in Flexed Position (s)	Change Activation Threshold in Flexed Position during Trial	Change Threshold in Session	Activate Above Threshold in Flexed Position*	Execute Double Pulse	Execute Constant Contraction
gFFMT	Ant Upper Trunk	16.8	11	10	Yes	0 (0)	No	Yes	Yes	Yes	Yes
	ICN	6.9	5	5	Yes	7.5 (2.6)	No	No	Yes	No	No
	ICN	24	7	3	Yes	4 (2)	No	No	Yes	Yes	NA
	ICN	32	12	4	Yes	2.3 (0.9)	Yes	Yes	Yes	Yes	Yes
	ICN	63.9	10	9	Yes	1.5 (1)	No	Yes	Yes	Yes	Yes
	ICN	155.1	5	8	Yes	1.5 (1.1)	No	No	Yes	Yes	No
	SPA	7	Unable to detect elbow flexor signal with electrode								
	SPA	8.2	5	3	Yes	1.2 (0)	Yes	Yes	Yes	No	Yes
	SPA	8.2	7	6	Yes	0 (0.4)	No	Yes	Yes	Yes	No
	SPA	8.6	Instrumentation Failure								
	SPA	9.8	11	9	Yes	2 (1.3)	Yes	Yes	Yes	Yes	Yes
	SPA	13.8	13	11	Yes	6 (16)	No	Yes	Yes	Yes	Yes
	SPA	15.8	6	4	Yes	2.5 (9.9)	Yes	Yes	Yes	No	Yes
	SPA	26.8	16	19	Yes	0 (0)	No	No	Yes	Yes	Yes
	SPA	34.1	8	5	Yes	1 (1.4)	No	Yes	Yes	Yes	No
Nerve Transfer	SPA†	23.1	12	4	Yes	0.8 (1.1)	Yes	Yes	Yes	Yes	NA
	SPA†	26.1	7	12	Yes	1 (2.7)	No	No	Yes	Yes	Yes
	Ulnar	6.3	13	9	Yes	NA	Yes	Yes	Yes	Yes	Yes
	Ulnar	12.1	2	3	Yes	5 (7)	No	No	Yes	No	No
	Ulnar	12.4	9	10	Yes	0.5 (4.1)	No	No	Yes	Yes	Yes
	Ulnar	12.6	9	10	Yes	3 (1.5)	No	No	Yes	Yes	Yes
	Ulnar	14.7	11	14	Yes	1.6 (1.3)	No	No	Yes	Yes	Yes
	Ulnar	17.2	5	5	Yes	1 (0.5)	No	Yes	Yes	Yes	No
	Ulnar	25.2	9	10	Yes	1.1 (1.9)	No	Yes	Yes	Yes	No
	Ulnar	46	6	9	Yes	1 (0.5)	No	No	Yes	Yes	Yes
Nerve Graft	Musculocutaneous	41.5	5	5	Yes	0.3 (1.7)	No	No	Yes	No	Yes
	SPA, Upper Trunk	21.1	10	8	Yes	0.8 (14.5)	No	Yes	Yes	Yes	Yes

*After activation threshold adjustment to accommodate change in baseline signal in flexed position, if necessary.
†Same patient, separate test dates. Abbreviations: ICN = intercostal nerves, SPA = spinal accessory nerve, Ulnar = ulnar nerve to biceps motor branch.

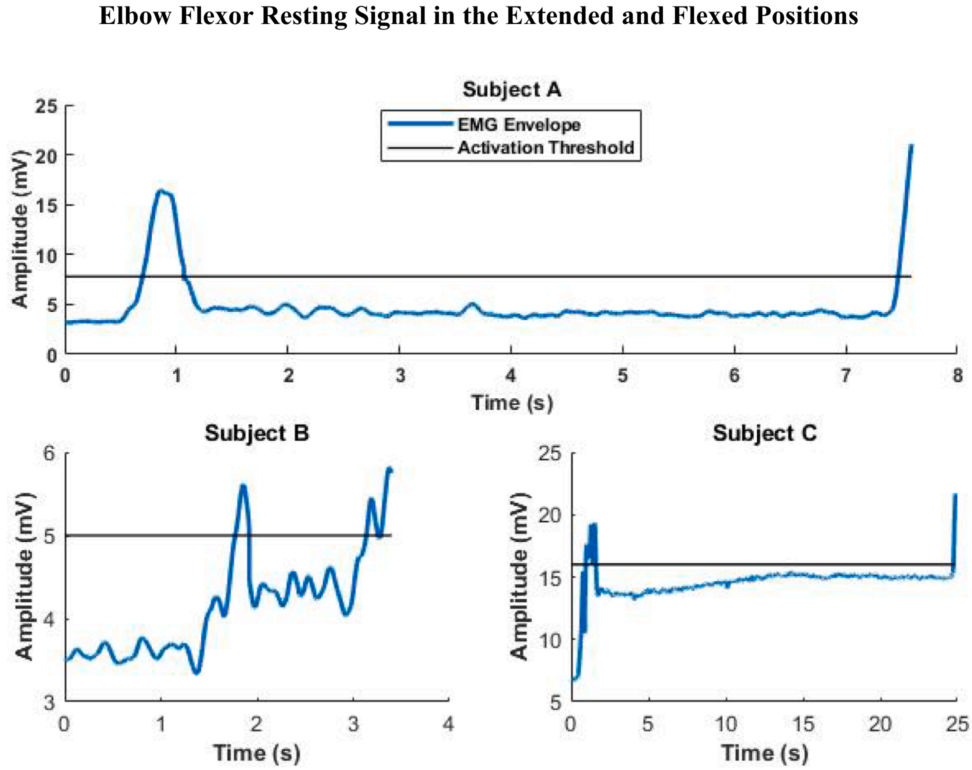

Fig. 2. Representative patient data for elbow flexor resting signal in extended and flexed positions. Subject A (Nerve Transfer, Ulnar Nerve, 12.4 mo. post-op) represents a similar resting elbow flexor signal in the extended and flexed positions. Subjects B (Nerve Transfer, SPA, 23.1 mo. post-op) and C (Gracilis, SPA, 34.1 mo. post-op) represent different resting elbow flexor signals in the extended and flexed positions, where the activation threshold was established to accommodate the flexed, supported position.

typically consider muscle strength and range of movement (Miller et al, 2021). This will ensure a control strategy specific to the patient's ability. For example, for patients who can only generate an elbow flexor signal greater than the activation threshold in the flexed, supported position, the elbow flexor signal may only be implemented to release the device and return the arm to an extended position. However, for patients who can generate multiple discrete signals in the supported, flexed position, additional control strategies could be implemented for bi-directional device operation in the flexed position. Future steps for this research include implementing the control strategy developed for this study in a prototype exoskeleton (Vignola et al, 2024), testing the prototype in a controlled laboratory environment and in home-use field studies, and modifying the control algorithms based on laboratory and real-world findings.

There were limitations to this study. The patients enrolled in this study were a sample of convenience dictated by the clinic schedule and the data collections were adjusted to accommodate the patient's clinical appointment schedule, pain, and fatigue. Additionally, the patient's rehabilitation and therapy history and history of pain were not included in the data collection and were not used to evaluate the patients' performance in this study. The performance of the subset of patients who could not execute two quick pulses or execute a prolonged contraction may have been limited due to lack of training, pain, and fatigue. Overall, each patient with a BPI was unique and there were multiple reconstructive scenarios based on the available functioning brachial plexus elements as well as non-brachial plexus elements. Vascular injury, injury to leg muscles used for potential free functioning muscle transfers, soft tissue upper extremity injuries all affected outcome. Additionally, time from injury to surgery, type of surgery and patient age all affect outcomes. The number of variables was tremendous.

5. Conclusion

Patients with a BPI and a reconstructed elbow flexor can meet specific criteria to control an exoskeleton. The activation threshold established in the extended relaxed position was appropriate for 76 % of the patients enrolled in this study. This indicated that while a single activation threshold can be utilized for exoskeleton control, the calibration routine should consider the resting signal for both the extended and flexed positions. The 'settle time' decreased across the duration of the data collection and decreased as post-operative recovery time increased. Additionally, 92 % of participants were able to execute at least one method for bidirectional control. These results demonstrated that with a properly designed control strategy, patients with a BPI can use a viable EMG signal for exoskeleton control. Finally, the results did not support our initial hypothesis. Reconstructed elbow flexor signal control capabilities were patient specific and not limited to surgery type, nerve implemented and post operative recovery time.

CRediT authorship contribution statement

Emily J. Miller: Writing – original draft, Validation, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Sandesh G. Bhat:** Writing – review & editing, Validation, Software, Methodology, Formal analysis, Data curation. **Paul H. Kane:** Writing – review & editing, Project administration, Investigation. **Alexander Y. Shin:** Writing – review & editing, Supervision, Methodology, Investigation, Conceptualization. **Kenton R. Kaufman:** Writing – review & editing, Visualization, Resources, Funding acquisition, Formal analysis, Conceptualization.

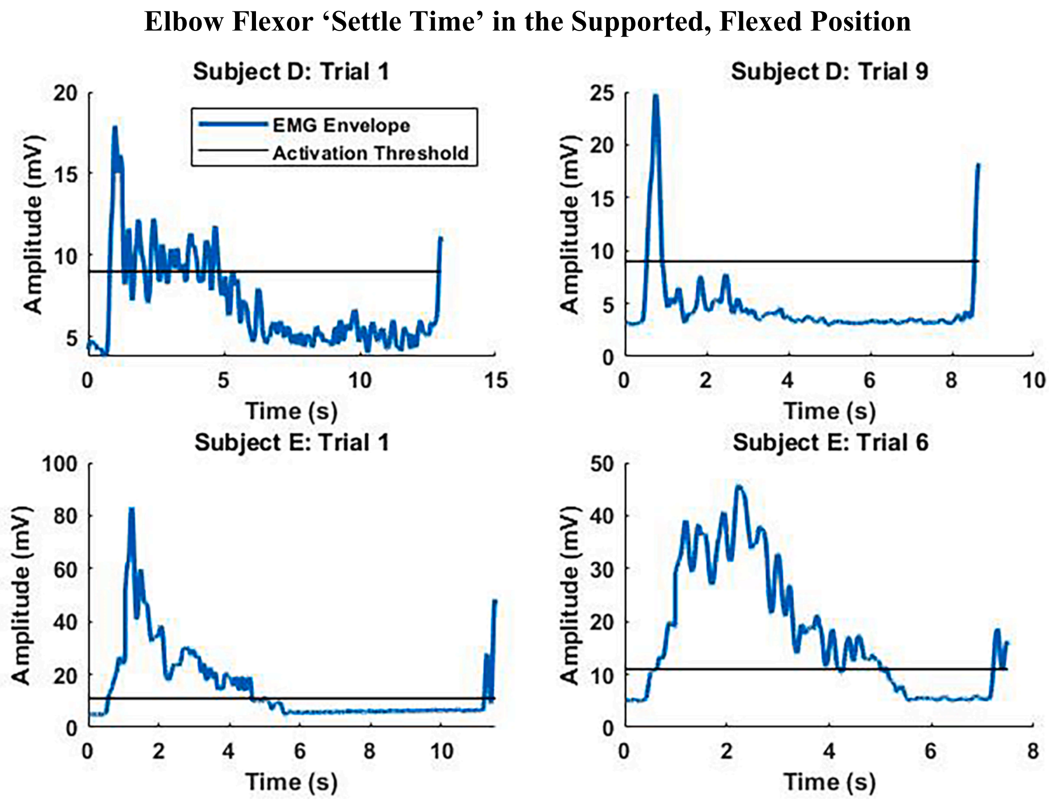

Fig. 3. Representative patient data for 'settle time' (time to fall below activation threshold) in the supported, flexed position from the beginning to end of the data collection. Subject D (Gracilis, SPA, 26.8 mo. post-op), compared to the beginning of the data collection (Trial 1) was able to immediately stop activating the elbow flexor in the supported, flexed position by the end of the data collection (Trial 9). Subject E (Nerve Transfer, Ulnar Nerve, 12.6 mo. post-op), compared to the beginning of the data collection (Trial 1) still required almost 5 s to stop activating the elbow flexor in the supported, flexed position by the end of the data collection (Trial 6).

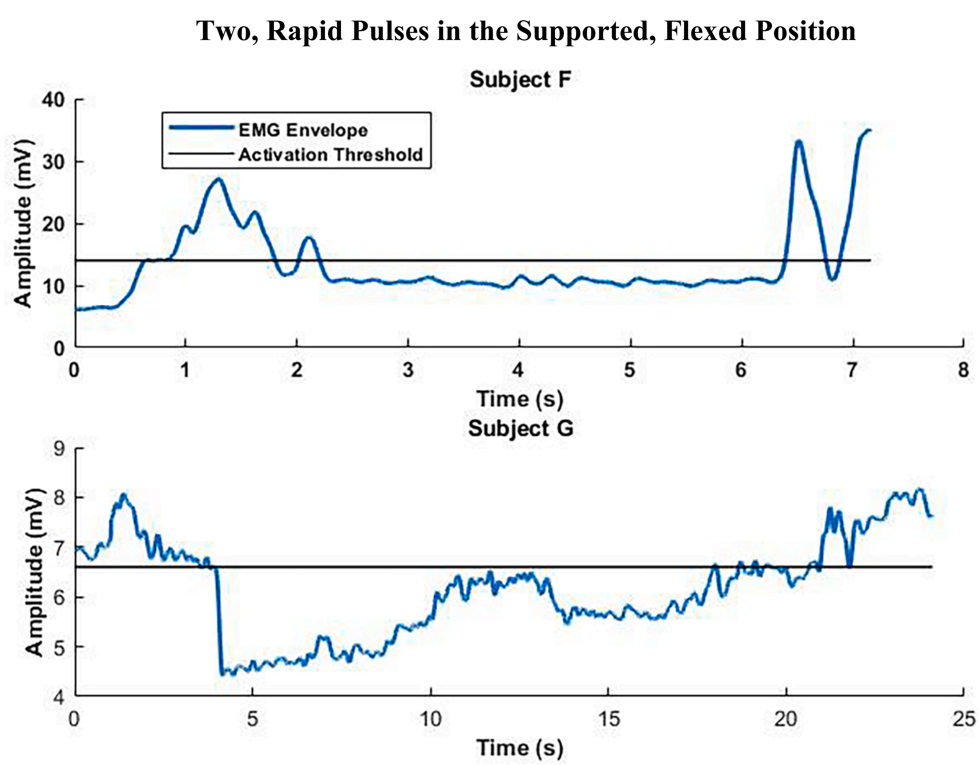

Fig. 4. Representatve patient data for two rapid pulses (circled in trial) in supported, flexed position. Patient F (Nerve Transfer, Ulnar Nerve, 25.2 mo. post-op) was able to generate two distinct, rapid pulses. Patient G (Gracilis, SPA, 8.2 mo. post-op) was not able to elicit two, distinct, rapid pulses.

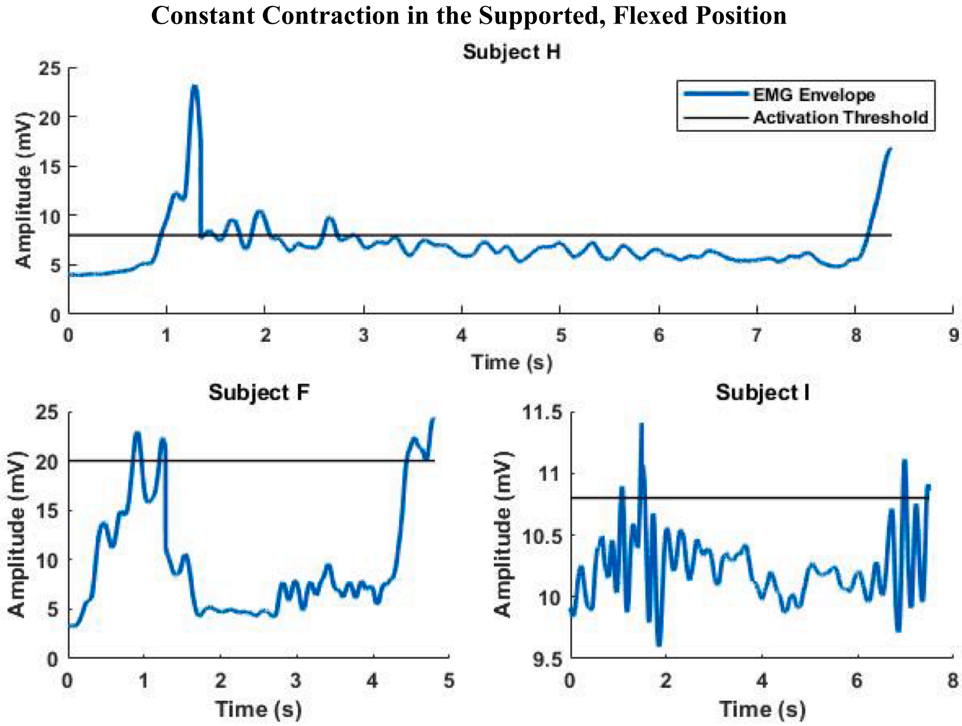

Fig. 5. Representative patient data for a constant contraction (circled in trial) in supported, flexed position. Subject H (Nerve Graft, SPA and Upper Trunk, 21.1 mo. post-op) was able to generate a clear, constant contraction. Subject F (Nerve Transfer, Ulnar Nerve, 25.2 mo. post-op) was not able to generate a constant contraction above the activation threshold. There was a decrease in signal followed by a secondary increase. Subject I (Nerve Transfer, Ulnar Nerve, 12.1 mo. post-op) was only able to active the elbow flexor above the activation threshold in the supported, flexed position.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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