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Short communication

Characterization of elbow flexion torque after nerve reconstruction of patients with traumatic brachial plexus injury

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ABSTRACT

Background: The modified British Medical Research Council muscle grading system remains the primary method for assessing outcomes following surgical intervention despite its subjectivity and numerous inherent flaws. A new objective outcome measure of elbow function in patients with a brachial plexus injury is proposed.
Methods: 11 patients with a reconstructed brachial plexus (nerve reconstruction) and 10 unimpaired control subjects were evaluated. A custom apparatus measuring elbow flexion torque was developed. The subjects were asked to match their elbow flexion torque to a predefined torque. Time taken to achieve this predefined elbow flexion torque (latency) and duration of steady torque output were used as outcome measures.
Results: Healthy individuals were better at maintaining and regulating elbow torque. The patients with a brachial plexus injury showed similar latency while increasing their elbow torque (normalized to maximum elbow torque) but lacked the ability to modulate the latency with demand as the healthy subjects.
Interpretation: This novel measure provides objective information regarding the patient's ability to control elbow torque after nerve reconstruction.

1. Introduction

Brachial plexus injuries (BPI) are serious and life-altering injuries resulting in physical disability, psychological distress, and socioeconomic hardship (Bayot et al., 2018; Noland et al., 2019). An increase in motor vehicle accident survivors has led to an increase in the prevalence of these traumatic injuries (Siqueira and Martins, 2011). Surgical reconstructive treatments are often required. While surgical reconstruction strategies continue to evolve, modifications are often made based on outcome measures.

Currently, manual muscle testing (MMT) is the most prominent functional outcome measure, which measures muscle strength. MMT is often graded using the British Medical Research Council (BMRC) system (Dyck et al., 2005) or modified versions of the BMRC system. BMRC scores increase with the strength in the patient's muscle, with a grade of 0 indicating no muscle contraction, and 5 indicating normal muscle strength. The BMRC is subjective and variations have made comparisons difficult (Bhardwaj and Bhardwaj, 2009; Cuthbert and Goodheart Jr., 2007). Assessment of the ability to modulate motor function control or fatigue, both of which may be more important than strength measurement, is not possible using BMRC. Better muscle control would enable the patient to more easily perform everyday tasks such as eating, drinking, dressing themselves, etc. Evaluation and treatment resulting from BMRC "remains and will always remain an art" that may not be translatable between surgeons and countries (Cuthbert and Goodheart Jr., 2007).

Accurate assessment of the patient's muscle control in addition to range of motion is important to guide post-surgery treatment decisions and rehabilitation efforts. Current methods of assessing patient outcomes fail to quantify muscle control. This study proposes as an objective measure to assess the ability to modulate the force output in BPI patients who undergo surgical reconstruction for elbow flexion.

Abbreviations: BPI, Brachial Plexus Injury; MMT, Manual Muscle Testing; BMRC, British Medical Research Council; FFMT, Free Functioniong Muscle Transfer.

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Table 1
Study demographics (NA: Not Applicable).

	BPI Group	Control Group	Statistical Difference
	Mean ± std. dev. (range)	Mean ± std. dev. (range)	
Subjects (N)	11	10	NA
Age (years)	39.72 ± 12.68 (26–65)	28.8 ± 2.82 (25–33)	$P = 0.02$
Weight (kg)	89.09 ± 19.32 (63.9–123)	86.89 ± 11.09 (76.2–116)	$P = 0.767$
Height (cm)	174.26 ± 8.06 (158–190)	181.26 ± 10.36 (171–208)	$P = 0.115$
Months Pre-Op (Time Between Injury and Surgical Procedure)	6.13 ± 1.19 (4.9–8.77)	NA	NA
Months Post-Op (Time Between Surgical Procedure and data collection)	17.26 ± 10.17 (7.1–43.2)	NA	NA
mBMRC Grade (N)	2(5); 3(1); 4(5)	NA	NA
Type of Procedure (N)	Ulnar nerve transfer (6); Sural graft (2); Spinal Accessory Nerve transfer (2); Median nerve transfer (1)	NA	NA

2. Methods

2.1. Subject selection and recruitment

Adult patients (age 18–65) who underwent nerve reconstructive surgery to restore elbow flexion following a BPI were identified at the Brachial Plexus Clinic, Mayo Clinic, Rochester, MN. Elbow flexion strength was graded using a modified BMRC grade (mBMRC) (Giuffre et al., 2010; O'Brien, 2010) by the patient's attending physician. The BMRC modification used in this article required full motion in the passive arc of motion to obtain a mBMRC grade of 3. A high grade could not be obtained unless the criteria of the lower grade was met. Patients with the following criteria were excluded:

- <6 months post-operative recovery time due to insufficient nerve recovery (Noland et al., 2019).
- Underwent a free functioning muscle transfer (FFMT) procedure.
- BMRC grade of 1 or 5.
- Unable to understand and follow verbal directions.

A control group in good neuromuscular health with no previous diagnosis of musculoskeletal disease were recruited by word of mouth. This study was approved by the Clinic Institutional Review Board (IRB # 19–008401).

Eleven subjects with a BPI and consequent reconstructions were recruited. The BPI group had a mean age of 39.72 ± 12.68 (range 26–65) years. The Control group consisted of 10 unimpaired subjects with a mean age of 28.8 ± 2.82 (range 25–33) years. The two groups were similar in height and weight (Table 1).

2.2. Data collection

A custom-built apparatus with a torque transducer (TS11–20, Interface Inc., Scottsdale, AZ) was used for the experiment (Fig. 1) with the data sampled at 500 Hz similar to a prior study (Bhat et al., 2023). The elbow axis of rotation was aligned with the torque transducer axis, with the elbow flexed at approximately 90 degrees. Trials were repeated if the elbow angle changed drastically during experimentation. The forearm was secured by a hook-and-loop strap at the subject's wrist. The dominant arm of the control subjects, and the affected arm for the patients with a BPI were tested.

A custom software was developed to display an ascending and descending stair step torque trace in LabVIEW 2019 (National Instruments, Austin, TX). An initial calibration trial was performed where the subjects generated a maximum elbow flexion torque. Real-time subject torque output was displayed as visual feedback via a custom software, where the subjects were blind to the scale and the exact value of their elbow flexion torque (Fig. 2). The only instruction given to the subjects was "you can control the red line with your elbow flexion force. We want you to match the red line to the black line as closely as possible." A moving average filter of 75 samples was applied in real-time to the torque data.

The data collection consisted of eight unique trials. The subjects were given at least two minutes between consecutive trials to avoid fatigue. The target traces were scaled to each individual subject's maximum torque. To prevent subjects from memorizing the amount of effort needed to generate a certain torque response, the trials were divided into steps which changed non-linearly (Table 2). Each subsequent trial and

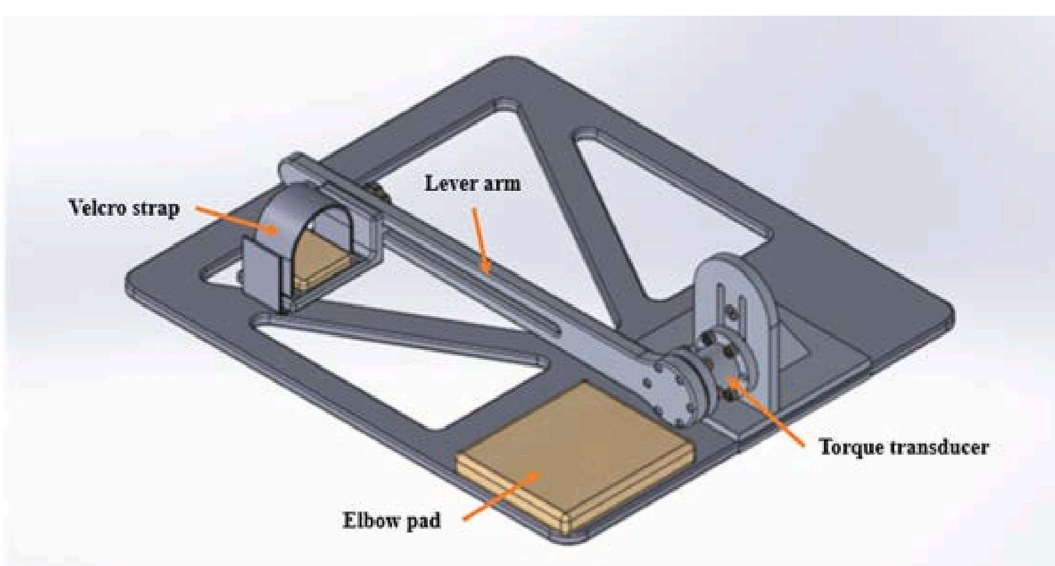

Fig. 1. CAD model of the test setup.

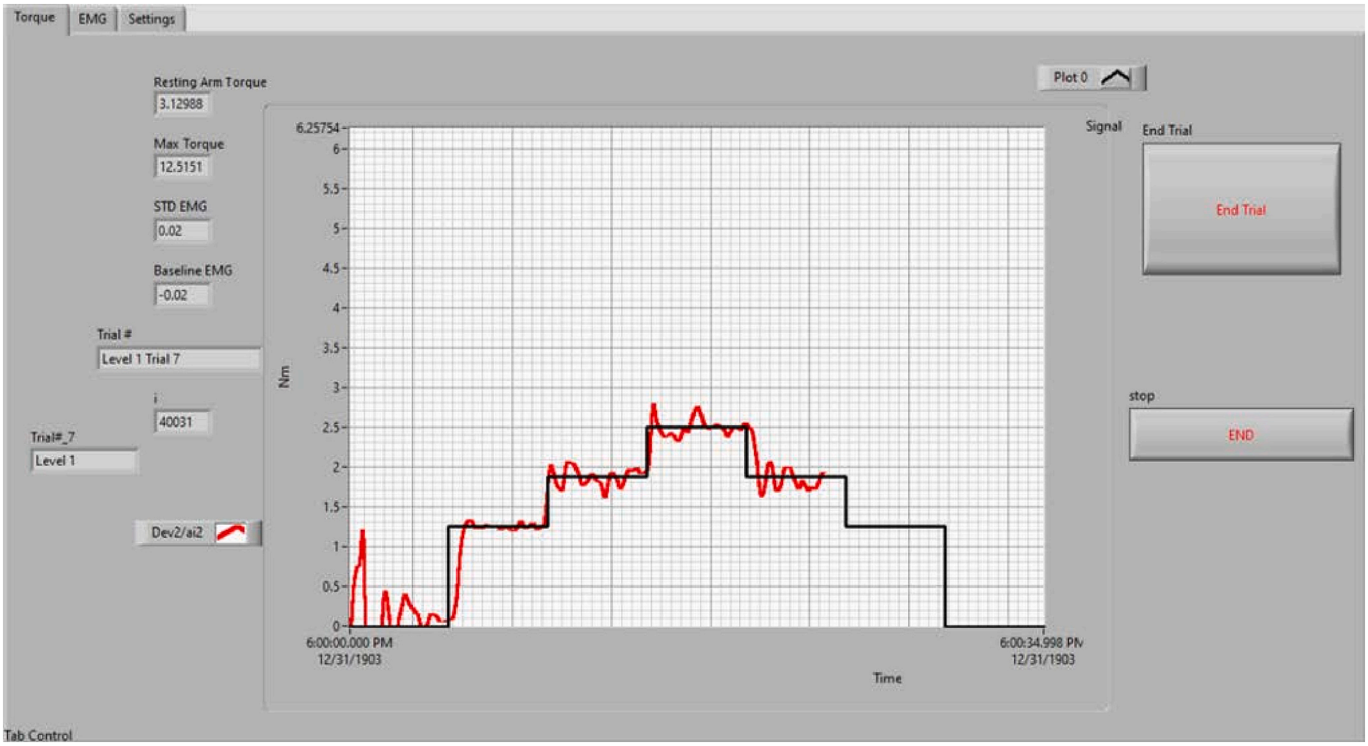

Fig. 2. LabVIEW display of torque output during trial 7. The red line represents the subject's torque output, cascading from left to right in real time. The black line represents the target trace to be followed by the subject. (Bhat et al., 2023). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Target Torque Values (as a percentage of Subject's Maximum Torque) (Bhat et al., 2023).

Trial	Step 1	Step 2	Step 3	Step 4	Step 5
1	10	15	20	15	10
2	15	20	25	20	15
3	10	20	30	20	10
4	20	25	30	25	20
5	15	25	35	25	15
6	25	30	35	30	25
7	20	30	40	30	20
8	30	35	40	35	30

step had a different target torque value and if the value was similar, the amount of elbow torque increase required to reach the target torque was different (e.g., step 2 for trials 2 and 3 demanded 20% of the maximum torque, while the subject had to increase their elbow torque by 5% in trial 2 and 10% in trial 3). The percentage value of each step was unknown to the subjects. Each step was maintained for a duration of 5 s, with the entire trial being 30 s long.

Two metrics, hold time and latency, were used to quantify voluntary torque control for each subject. Hold time was defined as the amount of time that the subject maintained their elbow torque output within ±5% of the target torque demand. The average hold time was computed at each of the target torque percentages for every subject. Hold time is indicative of the subject's ability to hold an object in the flexed elbow position for some time. Latency was defined as the time taken by the subject's elbow torque to reach the target torque. Due to the stair-step configuration used in the trials, the target torque increased and then decreased. The amount of elbow torque increase and decrease were ± 5% or ± 10%. The mean latencies (increasing and decreasing) were indicative of the subject's muscle force regulation capability and were calculated for each of the target torque percentages and the different amounts of elbow torque increase and decrease for every subject. The mean latency (increasing) was not calculated for step 1 of each trial, since the subjects were not asked to maintain an elbow flexion torque of 0 Nm (the initial target torque for each trial).

2.3. Statistical analysis

The data was checked for normality using the Shapiro-Wilk test. A two-way mixed ANOVA test was performed with the hold time as the dependent variable, and group and target torque as the independent variables. A three-way mixed ANOVA test was performed with the latencies (both increasing and decreasing) as the dependent variables, and groups, target torque, and the amount of increment/decrement in torque as the independent variables. Group was a between-subject factor, and target torque and the amount of increment/decrement in torque were within-subject factors. A pairwise *t*-test was used to assess the differences between individual pairs of target torque or increment in torque. Sture Holm's method (Holm, 1979) was used to adjust the *P*-values to avoid rejecting a true null hypothesis. All the analyses were performed in R using the "stats" and the "rstatix" package (Kassambara, 2020; R Core Team, 2021). A *P*-value <0.05 was defined as statistically significant.

3. Results

The control group's average hold times were 1.8 times higher than that of the BPI group ($P < 0.001$) (Fig. 3). The mean hold times were different between most of the torque levels in the Control group (Fig. 3 (b)), while the BPI group showed no such difference (Fig. 3 (a)). Overall, the Control group was better at controlling their elbow torque output and modulating it to meet the required torque level. The BPI group did not show any trend with respect to BMRC grades in hold time (Fig. 3 (c)).

The two groups had similar latency times when increasing their elbow torque output ($P > 0.05$). The latency times were 1.5 times higher

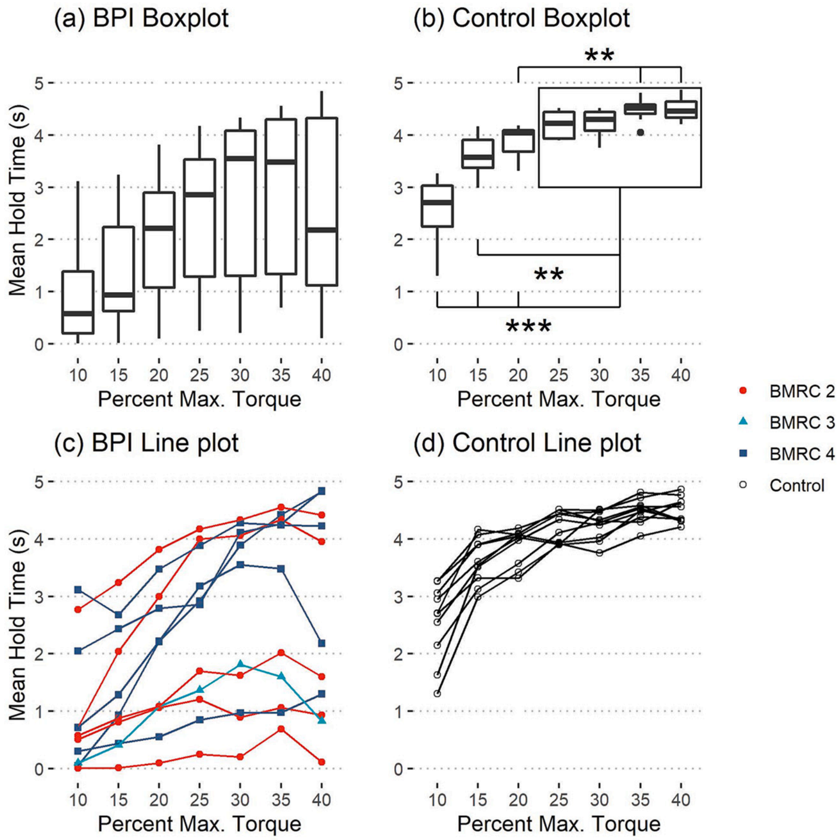

Fig. 3. Mean hold time for the (a) BPI and (b) Control group and line plot for individual subjects in the (c) BPI and (d) Control group. Both the groups were statistically different ($P < 0.001$). (**:$P < 0.01$; ***: $P < 0.001$).

for a 10% increment compared to 5% increment ($P = 0.024$). The BPI group's latency did not differ significantly with the different torque levels (Fig. 4 (a) and (c)). The Control group had different latencies between the lowest and highest torque levels (Fig. 4 (b) and (d)). Overall, the BPI group matched the Control group's ability to instantaneously increase their elbow torque but did not show a similar modulation of latency as the Control group.

The Control group's latency when responding to a decrease in elbow torque output was, on average, 3.5 times lower than the BPI group ($P = 0.023$) (Fig. 5). The torque levels were a significant factor ($P < 0.001$) with a significant interaction with the group factor ($P = 0.029$), but the amount of decrement of torque did not have any significant effect ($P > 0.05$). The Control and BPI groups had different latencies between the lower and higher torque conditions (Fig. 5 (a), (b), (c), and (d)), but the control group displayed better modulation of their elbow torque.

4. Discussion

This article describes a novel method for objectively characterizing functional outcome after nerve surgery to reconstruct elbow flexion following a BPI. The ability of the subject to maintain elbow torque at different levels, and the latency to achieve these levels was measured. The two metrics indicated that healthy individuals might have a better control on their elbow torque output than the subjects who underwent reconstructive surgery.

The reconstructed patients lacked the ability to relax their elbow flexor efficiently to reduce their elbow torque output. A similar observation was made for shoulder flexors by Fredin et al. when they tested patients with chronic symptoms after whiplash trauma of the neck (Fredin et al., 1997). They concluded that damage to the afferent nerve feedback loop in the ligaments might have resulted in the loss of muscle stiffness. Patients with BPI injuries have no afferent signals secondary to avulsion of the dorsal roots. This requires future evaluation.

This study focused on elbow torque control. Elbow flexor strength was not considered a functional outcome measure but was used to scale the target torque values. The mBMRC grade is used as a primary method to gauge patient strength recovery. It is a subjective metric where strength is often evaluated without regard to range of motion, or position of the arm. As discussed by MacAvoy and Green, a mBMRC grade of 4 is considered good, but is analogous to "at least 4% strength" (MacAvoy and Green, 2007). A study by Shahgholi et al. demonstrated the inaccuracy of seasoned BP surgeons in grading elbow flexion and extension using the BMRC compared to biomechanical testing of strength normalized to the normal side (Shahgholi et al., 2012). Augmenting the mBMRC scale with +,- signs has been a common practice (Kendall and McCreary, 1983). Hence, the mBMRC grade scale is not suitable to be used as a sole indicator of patient recovery, and the use of quantitative measures would be an improvement.

The limitations of the study are recognized. The current study's population size was limited. Many other studies on BPI have small sample sizes due to the rare nature of the injury (6 subjects (Brown et al., 2018); 9 per group (Tsai et al., 2015); 9 subjects (Estrella, 2011)). The control group is different than the BPI group in terms of age. The patients who underwent a FFMT procedure were excluded from the study since they represent a completely different method of elbow flexion reconstruction. Randomizing the order of target torque values displayed to the subjects, similar number of repetitions for all the target torque values, and a better visual feedback system (e.g., displaying only the current torque value and not the entire stair-step pattern) would lead to a more robust study design. The amount of increment in elbow torque was a significant factor, but the amount of decrement did not significantly affect the latency. Hence, it is recommended that more

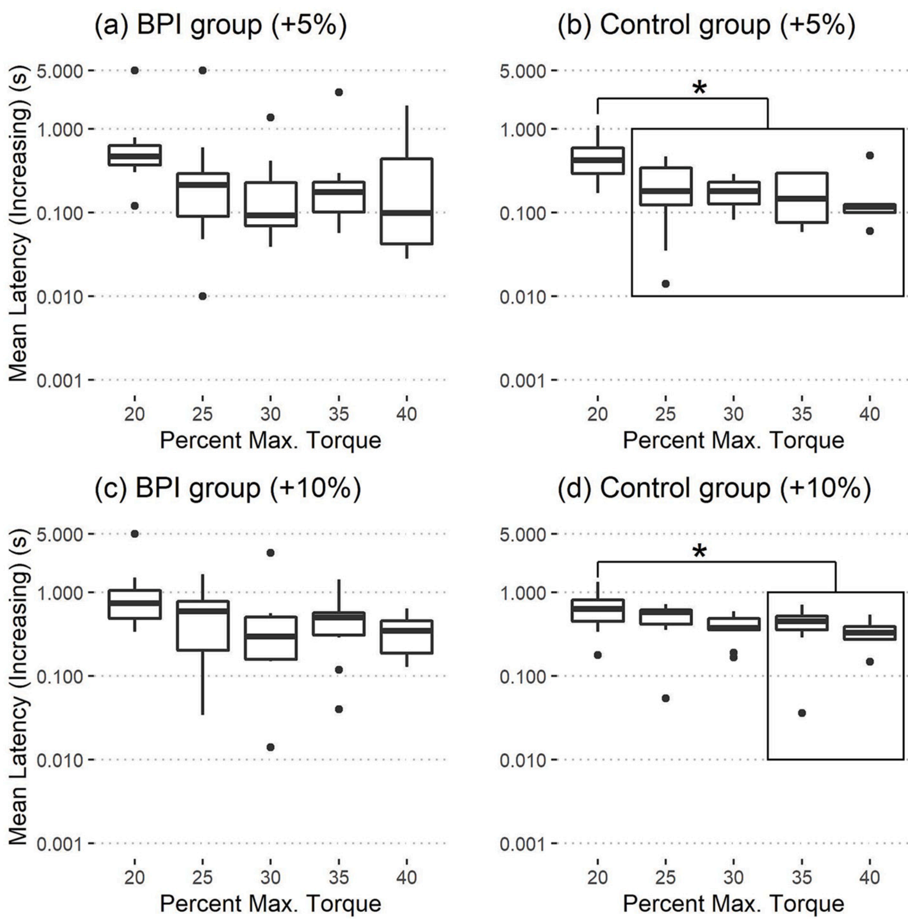

Fig. 4. Mean latency for increasing elbow torque output for the (a) BPI group at 5% increment, (b) Control group at 5% increment, (c) BPI group at 10% increment, and (d) Control group at 10% increment. Y axis is a logarithmic scale with base 10. Both the groups were statistically similar ($P > 0.05$), while amount of increment was a significant factor ($P = 0.024$). (*:$P < 0.05$).

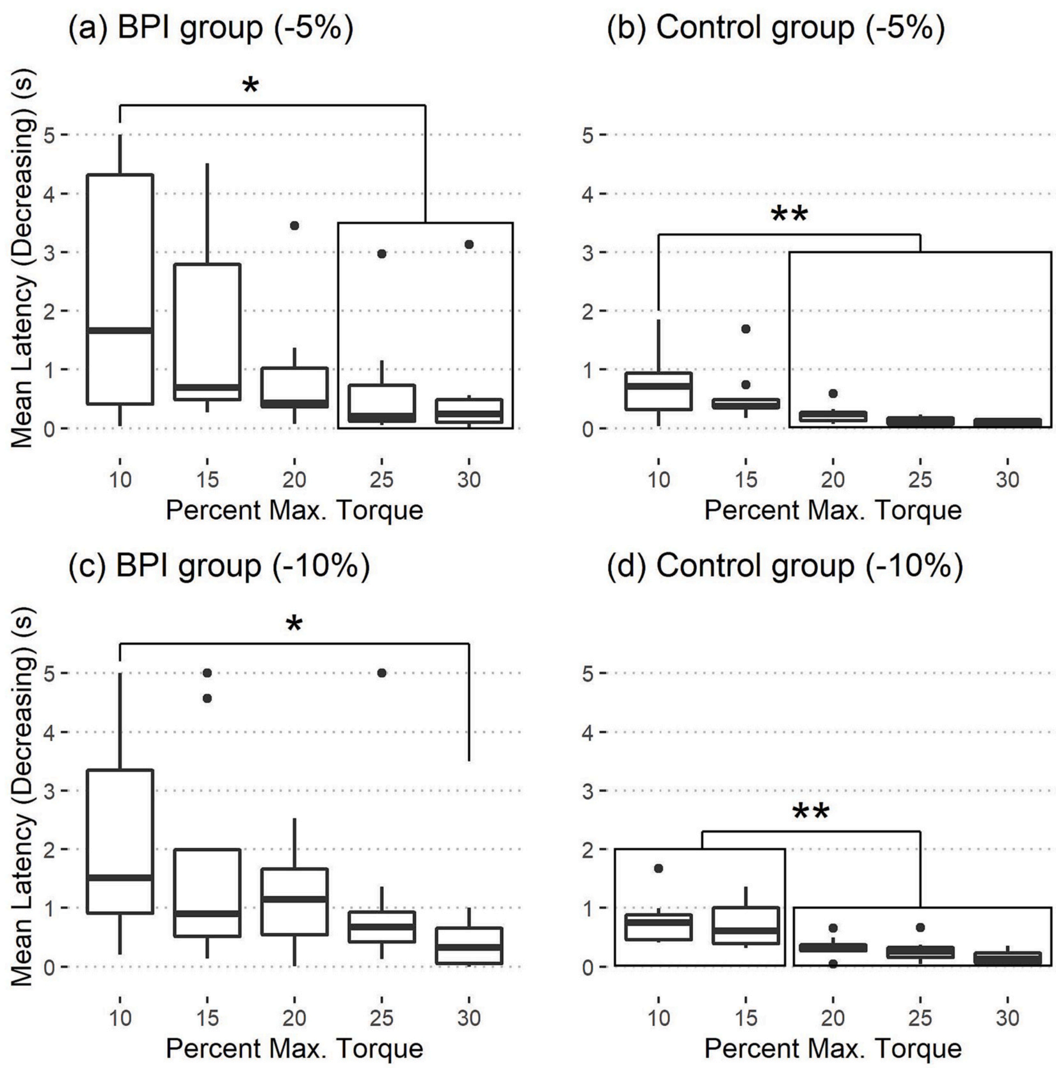

Fig. 5. Mean latency for decreasing elbow torque output for the (a) BPI group at 5% decrement, (b) Control group at 5% decrement, (c) BPI group at 10% decrement, and (d) Control group at 10% decrement. Both the groups were statistically different ($P = 0.023$) while the amount of decrement did not have a significant effect ($P > 0.05$). (*:$P < 0.05$; **: $P < 0.01$).

increment/decrement levels of elbow torque be incorporated in the study design to explore this relationship. Further data collection is recommended to identify a threshold for the proposed metrics that has clinical utility. Future studies are planned to evaluate how a transplanted muscle changes the elbow torque control.

5. Conclusion

This study reported a quantitative method to assess elbow torque control of BPI patients who underwent nerve reconstruction for elbow flexion. The measures were successful in objectively differentiating between healthy individuals and BPI patients. The method presented in the current study is a quantitative measure to accurately assess patient recovery.

Declaration of Competing Interest

The authors did not receive, directly or indirectly, any benefits from the topic of research in this article.

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