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Research paper

Challenges in evaluating forearm muscle activity based on the compound muscle action potential of the flexors of the whole forearm

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ABSTRACT

Objective: Muscle strength, which correlates with the compound muscle action potential (CMAP), can also be estimated by measuring the CMAP. Therefore, we evaluated the CMAP of the flexor muscles of the whole forearm to identify their muscle strength.

Methods: Fourteen healthy volunteers were enrolled. The elbow was determined to be the stimulation point, and the recording site for the flexor muscles of the whole forearm was set at approximately 8 cm distal to the elbow. We prospectively evaluated the baseline-to-peak amplitude of the CMAP of the whole forearm flexor muscles (WFFM), including that obtained from the median nerve stimulation (WFFMm), ulnar nerve stimulation (WFFMu), and their sum (WFFMsum). Additionally, we analyzed the relationships between WFFMm and WFFMu amplitudes with other quantitative parameters, including grip strength and routine CMAP amplitudes.

Results: The CMAP's test–retest analysis revealed high reliability. Grip power was significantly correlated with WFFMm and WFFMsum and mildly correlated with WFFMu. Tip-pinch strength with WFFMm and flexor pollicis longus (FPL) measurements correlated significantly. Lateral-pinch strength was significantly correlated with the first dorsal interosseous muscle (FDI) measurements but not with WFFM. The abductor digiti minimi (ADM) and abductor pollicis brevis (APB) were not correlated with grip power or pinch strength.

Conclusions: By electrophysiology examination, this study demonstrated that WFFMm is involved in grip power and other pinch strengths. This method may serve as a novel tool for measurement of distal muscle strengths.

Significance: This is the first study to attempt to evaluate the muscle strength of forearm flexor muscles by measuring the CMAP.

1. Introduction

The flexor muscles of the whole forearm work to control the various possible human hand and finger movements, such as grasping and manipulating objects, in coordination with the adjacent extrinsic and intrinsic hand muscles (Sinclair, 1972). Muscle strength evaluation of the upper arm is clinically important, including grip strength and pinch strength. Although surface electromyography has been used to measure forearm muscle activity (Buchanan et al., 1989), these data have not been useful for quantitative evaluation. A nerve conduction study (NCS) reported the correlation between muscle strength and the compound muscle action potential (CMAP) (Won et al., 2016). The flexor muscles of the arm are innervated by the median nerve, ulnar nerve or both, for example the anatomical variation in the FDP (Haugstvedt et al., 2001; Muscle et al., 1995). The median or ulnar nerve lesions in the elbow region cause variable weakness or paralysis of the finger's distal phalanx flexion (Spinner, 1978; Oh et al., 2009). Therefore, we hypothesized that CMAP of the whole forearm flexor muscles (WFFM) is associated with finger function. In the present study, we attempted to assess muscle strength in the upper arm using CMAP of WFFM and used the NCS technique to test whether

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anterior interosseous nerve (AIN), the ulnar nerve (UN), or both AIN and UN are related to grip strength or pinch strength.

2. Methods

2.1. Participants

We included Japanese volunteers (hospital staff) aged between 20 and 50 years that were capable of ambulatory hospital visits. Individuals with a history of cervical spondylosis, myelopathy, plexopathy, peripheral neuropathy, or diabetes mellitus were excluded. The NCSs and the muscle strengths, including grip and pinch strength, were examined three times each in all participants to maintain reproducibility. To ensure reproducibility, a different examiner performed another NCS, at a different time, with removal and reapplication of all stimulating/recording electrodes. All examiners moved the recording and stimulating electrodes around to ensure maximal amplitudes were obtained. All participants signed an informed consent form before evaluation. The Ethics Committee approved this study at Nara Medical School Hospital (2391).

2.2. The whole forearm flexor muscles' compound muscle action potential response recorded from the median and ulnar nerve stimulation

An electromyography machine performed all the NCSs (Nicolet Synergy EDX system, Natus, Middleton, WI, USA) with an eight-channel amplifier and disposable surface electrodes. The band-pass filter settings were 3 Hz and 10,000 Hz for the low and high frequencies, respectively. The notch filter was not used. The stimuli were rectangular electrical pulses with a duration of 0.2 ms. The participants lay in a supine position in a relaxed posture. The skin temperature at the shoulder surface was measured and maintained at ≥ 32 °C.

The electrophysiological evaluation measured the WFFM compound muscle action potential (CMAP) with a novel technique. The recording site was placed just lateral to the posterior margin of the ulna, approximately 8 cm from the elbow, and the reference electrode was placed distally (Felsenthal et al., 1986). The site with the highest amplitude in the surface electromyogram, when the fingers were flexed, was determined to be the whole forearm flexor and selected as the site just above the constructed whole forearm flexor muscles (Fig. 1). The standard technique involves studying motor conduction with stimulation proximal to in the antecubital fossa medial to the brachial artery at the elbow joint for the median nerve and 2–3 cm distal to the medial epicondyle near the ulnar notch for the ulnar nerve. We identified the point at which the flexor muscles of the whole forearm originated by locating the largest CMAP that appeared following stimulation of each nerve at intervals of approximately 5 mm. An appropriate stimulation point with the lowest threshold was determined before measurement. Supramaximal stimulation was assured by increasing the stimulus intensity by 30%–40% beyond the intensity at which a CMAP increased continuously up to the maximum. We prospectively used supramaximal intensity and evaluated the baseline-to-peak amplitude of the CMAP of the WFFM. Recordings were made of the WFFM CMAPs obtained by median nerve stimulation (WFFMm), ulnar nerve stimulation (WFFMu), and other routine CMAPs. Additionally, WFFMm and WFFMu were added to calculate the WFFMsum. Furthermore, we performed NCS for evaluating the first dorsal interosseous muscle (FDI) CMAP and abductor digiti minimi (ADM) CMAP using UN stimulation and for evaluating abductor pollicis brevis muscle (APB) CMAP and flexor pollicis longus muscle (FPL) CMAP using median nerve stimulation.

2.3. Strength evaluation

Grip strength and pinch strength were measured after a 10-minute rest. Grip strength, a measure of muscular strength or the maximum force the forearm muscles generate, can be used as a screening tool for measuring upper body and overall strength. Pinch strength reflects the ability to hold something between the thumb and index finger. The thumb applies an inward force, balanced by one or more fingers applying a force back toward the thumb. We measured two pinch strengths (tip and lateral pinch) three times at 1-minute intervals and recorded the maximum strength each time. The medical research council (MRC) measures limb strengths, an established multifactorial scoring system with a total score between 0 and 60. The MRC sum score evaluates global muscle strength, combining the scores of six muscles (shoulder abductors, elbow flexors, wrist extensors, hip flexors, knee extensors, and ankle dorsiflexors), bilaterally evaluated.

2.4. Statistical analyses

Differences in categorical variables were assessed using the χ^2 test. Intraclass coefficients were calculated to determine the test–retest reliability of WFFM CMAP; the same examiner performed both "test" and "retest" assessments. The Shapiro–Wilk test was used to assess the distribution of the data, and Pearson's correlation coefficients (r) were calculated to evaluate the association between muscle CMAP and muscle strength. Based on the r values, the correlation was categorized as mild ($r = 0.30–0.39$) or significant ($r = 0.40–1.00$). We used the *t*-test to compare the WFFMm and WFFMu, and the Tukey–Kramer post hoc test was used for multiple comparisons. Statistical significance was set at $P < 0.05$. Statistical analyses were performed using SPSS version 22.0 (SPSS Japan, Tokyo, Japan).

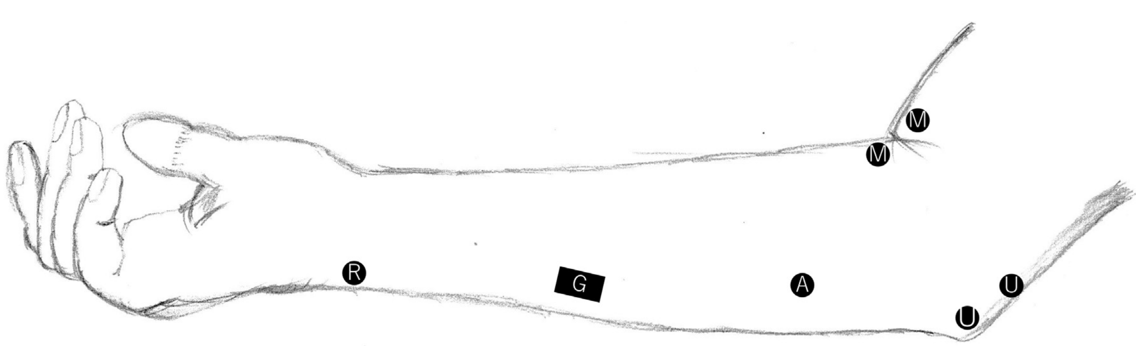

Fig. 1. The whole forearm flexor muscle stimulation technique. A: active recording electrode, R: reference electrode, G: ground electrode. M: The median nerve stimulation sites and electrode. U: The ulnar nerve stimulation sites and electrode.

Table 1
Demographic characteristics of the participants.

Clinical features	Participants (n = 14)
Sex (female)	3 (21.4%)
Age at examination (years)	30.1 ± 4.9 (25–43)
MRC sum score	60.0 ± 0.0 (60.0–60.0)
Grip strength	32.8 ± 7.6 (22.0–51.0)
Tip-pinch strength	3.2 ± 0.66 (2.2–4.5)
Lateral-pinch strength	7.0 ± 1.2 (5.5–10.3)
WFFMsum CMAP amplitude (mV)	12.9 ± 2.7 (7.9–19.0)
WFFMm CMAP amplitude (mV)	9.0 ± 1.9 (5.6–13.1)
WFFMu CMAP amplitude (mV)	3.8 ± 1.4 (2.3–7.8)
APB CMAP amplitude (mV)	12.3 ± 2.8 (5.4–16.9)
ADM CMAP amplitude (mV)	11.7 ± 1.6 (8.7–17.8)
FPL CMAP amplitude (mV)	6.6 ± 1.6 (3.7–10.3)
FDI CMAP amplitude (mV)	16.8 ± 2.3 (12.6–20.7)

Data are shown as mean ± standard deviation (range) and number (percentage). MRC; medical research council, WFFM; whole forearm flexor muscles, CMAP; compound muscle action potential, APB; abductor pollicis brevis muscle, ADM; abductor digiti minimi muscle, FPL; flexor pollicis longus muscle, FDI; the first dorsal interosseous muscle.

3. Results

3.1. Clinical characteristics and WFFM CMAP

We enrolled 14 healthy volunteers (3 women and 11 men; mean age, 30.1 years), and in 28 arms of 14 healthy individuals, WFFM CMAP was recorded, and all the volunteers completed the examinations. The clinical characteristics of the participants are summarized in Table 1. Additionally, a comparison of the WFFM CMAP between median and ulnar stimulation is presented in Fig. 2A.

3.2. Test-retest reliability of the measurement of WFFM CMAP

The WFFM CMAP's intraclass coefficient, indicating excellent test–retest reliability, was 0.974 (Fig. 2B-D).

3.3. Relationship between CMAP values and muscle strength measurements

3.3.1. Grip strength

Grip power was significantly correlated with WFFMm, WFFMsum, and FDI and mildly correlated with WFFMu and FPL. However, the CMAP of ADM and APB was not correlated with grip power (Table 2).

3.3.2. Tip-pinch strength

The tip-pinch strength was significantly correlated with WFFMm and FPL measurements. However, the CMAP of WFFMu was not correlated with tip-pinch strength.

3.3.3. Lateral-pinch strength

The correlation between lateral-pinch strength and FDI was significant, and no correlation was found between lateral-pinch strength and WFFM measurements.

4. Discussion

This study is the first to use NCS to evaluate the strength of the flexors of the whole forearm. Although evaluating the muscle strength of the flexors of the whole forearm is complicated, their electrophysiological evaluation can serve as a good indicator of distal muscle strength. Additionally, we found a correlation between WFFM CMAPs and grip power.

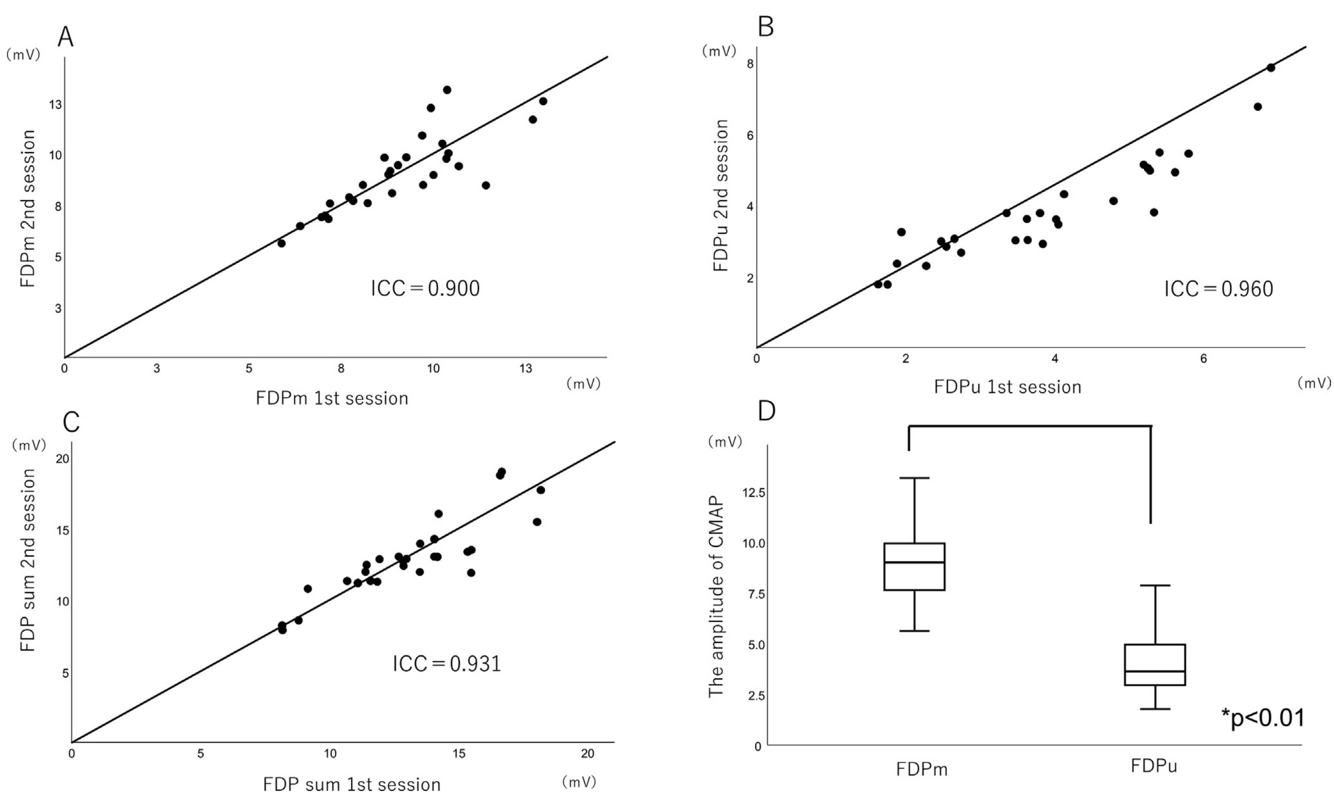

Fig. 2. Analysis of WFFM CMAP. A: The comparison of the WFFM CMAP between median and ulnar stimulation. B-D: Test-retest reliability of the measurement of WFFM CMAP. WFFM: whole forearm flexor muscles, CMAP: compound muscle action potential.

Table 2
Correlation between strength and muscle compound muscle action potential.

		Median Nerve stimulation			Ulnar Nerve stimulation		
	WFFM sum	WFFMm	FPL	APB	WFFMu	FDI	ADM
Grip strength	$r = 0.518$ $p < 0.01$	$r = 0.448$ $p < 0.05$	$r = 0.431$ $p < 0.05$	$r = 0.015$ $p = 0.938$	$r = 0.386$ $p < 0.05$	$r = 0.541$ $p < 0.01$	$r = 0.038$ $p = 0.848$
Tip strength	$r = 0.356$ $p = 0.063$	$r = 0.388$ $p < 0.05$	$r = 0.436$ $p < 0.05$	$r = 0.262$ $p = 0.178$	$r = 0.160$ $p = 0.417$	$r = 0.300$ $p = 0.121$	$r = 0.097$ $p = 0.625$
Lateral Strength	$r = 0.151$ $p = 0.442$	$r = 0.129$ $p = 0.513$	$r = 0.331$ $p = 0.085$	$r = 0.275$ $p = 0.156$	$r = 0.116$ $p = 0.558$	$r = 0.454$ $p < 0.05$	$r = -0.058$ $p = 0.768$

WFFM; whole forearm flexor muscles, APB; abductor pollicis brevis muscle, ADM; abductor digiti minimi muscle, FPL; flexor pollicis longus muscle, FDI; the first dorsal interosseous muscle.

Although we observed poor separation from other forearm flexors, the WFFMm CMAP had a larger amplitude than the WFFMu CMAP and had a more significant effect on grip strength.

The median nerve response was far larger than the ulnar nerve response, even in the ulnar nerve-innervated ulnar FDP and flexor carpi ulnaris (FCU), indicating that deeply situated median nerve-innervated muscles considerably contributed to these responses. Additionally, this phenomenon suggests that our recording site was more anterior than that of the FCU. When the median nerve is stimulated, all the median nerve-innervated muscles are activated. The contribution of the FDS is the largest among all the stimulated muscles, as it is closest to the active electrode, followed by the FDP and flexor carpi radialis (FCR). In our study, WFFMm correlated with grip strength, confirming that grip strength involves not only the FDP but also the FDS, which is innervated by the median nerve. This suggests that the median nerve-innervated muscles of the forearm are more involved in grip strength than the ulnar nerve-innervated muscles.

Our results suggested that the tip-pinch strengths were more strongly related to WFFMm than to WFFMu. Among pinch forces, tip muscle strength was weakly associated with median nerve-innervated muscles. This is thought to be due to the effect of the thenar muscle and the flexor pollicis longus innervated by the anterior interosseous nerve (AIN). As the measurement method for the tip pinch used the thumb and index fingers, our results suggested that the median nerve innervated the distal interphalangeal (DIP) joint of the index finger. Previous anatomical studies have shown that FDP innervation varies between individuals. However, most anatomy textbooks state that the AIN originates from the median nerve and innervates the lateral part of the FDP (Muscle, 1995; Bhadra et al., 1999; Segal et al., 2002). The results of this study confirmed that the AIN innervates the FDP of the index finger. Thumb function affects tip pinch; however, we observed an association with the FPL CMAP but not with the APB. The APB is mainly involved in abducting the thumb and is not involved in movements involving thumb opposition, such as pinching the fingertips. When measuring pinch strength, the muscles used differed depending on the angle made by the fingers; therefore, during muscle strength measurements, the position of the fingers should also be measured and considered (Ingram et al., 2008).

Consideration should also be given to neural interactions due to innervation. The neural interactions, such as mechanical connections and interactions between compartments, influence individual finger movements. For example, the compartment up to the middle finger cannot torque around the DIP joint when the PIP joint is flexed and the adjacent fingers (index and ring) are fully extended (Garland and Miles, 1997).

Myopathy, peripheral neuropathies such as neuromuscular atrophy, and lower cervical radiculopathy should be differentiated when examining forearm muscle dysfunction. Our method may be useful for identifying lesion sites. Furthermore, we sought to address important challenges related to the identification of surrogate biomarkers for evaluating finger function.

Human movement involves a wide range of combinations between peripheral nerves and muscles, and we evaluated the CMAPs for only a few of them. As deep muscles cannot be evaluated using superficial electrodes, multiple nerves and muscles are studied in combination to evaluate deep muscles, as in this study. To the best of our knowledge, this is the first study to evaluate the flexors of the whole forearm using CMAP of both median nerve stimulation and ulnar nerve, and our results may widen the applicability of neuroelectrophysiological examinations in the future. The limitations of this study include the small sample size, which reduced the generalizability of our findings, and predominantly male participants, indicating a skewed sex ratio. Additionally the study population was young and relatively uniform muscle force distribution, and the CMAP amplitudes and strength variations obtained were less than desired, as seen from the small standard deviation values. A larger sample size of healthy controls and a more diverse population with various strengths is therefore needed. Furthermore, several other factors, such as muscle mass, tissue fat, other forearm flexors such as the FDS and FCR, and the exact position of the limb at the time of obtaining the CMAP or measuring the strength, could have influenced the results. Additionally, the spread of stimulating currents to adjacent nerves and unwanted volume conduction recordings from adjacent muscles could also influence the size of the CMAP; however, this is not exclusive to this study. The WFFM CMAP measurements are expected to have many clinical applications, such as preoperative evaluation and prognosis prediction of hand surgery or pathophysiological evaluation of diseases that selectively impair the WFFMs. Because the ulnar nerve-innervated muscles are in the deep layer compared to the median nerve-innervated muscles, it is possible that the CMAP of the ulnar nerve-innervated muscles was low on surface electromyography.

We believe that using WFFM CMAP in combination with other anatomical factors such as muscle moment arms and physiological cross-sections can improve the understanding of forearm function. This information may be useful for decision-making regarding rehabilitation therapy and surgery and for upper extremity modeling. This study was a pilot study, and this method should be further validated the accuracy and verified by other EMG labs. The validation studies should include patients with anterior interosseous and ulnar neuropathy.

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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Declaration of Generative AI and AI-assisted technologies in the writing process

None.

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