Cooperative activities of forearm muscles under loading applied to thumb or each finger

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Abstract

Human thumb and fingers are usually subjected to an external loading during daily activity. The information of how muscles in the forearm cooperate with each other in order to response to the external loading is still unknown. Such information may be helpful in understanding muscle function pathology and motor disorder. A novel method called electromyography computed tomography (EMG-CT) was developed to visualize muscle activity within a whole cross-section of the forearm by measuring surface EMG signals around the forearm. The current study aimed to extend the previous work by using the EMG-CT to investigate muscle cooperative activity under loading application to thumb or each finger. Loads of 0.98-9.8 N were applied to the thumb or each finger of four subjects in eight loading directions. The loading directions on thumb and index, middle, and little fingers were inner, outer, and upper directions. EMG signals around the subject’s forearm were recorded during the loading by using EMG band consisting of 40 pairs of bipolar electrodes. The results show different muscle cooperative activity pattern between loading conditions. During load was applied to thumb, muscle in lower region in pronation cross-section were highly active. When load was applied to a finger, muscles in lateral-lower region were highly active. In all subjects, total muscle activity in the whole cross-section and the maximum value of muscle activity increased in proportion to loading. This study demonstrates effectiveness of EMG-CT method by showing that the muscle cooperative activity of an individual is specific to force application conditions.

Keywords: Electromyography, Tomography, Muscle activity, Muscle cooperation, Forearm, Fingers, Thumb

1. Introduction

Human fingers can move either independently or in synchrony with each other to achieve daily tasks such as grasping, gripping, and pinching. Loss of finger and hand function may be caused by neuromuscular diseases, such as Parkinson’s and muscular dystrophy. An observation of muscle cooperative activities is important for developing rehabilitation processes or treatments for neuromuscular disorders. Researches attempted to understand muscle cooperative activities using cadaveric models (Garcia-Elias et al., 1991; Haugstvedt et al., 2001) and implanted force transducers in vivo (Schuind et al., 1992; Dennerlein, 2005). Garcia-Elias et al. (1991) used a stereophotogrammetric measurement system to study extensor mechanism of the fingers in human forearm specimens. Changes in length and orientation of different zones of the extensor mechanism at different finger configurations were reported. Haugstvedt et al. (2001) used human
cadaveric upper extremity specimens to determine torque generated by the muscles rotating the forearm at various pronation/supination. The relationships between moment arm and angle of the flexor carpi ulnaris, extensor carpi ulnaris, supinator, biceps, pronator teres, and the pronator quadrates were reported. Studying from cadaveric model gains us insights of anatomical aspect of muscles, but the effects of physiological forces such as muscle contraction cannot be considered by this approach. Furthermore, Schuind et al. (1992) applied force transducers to the flexor pollicis longus and flexor digitorum superficialis, and profundus tendons of the index finger of patients. The tendon forces generated during passive and active motion of the wrist and fingers were recorded and reported. Dennerlein (2005) measured the in vivo tendon force of the flexor digitorum superficialis of the long finger during open carpal tunnel release surgery using force transducer. Forces were measured during isometric pinch and dynamic tapping of the finger. The results showed that tendon forces were a complicated function of fingertip force and motion. These studies provide insights of how forearm muscles generate forces during contraction. However, the measurements using force transducers were invasive and cannot provide the distribution of muscle activity within the whole cross-section in detail.

The authors have proposed an electromyography computed tomography (EMG-CT) method that provides a visual image of muscle activity within a whole cross-section of the forearm by measuring surface EMG signals using an EMG band comprising 40 pairs of bipolar surface electrodes (Nakajima et al., 2014). An EMG conduction model was formulated for reverse-estimation of muscle activities from measured EMG signals. By minimizing the difference between the estimated EMG values from the conduction model and the measured values, the muscle activities were estimated. The EMG-CT method provides a muscle activity distribution in the forearm in a noninvasive manner and will provide new information regarding the muscle cooperative activity within the forearm cross-sectional area.

In previous study, a visual image of muscle activity within the forearm during loading applied to the proximal interphalangeal joint of the middle finger in the inner direction was obtained using EMG-CT method as the first trial (Nakajima et al., 2014). The method is expected to contribute to investigate the relationship between muscle cooperative activity pattern and the external loading response of human thumb and finger by visualizing a complex muscle activity within the forearm. This study aimed to investigate muscle activity patterns within a whole cross section of the forearm by EMG-CT under simple loadings in the inner, outer, and upper directions applied to the thumb and index, middle, and little fingers, in which the muscles in the forearm may work together in a complex manner. The EMG tomographic images reveal muscles cooperative activity within the forearm when different load conditions are applied to fingers.

2. Method
2.1 Subjects

Four healthy right-hander male subjects participated in the experiment and right forearm was examined. The subjects had no history of neuromuscular disorders of the forearm. Forearm length, circumference, and fat thickness for each subject were measured. Forearm length was defined as the length between the lateral epicondyle of the humerus and the styloid prominence. Circumferential length was measured at the midpoint of the forearm length. Fat and skin thickness were recorded as average values from the medial, lateral, anterior, and posterior midpoint of the forearm measured with a skinfold caliper. Table 1 shows age, height, weight, forearm length, circumferential length, and average fat and skin thickness of the subjects.

| Subject | Age (year) | Height (cm) | Weight (kg) | Forearm length (mm) | Circumferential length (mm) | Average fat and skin thickness (mm) | The number of elements in model |
|---------|------------|-------------|-------------|---------------------|-----------------------------|------------------------------------|--------------------------------|
| A       | 21         | 165         | 56          | 243                 | 214                         | 1.3                                | 882                            |
| B       | 21         | 170         | 62          | 233                 | 239                         | 1.7                                | 978                            |
| C       | 22         | 167         | 57          | 251                 | 215                         | 1.9                                | 920                            |
| D       | 23         | 178         | 62          | 299                 | 218                         | 1.8                                | 884                            |
| Mean ± SD | 21.8 ± 1.0 | 170 ± 5.0  | 59.3 ± 3.0  | 257 ± 25            | 222 ± 10                    | 1.7 ± 0.2                          | 916 ± 45                       |
2.2 Experimental procedure

Each subject sat comfortably on a chair with his forearm placed on an adjustable stand, shoulder abducted and flexed at approximately 45°, elbow joint flexed at approximately 45°. Forearm and wrist held in pronation on the table, palm held with bars (Fig. 1). The subject was requested to relax his fingers and maintain this position. Load was applied to the subject’s finger with a weight-and-pulley system. Eight loading types were examined in the study as shown in Table 2. Inner, outer, and upper loadings were applied to the thumb at the distal phalanx (Fig. 2A). The muscle activities to resist applied inner, outer, and upper loadings correspond to thumb extension, flexion, and abduction, respectively. Inner loadings were applied to the index, middle and little fingers at the proximal phalanx (Fig. 2B), corresponding to the muscle activities of finger extension. Outer loadings were applied to the middle finger at the distal and middle phalanges (Fig. 2B), corresponding to the muscle activities of finger flexion. The weights of these loadings were 0.1, 0.3, 0.5, and 1.0 kg. A loading was applied approximately 5 s three times with 5 s rest intervals. The subjects were instructed to maintain the posture during load applied. The procedures were approved by the Ethical Review Board for the Protection of Persons in Biomedical Research, Graduate School of Engineering, Hokkaido University, and all subjects signed an informed consent agreement.

Figure 1  Experimental setup. The subject’s arm was strapped to the stand and the hand was held with bars. A multi surface electrode band was bound around the forearm to detect EMG signals.

Figure 2  (A) Directions of the loading applied to thumb. (B) Directions of the loading applied to index, middle, and little fingers.
2.3 EMG setup and data acquisition

EMG signals from the forearm were recorded with an EMG band, consisting of 40 pairs of bipolar surface electrodes (3-mm diameter disciform brass electrodes). Each four electrodes were placed on a custom-built electrode plate (Fig. 3). The inter-electrode distances of the bipolar electrodes were 15 and 45 mm. The middle point of the EMG band was positioned at the midpoint of the forearm length. The circumferential position of ulna was find by hand and a specific electrode plate was placed on the skin surface above ulna. The ground electrode was placed at lateral epicondyle. Before attachment of the electrode band, the subject’s forearm skin was shaved with a razor and cleaned with an alcohol swab. To keep constant contact pressure of the electrodes to the skin surface in the measurements, a fabric elastic band was wrapped around the electrode band. All EMG signals were amplified by a factor of 367, sampled at 1000 Hz and filtered with a third-order 9-Hz Butterworth high-pass filter followed by a second-order 570-Hz Butterworth low-pass filter. The EMG signals were collected for 30 s per trial using a custom program (LabVIEW 8.5, National Instruments, TX, USA). The signals were filtered using a second-order 10-Hz Butterworth high-pass filter, a second-order 100-Hz Butterworth low-pass filter, and band-stop filters using a custom program (MATLAB, MathWorks, USA). The root mean square (RMS) value and mean power of each channel were calculated from the recorded signals in 500-ms windows. The average data were calculated from three trials for each loading condition.

Table 2  Eight loading types examined in the study. Muscle activity column indicates the thumb and each finger motion that corresponds to the muscle activity pattern required to resist each external loading.

| Experiment No. | Loading direction             | Muscle activity |
|----------------|-------------------------------|-----------------|
| (A) T-ED       | Inner at distal phalanx       | Extension       |
| (B) T-FD       | Outer at distal phalanx       | Flexion         |
| (C) T-AD       | Upper at distal phalanx       | Abduction       |
| (D) I-EP       | Inner at proximal phalanx     | Extension       |
| (E) M-EP       | Inner at proximal phalanx     | Extension       |
| (F) M-FD       | Outer at distal phalanx       | Flexion         |
| (G) M-FM       | Outer at middle phalanx       | Flexion         |
| (H) L-EP       | Inner at proximal phalanx     | Extension       |

Figure 3  An image of the EMG band. The band consists of 20 electrode plates in which two bipolar electrode pairs were constructed. The inter-electrode distances in the differential bipolar electrode were 15 and 45 mm.
### 2.4 Reverse calculation of muscle activation

An EMG conduction model for the reverse calculation of muscle activation was developed (Nakajima et al., 2014). The cross-sectional area of the subject’s forearm was modeled as a circular region. The circumferential length of the circular region was set to the measured circumferential length. The muscle region was divided into elements for calculation (Fig. 4). The set of element nodes was distributed across the circular region with an element size of 1 mm for the surface region and 5 mm for the inside region. The number of elements in the model was 916 ± 45 (Table 1).

During contraction, a muscle fiber depolarizes and generates current. Muscle action current was used to quantify levels of muscle activity. The strength of the muscle activity of activated virtual fiber \( k \) in element \( j \) (\( m_k \)) (mA) was defined as in Eq. (1)

\[
\bar{V}_{ik}^2 = V_0(d_i)^2 m_k^2 \left( \frac{l_{ik}}{l_0} \right)^{2b(d_i)}
\]  

(1)

where \( \bar{V}_{ik} \) (mV) is the mean square value of muscle action potential from muscle fiber \( k \) recorded by bipolar electrode \( i \), \( d_i \) is the distance between the pair of bipolar electrodes \( i \), \( V_0(d_i) \) (mV/mA) is a transformation coefficient depending on \( d_i \), \( l_{ik} \) (mm) is the distance between muscle fiber \( k \) and bipolar electrode \( i \), \( l_0 \) is the unit length (1 mm), and \( b(d_i) \) is the power exponent of the attenuation as a function of \( d_i \) (Nakajima et al., 2014). In the study, \( d_i \) was 15 and 45 mm. \( V_0 \) and \( b \) were 162 mV/mA and -2.12 at 15 mm and 115 mV/mA and -1.74 at 45 mm, respectively (Nakajima et al., 2009, 2014).

The mean square value of muscle action potential from all muscle fiber \( k \) detected by bipolar electrode \( i \), \( \bar{V}_i \) was described as

\[
\bar{V}_i^2 = \sum_k \bar{V}_{ik}^2 = V_0(d_i)^2 \sum_k \left\{ m_k^2 \left( \frac{l_{ik}}{l_0} \right)^{2b(d_i)} \right\}
\]  

(2)

The muscle action potential from an element \( j \) is a superposition of the contributing action potentials from all the fibers within the element. When \( m_j \) within the element \( j \) is assumed as a constant value of \( m_j \), \( \bar{V}_i \) can then be rewritten as

\[
\bar{V}_i^2 = V_0(d_i)^2 \sum_j \left\{ m_j^2 \sum_{k \in j} \left( \frac{l_{ik}}{l_0} \right)^{2b(d_i)} \right\}
\]

(3)

![Figure 4](image.png)  

Figure 4  Representation of an electromyography conduction model used for calculations.
To estimate \( m_j \), an objective function described as Eq. (4) was minimized, where \( \tilde{V}_{MI} \) was measured and \( \tilde{V}_i \) was calculated from the EMG conduction model as in Eq. (3) at bipolar electrode \( i \).

\[
    f = \sum_i (\tilde{V}_i - \tilde{V}_{MI})^2
\]

(4)

The total muscle activity \( S \) was defined as the summation of muscle activity \( m_j \) weighted by the area of element \( a_j \) within the forearm as in Eq. (5).

\[
    S = \sum_j a_j m_j
\]

(5)

3. Results

The muscle activity in the forearm of subject A is presented in a tomographic image as a typical example. Figure 5 shows the strength of the muscle activation weighted by the area of each element within the cross-section under each loading. Figure 6 shows a typical pattern of muscle alignment in the middle part of the forearm obtained from a MR image. The tomographic images were shown in the pronation posture as in Fig. 6, by circumferentially arranging the surface EMG signals within the conduction model with reference to the position of the ulna in the calculations. In the study, thirteen muscles that were observed in the cross section were focused on: the extensor carpi ulnaris (ECU), extensor digiti minimi (EDM), extensor digitorum communis (EDC), extensor pollicis longus (EPL), abductor pollicis longus (APL), extensor carpi radialis longus (ECRL), extensor carpi radialis brevis (ECRB), flexor digitorum profundus (FDP), flexor pollicis longus (FPL), brachioradialis (BR), flexor carpi ulnaris (FCU), flexor digitorum superficialis (FDS), and palmaris longus (PL). Patterns of muscle cooperative activity could be observed under all investigated loadings. Differences of patterns with the loadings in an individual were clearly observed. The activated area and the maximum value of muscle activity increased with loads in all subjects. Examples of the muscle activity pattern of all subjects during 4.9 N loading are presented in Fig. 7.

The relationships between external loading and total muscle activity in all subjects are presented in Fig. 8. The slopes varied with different subjects and applied loadings. In contrast, the coefficients of determination (\( R^2 \)) was high for all subjects and loadings (\( R^2 = 0.93 \pm 0.10 \)), indicating a strong linear relationship between load application and muscle activation.

4. Discussion

In this study, EMG-CT was used to observe muscle cooperative activities in the forearm during loadings applied to thumb and each finger. The intensity level of each element was calculated from the detected EMG signals. EMG-CT method provided a visual image of muscle activity in the whole cross section of the forearm.

When loadings were applied to the thumb in different directions, differences of patterns in an individual were clearly observed. For example, during inner loadings in subject A (Fig. 5A), the lateral–lower region was activated. When the load was increased, it could be observed that more muscle elements in the inner upper and medial regions were also activated as synergistic muscles to stabilize the joint. During outer loadings (Fig. 5B), the active regions were the medial and lower regions. More muscle elements in medial region were activated when the loading increased, although the activated area was smaller than that during inner loadings. During upper loadings (Fig 5C), the medial and lateral–lower regions were activated. When the loading increased, muscle elements in the lateral–lower region were more highly activated. Kaufman et al. (1999) measured EMG signals of FPL, EPL, and APL with needle electrodes during thumb extension/flexion and adduction/abduction, and reported that these muscles were activated during the motions. The activities of APL and EPL were large during thumb extension, whereas those of FPL were large during thumb flexion. In general, EPL and APL lie in the inner lateral-lower part and FPL in the central part of the measured cross section. The present results as shown in Figs. 5 and 6 agree with this trend, although it is difficult to recognize exactly the activities of specific muscles in our imaging.

When an outer loading was applied to the distal phalanges of the thumb and middle finger, differences in patterns were also clearly observed, as shown in Figs 5B and 5F. In contrast, when an inner loading was applied to the proximal
phalanx of the index (Fig. 5D), middle (Fig. 5E), and little (Fig. 5H) fingers, the patterns of muscle activity distribution appeared similar. Using needle electrodes, Darling et al. (1994), Maier and Hepp-Reymond (1995), and Valero-Cuevas et al. (1998) found that FDP, FDS, and EDC were activated during finger motions. FDP and FDS lie in the medial part and EDC on the surface of the lateral–lower part. The present results agree with the previously reported trend. In addition, when the point of force acts on the middle phalanx (Fig. 5G), the moment arm of the loading decreases compared with the case when the force is on the distal phalanx. This decrease was evident in the different total muscle activity, although the same muscle activation patterns were observed.

Figure 5  Electromyography computed tomography of subject A when a load (1, 2.9, 4.9, or 9.8 N) was applied to thumb and each finger: (A) inner loading to distal phalanx of thumb (T-ED), (B) outer loading to distal phalanx of thumb (T-FD), (C) upper loading to distal phalanx of thumb (T-AD), (D) inner loading to proximal phalanx of index finger (I-EP), (E) inner loading to proximal phalanx of middle finger (M-EP), (F) outer loading to distal phalanx of middle finger (M-FD), (G) outer loading to middle phalanx of middle finger (M-FM), and (H) inner loading to proximal phalanx of little finger (L-EP). The images are viewed from proximal to distal under the pronation posture of the forearm.
Figure 5  Electromyography computed tomography of subject A when a load (1, 2.9, 4.9, or 9.8 N) was applied to thumb and each finger: (A) inner loading to distal phalanx of thumb (T-ED), (B) outer loading to distal phalanx of thumb (T-FD), (C) upper loading to distal phalanx of thumb (T-AD), (D) inner loading to proximal phalanx of index finger (I-EP), (E) inner loading to proximal phalanx of middle finger (M-EP), (F) outer loading to distal phalanx of middle finger (M-FD), (G) outer loading to middle phalanx of middle finger (M-FM), and (H) inner loading to proximal phalanx of little finger (L-EP). The images are viewed from proximal to distal under the pronation posture of the forearm. (Continued)
Figure 6  Typical alignment of muscles in the middle part of forearm under the pronation based on a MR image.

Figure 7  Representative of electromyography computed tomography of all subjects when 4.9 N load was applied to thumb and fingers: (A) inner loading to distal phalanx of thumb (T-ED), (B) outer loading to distal phalanx of middle finger (M-FD), and (C) inner loading to proximal phalanx of little finger (L-EP). The maximum of color scale of each figure corresponds to the maximum value of each experiment. The images are viewed from proximal to distal under the pronation posture of the forearm.
Figure 8  The total muscle activity of all subjects under each loading type according to Table 2 (with slope mean ± SD [mA/N]) for (A) T-ED (171.7 ± 51.8), (B) T-FD (34.9 ± 19.7), (C) T-AD (122.2 ± 51.0), (D) I-EP (86.7 ± 39.7), (E) M-EP (107.5 ± 68.5), (F) M-FD (60.6 ± 30.8), (G) M-FM (33.4 ± 15.9), and (H) L-EP (194.5 ± 57.4). The error bars indicate the standard deviation of three trials in each loading.
During inner loading applied to little finger (Fig. 7C), all subjects seem to use similar muscle activity distribution pattern. This reflects the validity of the method. During outer loading applied to middle finger (Fig. 7B), subject B, C, and D use largely similar pattern. It is noted that subject A seems to use more muscles in lateral-lower part. During inner loading applied to thumb (Fig. 7A), different patterns were observed. Although main active muscles were in lateral-lower part, subject B seems to use more muscles in upper part and subject D use more muscles in medial part. Difference of muscle activity distribution pattern in thumb may be caused by the fact that many muscles were used to control thumb while other fingers used fewer muscles.

Furthermore, there was a strong linear correlation between total muscle activity and applied loading (Fig. 8). The same trend was observed in every subject. When the loading increased, higher muscle forces were required to maintain static equilibrium. The increase in total muscle activity indicates that more muscles are activated to produce force. Differences in total muscle activity may have been caused by differences in coactivation under each loading. High total muscle activity may indicate high coactivation between muscles. This observation indicates that the strategy to activate muscles to resist loadings may vary. Some loading types, such as inner loading on the thumb and little finger (Fig. 8A and H), require high coactivation levels. Further analysis of the relationship between force and muscle activity will allow the development of a model for estimating muscle force sharing in the forearm. However, there was also large variation in total muscle activity between subjects. This variation between subjects may have been associated with differences in individual muscle structures, including muscle size and muscle position.

In this study, palm and forearm were held, but this condition did not guarantee that the subject did not use finger muscles during a thumb loading. During the thumb motions, the surface of the medial part, which may include FCU, was activated. This activation may have resulted from unintentional wrist movements by the subject during the experiments, whereas the other muscles may have operated synergistically to stabilize the joint. In other words, this method may be able to detect such effects in detail. Also, the loading types examined in this study were limited to the forearm in pronation posture, and a change in arm posture may affect muscle cooperative activities.

The EMG conduction model did not consider the bone region within the forearm. Because this region does not generate muscle activity, the results may not have been affected by this omission. In further studies, determining how to detect the bone region in the cross section using the EMG band will be an important issue. In addition, the muscle activity was represented as mA dipole/s which passes normally through the cross-sectional area, although muscle fibers are not exactly aligned to the longitudinal direction of the forearm. The subjects in this study were young. It is known that age also affects muscle function. To gain more understanding regarding ageing and pathology in live human, a various range of the subject’s age should be considered. This study measured activity only in extrinsic muscles within the forearm. It seems that during finger motion, intrinsic muscles also work during finger motion. Measuring intrinsic muscle activity will also improve our understanding of finger function.

This method provides tomographic information of muscle activity within the forearm that cannot be assessed with a needle electrode. This facility will be very useful in clinical application. The impaired muscle region can be identified and properly treated. Furthermore, changes in load sharing between muscles within the forearm can be used to characterize pathological changes that affect muscle function. Muscle dysfunction caused by neuromuscular disease can also be observed by the method, enabling the development of more efficient treatments. In addition, the accessibility of deep muscle activity can provide a more delicate control of a prosthetic arm using the pattern of muscle activity from EMG-CT.

In summary, the present study applied various loadings to the thumb and index, middle, and little fingers. The results provide effectiveness of EMG-CT method by showing that the muscle cooperative activity of an individual is specific to force application conditions.

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