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Measurement of the median nerve strain within the carpal tunnel using a capacitance-type strain sensor: A cadaver study

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ABSTRACT

Background: Direct and quantitative measurement of median nerve strain within the carpal tunnel has been difficult because of the technical limitations associated with conventional devices. We used capacitive sensors (C-stretch), which are thin and flexible, to measure the median nerve strain within the carpal tunnel.

Methods: We used 12 fresh frozen upper extremity specimens. The transverse carpal ligament was left in situ, and we attached the sensor to the palmar surface of the median nerve to measure the nerve strain at 60 degrees of wrist extension. The sensor measured the median nerve strain at both the carpal tunnel site and the proximal to the carpal tunnel site before and after the carpal tunnel release. The amount of nerve excursion during wrist extension was also measured with the length change of the attached suture by a digital caliper.

Findings: The mean median nerve strain within the carpal tunnel [8.07% (95 %CI:7.17–8.97)] was significantly higher than that proximal to the carpal tunnel [5.21% (95 %CI:4.46–5.97)] at the wrist extension. There was no significant difference of the mean nerve excursion within and proximal to the carpal tunnel. The mean nerve strain and excursion were unaffected by carpal tunnel release.

Interpretation: These results indicated that wrist extension position might lead to increased strain on the median nerve within the carpal tunnel compared with at the proximal to the carpal tunnel. We believe that the current study might provide new information and help us understand the pathogenesis of carpal tunnel syndrome.

1. Introduction

Carpal tunnel and cubital tunnel syndrome are the most common peripheral nerve entrapment neuropathies of the upper extremities (Atroshi, 1999; Mondelli et al., 2005). Several studies have demonstrated the pathogenesis and biomechanical factors of these disorders, such as nerve compression and strain (Gelberman et al., 1981; Gelberman et al., 1998; Iba et al., 2006; Ochi et al., 2013). Patients with these entrapment neuropathies have been found to have increased internal pressure at the entrapment site (Gelberman et al., 1981; Iba et al., 2006). Also, patients with cubital tunnel syndrome are significantly associated with abnormal nerve strain, suggesting that the increased nerve strain might be one of the mechanisms of this disorder (Ochi et al., 2013). It is suggested that strain on the nerve during joint movement causes impaired blood flow to the nerve, resulting in neuropathy(Clark et al., 1992; Ogata and Naito, 1986; Watanabe et al., 2001).

Peripheral nerve strain and excursion have been evaluated in previous studies (Aoki et al., 2005; Bay et al., 1997; Byl et al., 2002; Dilley et al., 2003; Wright et al., 1996). These studies indicated that the median and ulnar nerves proximal to the entrapment lesion were significantly stretched and gliding by the motion of the wrist and elbow joints. Of those studies, the strain on the median nerve was demonstrated by

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measurement using a strain gauge during various joint movements in cadaver specimens (Byl et al., 2002; Wright et al., 1996). However, there were few studies that assessed the strain on the median nerve directly and quantitatively within the carpal tunnel. It is difficult to directly measure such strain using conventional devices such as a linear transducer as the nerve entrapment site is covered by ligamentous components, and the nerve tract is curved within the carpal tunnel during wrist flexion and extension. Therefore, it has not been clarified whether carpal tunnel release alters median nerve strain within the carpal tunnel. We think that investigation of the median nerve strain within the carpal tunnel may provide new information for understanding the pathogenesis and treatment of carpal tunnel syndrome.

Capacitance sensors are made of a laminate with an elastomer film and stretchable electrodes (Yamaji et al., 2017). They have considerable adaptability and flexibility and can accurately measure tiny changes in longitudinal extension using capacitance values. In a previous study, we used this sensor to assess ankle instability, thereby showing its usefulness to measure ligament strain (Teramoto et al., 2021). The aim of this study was to measure the strain on the median nerve directly and quantitatively within the carpal tunnel using this capacitance-type elastic sensor. We hypothesized that the strain on the median nerve within the carpal tunnel would be higher than that at a site proximal to the carpal tunnel site and that the strain decreases after carpal tunnel release.

2. Methods

2.1. Experimental setup

The study was approved by the Institutional Review Board of Sapporo Medical University Hospital (No. 3–1-15). We obtained informed consent before death or from the respective families and stored the cadavers until use. Twelve fresh-frozen upper extremity specimens (2 bilateral and 8 unilateral) obtained from 5 female and 5 male cadavers (mean age, 85 years; range, 70–101 years) were amputated approximately 15 cm proximal to the wrist joint. Referring to the application form at the time of study enrollment and the medical certification of death, cadaver specimens were excluded when there was a history of carpal tunnel syndrome or other peripheral nerve diseases, including diabetes or glucose intolerance, thyroid disease, rheumatoid arthritis, osteoarthritis, gout, or traumatic injuries.

The specimens were thawed at room temperature before testing. All soft tissue was removed 5 cm distal to the amputation site to expose the proximal ends of the ulna and radius. The specimens were then mounted on the custom-made wooden jig at neutral forearm rotation, securing the ulnar and radius with three screws (Fig. 1). We ensured that the anatomical alignment of radiocarpal joint and the wrist complex were maintained in the jig by the radiographic finding. To fix the wrist using the external fixator, two screws were inserted into the index metacarpal bone from the radial side, and two screws were inserted into the distal radius. Before we performed measurements, the wrist was fixed in the neutral position with a static bridging external fixator (The Penning Dynamic Wrist Fixator; ORTHOFIX, Lewisville, USA) (Tanaka et al., 2011; Yamaguchi et al., 2008). A 12-cm skin incision was made longitudinally from the distal palmar crease to a site 5 cm proximal to the distal wrist crease. We removed the palmaris longus and palmar aponeurosis. The transverse carpal ligament, which forms the carpal tunnel, was defined that its longitudinal length was 3 cm distal from the transverse line between the scaphoid tuberosity and the pisiform (Nanno et al., 2015; Pacek et al., 2010). Nerve and tendon tension setups were performed with modifications based on previous studies(Evers et al., 2018; Kubo et al., 2018; Yamaguchi et al., 2008; Yoshii et al., 2008). Each fingertip was pulled by applying 50 g (g) of weight to maintain the fingers in the extended position. The median nerve and flexor tendons were exposed proximal to the edge of amputation, and a force of 50 g weight was applied to the median nerve during all measurements. At the proximal edge of the forearm, each flexor tendon was collectively pulled by a force of 250 g weight to maintain a physical load. During the experiments, physiologic saline was sprayed onto the specimen every 30 min to prevent drying, and the room temperature was maintained at 22 °C.

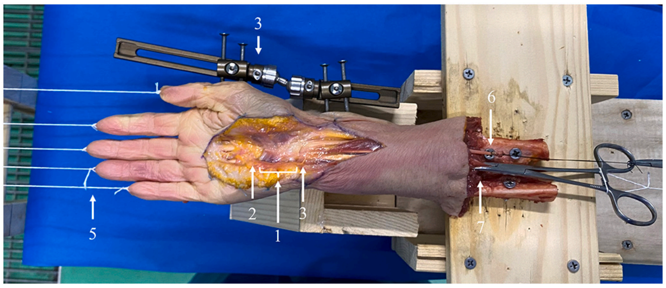

Fig. 1. The experimental setup.
Specimens were mounted on the wooden jig with the ulnar and radius secured with three screws at neutral forearm rotation. A static bridging external fixator was used to hold the wrist in an appropriate manner. A 12 cm skin incision was made longitudinally to expose the median nerve in the proximal carpal tunnel with the transverse carpal ligament and bursa intact. The palmaris longus and palmar aponeurosis were eliminated. To maintain finger tension, 50 g weights were affixed to each fingertip. During all tests, the median nerve and flexor tendons were exposed proximal to the edge of the incision, and a 50 g weight was attached to the median nerve to apply tension.
1. Transverse carpal ligament 2. Median nerve distal site 3. Median nerve proximal site
4. External fixator 5. Traction of each digit by 50 g 6. Traction of the median nerve by 50 g 7.Traction of the digital flexor muscle groups by 250 g

2.2. Measurement of median nerve strain

We measured median nerve strain using a capacitance-type stretching sensor which was taken out of an Ankle instability measure device that was developed in our previous study on the quantitative evaluation of ankle instability (C-stretch; Band Chemical Industries, Kobe, Japan: AT Measure; Aimedic MMT, Tokyo, Japan) (Teramoto et al., 2021; Yamaji et al., 2017). This sensor is a thin and flexible band consisting of a laminate containing an elastomer film and stretchable electrodes covered with an elasticated material, together with a transmitter and dedicated application that displays the amount of lengthening. The sensor is 15 mm in width, 30 mm in length, and 1 mm thick (Fig. 2). It has a wide dynamic range (up to 200% elongation), high responsiveness, and excellent measurement accuracy. The operating displacement range of the capacitance-type stretching sensor is 0–30 mm, the resolution is 0.1 mm, and its detection sensitivity for lengthening was 5.4 pF/mm

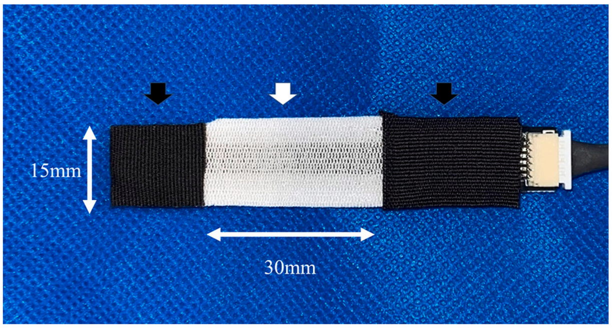

Fig. 2. The capacitance-type sensor.
The C-Stretch sensor is a band that consists of a laminate with an elastomer film and flexible electrodes coated in an elasticated material. The sensor area is 15 mm wide, 30 mm long, and 1 mm thick.
⇨.Sensor area ➡. Attachment area.

(±8%). The sensor capacitance was linearly converted to a voltage by a transmitter and further digitized at a 50-Hz sampling rate.

We measured the median nerve strain within the carpal tunnel site and at a site proximal to the carpal tunnel at 60° wrist extension from the neutral position. We defined the carpal tunnel site as the area just below the transverse carpal ligament and the site proximal to the carpal tunnel as the area 3 cm proximal to the proximal transverse carpal ligament. A wooden platform defining 60° of wrist extension was placed on the dorsal side of the wrist joint (Fig. 3). First, we measured the median nerve strain at the site proximal to the carpal tunnel. To measure strain in a neutral wrist position, the C-stretch sensor was fixed to the median nerve proximal to the carpal tunnel using a 3–0 nylon suture. The suture was passed through the median nerve epineurium so that the stretch sensor moved with median nerve bending and sliding. After placing the sensor, 50 g of tension was applied to the median nerve as a reference. Nerve elongation was then measured at 60° wrist extension. The change in median nerve strain was calculated by dividing the elongation measured by the C-stretch by the sensor length. In the same way, a linear transducer (Pulse Corder, Levex, Kyoto, Japan) was placed at the site proximal to the carpal tunnel, and we measured the nerve strain for comparison with that obtained by the C-stretch sensor. The Pulse Corder consisted of a brass pipe (31 mm long and 3 mm wide) and a rod-shaped coil sensor that generated the magnetic field. We have used this device in previous studies to measure nerve, tendon, and muscle strain (Aoki et al., 2005; Miyamoto et al., 2017; Shirato et al., 2017). The operating displacement range of the Pulse Coder was 3–15 mm, the resolution was 0.5 μm, the linearity error was <1%, and the sampling rate was set at 20 Hz. Measurements using the pulse coder were performed on eight specimens. Second, before carpal tunnel release, the C-stretch sensor was inserted within the carpal tunnel and secured to the median nerve, which was proximal and distal to the carpal tunnel to secure the sensor by a 3–0 nylon suture while keeping the carpal tunnel intact (Supplementary video 1). We measured the nerve strain within the carpal tunnel at 60°of wrist extension as those measured at the proximal of the carpal tunnel. Wrist extension measurements were performed three times by one investigator. After measurement of an intact carpal tunnel, the transverse carpal ligament was cut with a scalpel at a length of 3 cm to simulate carpal tunnel release. The measurement of nerve strain was also performed in the carpal tunnel and site proximal to it under the carpal tunnel released conditions (Fig. 4).

2.3. Measurement of median nerve excursion

The amount of nerve excursion within the carpal tunnel and the site proximal to the carpal tunnel during extension of the wrist joint was also measured. As in the previous study, a suture marker and bone landmark were used (Aoki et al., 2005). With the wrist at a neutral position, 3–0 nylon sutures were placed as a marker 1.5 cm distal and 3 cm proximal to the proximal end of the transverse carpal ligament. The distal suture was placed in the carpal tunnel, and one end of the thread was placed proximally through the carpal tunnel to establish a reference point on the suture. Then, a Kirschner wire (diameter, 2.0 mm) was inserted into the radius 1 cm proximal from the tip of the radial styloid as a bone landmark. The distance between the bone landmark and the suture marker on the nerve was measured using a digital caliper (Mefine; Shinwa Sokutei, Niigata, Japan) with an accuracy of 0.01 mm. The difference between the neutral and 60° extended wrist positions was calculated to determine the distance of median nerve excursion. Nerve excursion was also measured before and after carpal tunnel release with strain measurement.

2.4. Statistical analysis

All measured data were analyzed using EZR (Saitama Medical Center, Jichi Medical University, Saitama, Japan), a graphical user interface for R (The R Foundation for Statistical Computing, version 1.54). First, the Shapiro-Wilk test confirmed the normality of all outcome data. Secondly, we conducted a two-way analysis of variance with repeated measures to test for interactions at the site of measurement (proximal to carpal tunnel versus inside carpal tunnel) and condition of measurement (transverse carpal ligament intact versus transverse carpal ligament incised). As all outcome data showed a normal distribution, matched pair Student's *t*-test was used to demonstrate differences of strain and excursion before and after carpal tunnel release. A *p* value of 0.05 was chosen as the level of significance. We calculated 2-sided 95% confidence intervals (CIs). The reliability of the sensor was tested by analyzing the intrainvestigator intraclass correlation coefficients (ICCs). The ICCs were interpreted following Koo and Li's criteria, with <0.50 considered poor, 0.50 to 0.75 moderate, 0.75 to 0.90 good, and > 0.90 excellent (Koo and Li, 2016).

3. Results

3.1. Strain

The intrainvestigator ICC of the pulse coder was 0.864 (good) (95% CI:0.614–0.964), and that of the C-Stretch sensor was 0.988 (excellent) (95%CI:0.962–0.997). There was no significant interaction in the two

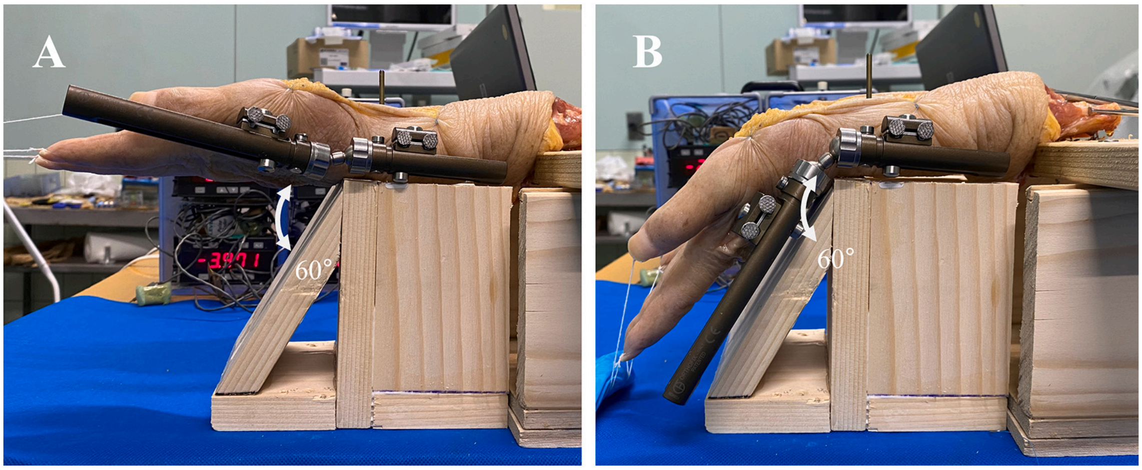

Fig. 3. Wrist extension motion.
A wooden platform was placed on the dorsal side of the wrist joint to define 60° of extension. After attaching sensors to the median nerve, the nerve strain during wrist extension was measured. (A) neutral wrist position (B) 60° of wrist extension.

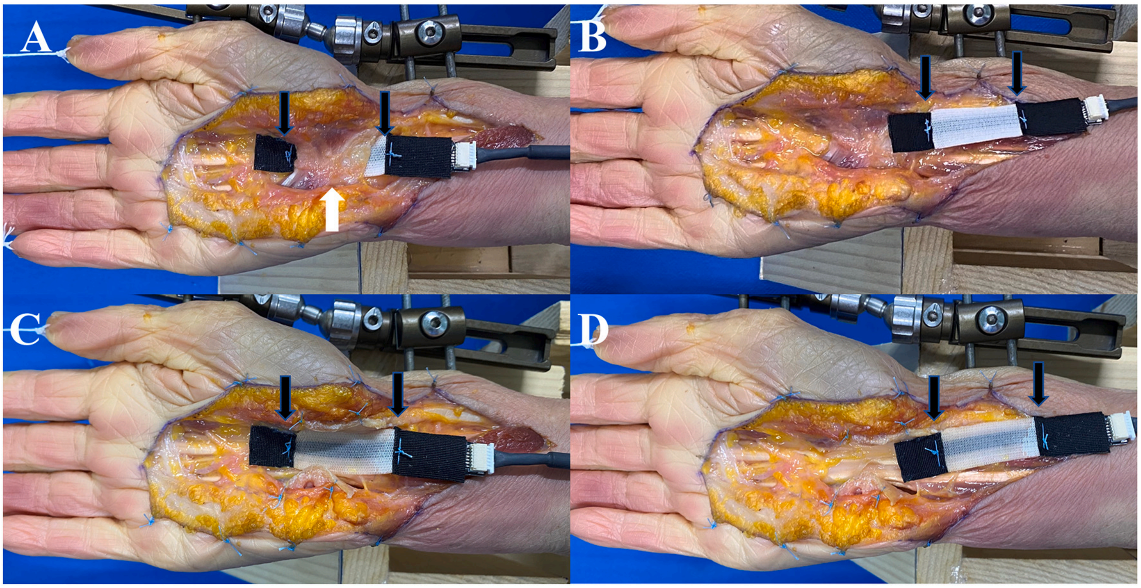

Fig. 4. The C-stretch setting within the carpal tunnel and at the site proximal to the carpal tunnel.
Before carpal tunnel release: (A) within the carpal tunnel (B) at the site proximal to the carpal tunnel.
After carpal tunnel release: (C) within the carpal tunnel (D) at the site proximal to the carpal tunnel.
➡Sutures on the device that attach to the median nerve⇨Transverse carpal ligament.

factors between the measurement site and carpal tunnel release condition ($P > .05$). Median nerve strain at the site proximal to the carpal tunnel measured before and after carpal tunnel release using the C-stretch sensor [5.90% (95%CI:4.37–7.43), 5.24% (95%CI:3.92–6.56), respectively] did not show any significant difference from those measured using the pulse coder [5.98% (95%CI:3.58–8.38), 7.13% (95%CI:4.02–10.23), respectively] (Fig. 5). Values for median nerve strain within the carpal tunnel both of before and after the release of the transverse carpal ligament [8.07% (95%CI:7.17–8.97), 7.19% (95% CI:6.55–7.83), respectively] were significantly higher than those at the site proximal to the carpal tunnel [5.21%(95%CI:4.46–5.97), 5.02% (95%CI:4.27–5.77), respectively] with the wrist at 60° extension (Fig. 6, $P < .05$). On the other hand, there were no significant changes in nerve strain between before and after the carpal tunnel release at either site within and proximal to the carpal tunnel (Fig. 6).

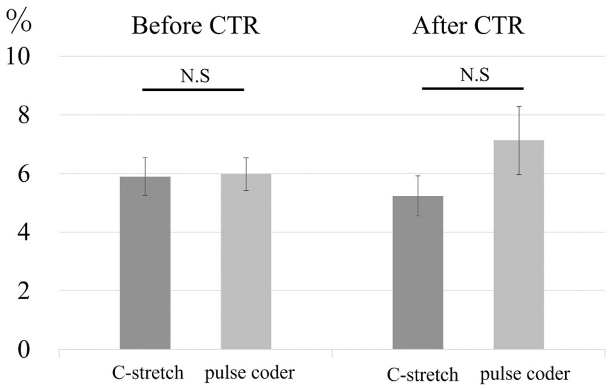

Fig. 5. Comparison of median nerve strain at the site proximal to carpal tunnel between C-Stretch and pulse coder.
There is no significant difference between the two instruments before or after carpal tunnel release.
CTR (carpal tunnel release) N·S (not significant).

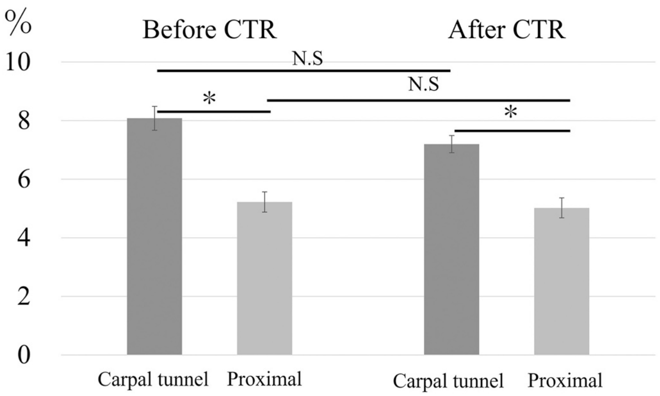

Fig. 6. Change in median nerve strain(%) before and after CTR.
Comparison of median nerve strain in the carpal tunnel and proximal to the carpal tunnel.
In both conditions before and after carpal tunnel release, the median nerve in the carpal tunnel was significantly more stretched than that proximal to the carpal tunnel ($P < .05$). There was no significant difference between before and after carpal tunnel release.
CTR (carpal tunnel release) N·S (not significant) $*P < .05$.

3.2. *Excursion*

There was no significant interaction between the two factors of measurement site and the carpal tunnel release condition for nerve movement ($P > .05$) as same as the measurement of nerve strain. Excursion of the median nerve within the carpal tunnel before and after transverse ligament release from neutral to 60° wrist extension [7.49 mm (95%CI:5.95–9.04), 6.25 mm (95%CI:4.67–7.84), respectively] did not significantly differ from the values proximal to the carpal tunnel [8.61 mm (95%CI:7.23–9.98), 6.19 mm (95%CI:4.74–7.64), respectively] (Fig. 7). In addition, there were no significant changes in the excursion between before and after carpal tunnel release at either site (Fig. 7).

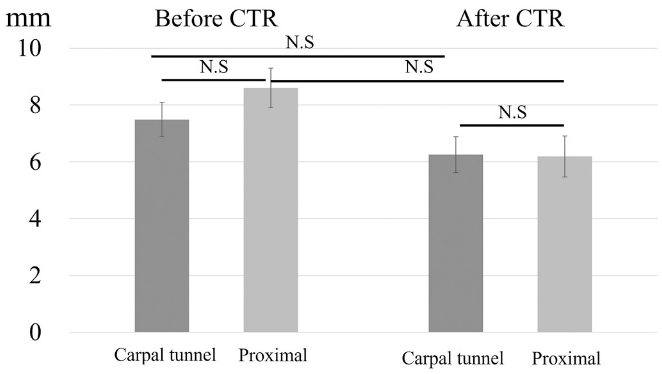

Fig. 7. Change in median nerve excursion(mm) before and after CTR.
Comparison of median nerve excursion in the carpal tunnel and proximal to the carpal tunnel. There was no significant difference in nerve excursion before and after carpal tunnel release. There was also no significant difference between measurement sites.
CTR (carpal tunnel release) N·S (not significant).

4. Discussion

We quantitatively measured the strain on the median nerve within the carpal tunnel using a stretchable capacitive strain sensor. The strain on the median nerve within the carpal tunnel was significantly higher than that at the site proximal to the carpal tunnel when the wrist was positioned at 60° extension. On the other hand, there was no significant difference of the mean nerve excursion within and proximal to the carpal tunnel during wrist extension. Before and after carpal tunnel release, there were also no significant changes in the strain and excursion of the median nerve either within or proximal to the carpal tunnel. These results suggest that increasing the strain on the median nerve within the carpal tunnel might be markedly affected by wrist extension compared with that on the median nerve proximal to the carpal tunnel. In addition, these changes tended to be unaffected by carpal tunnel release and excursion of the median nerve.

We think that direct and quantitative measurement of the strain within the carpal tunnel provides new information as studies have only shown the nerve strain at sites proximal to the carpal tunnel and indirectly demonstrated strain within the carpal tunnel. Carolyn et al. and Wright et al. measured the strain on the median nerve proximal to the carpal tunnel using cadavers (Byl et al., 2002; Wright et al., 1996). Aoki et al. reported ulnar nerve strain proximal to the elbow joint during a throwing motion (Aoki et al., 2005). They reported that the nerves in the proximal part of the joint were stretched during wrist dorsiflexion and elbow flexion movements. However, they did not show nerve strain at the entrapment area or the joint because of the difficulties in the measurement using conventional equipment such as a pulse coder. For measurement of nerve strain using a conventional strain gauge, the nerve should be in an open area and run straight. Thus, it is difficult to measure the strain on the median nerve in flexed joint position or without carpal tunnel release to allow the device to be attached to the nerve. The C-stretch is a stretchable capacitive strain sensor with excellent stretch response, flexibility, and detection accuracy, characteristics not found in conventional strain sensors (Yamaji et al., 2017). These characteristics allow measurement of strain in curved nerves at the joint. In addition, we think that the thinness of the C-stretch makes it possible to insert it into the carpal tunnel and measure nerve strain without carpal tunnel release.

We demonstrated no significant difference in the median nerve strain value at the site proximal to carpal tunnel measured using the C-stretch in comparison with the value obtained with a pulse coder as a conventional strain gage. In our previous study, we have shown the reliability and validity of the pulse coder to measure nerve and muscle strain (Aoki et al., 2005; Miyamoto et al., 2017; Shirato et al., 2017). We, therefore, think that the C-stretch is as reliable and valid as a pulse coder for the measurement of nerve strain. In the present study, the strain measurements using the pulse coder sensor tended to have wider confidence intervals and lower intrainvestigator reliability compared with those using the C-Stretch sensor. However, the previous study (Byl et al., 2002) demonstrated that the standard deviation for the strain measurements was 2 to 3%, which was similar measurement error with our results. Then, we think the results using the pulse coder sensor in the present study seem to be within a reasonable measurement error range.

Before carpal tunnel release, the median nerve at the site proximal to the carpal tunnel and within the carpal tunnel was elongated by about 5% and 8%, respectively, during wrist extension. Thus, we think that the median nerve within the carpal tunnel is stretched more than at sites proximal to the carpal tunnel during wrist extension. About one possible reason for that, we speculated that subsynovial connective tissues within the carpal tunnel might involve (Festen-Schrier and Amadio, 2018) a gentle connection between the median nerve and flexor tendons (Rath and Millesi, 1990), and affect median nerve strain.

Previous studies using cadavers have reported that the median nerve in the sites proximal to the carpal tunnel elongates by 7.6–9.6% during wrist extension exercises (Byl et al., 2002; Wright et al., 1996). On the other hand, the nerve strain at the sites proximal to the carpal tunnel before carpal tunnel release was by 5% elongation in the present study, which was likely to be lower than that in the previous studies. Regarding the difference of those results, we consider one of possible reasons might be due to the difference of the experimental conditions as our study used the specimens separated from the whole body while the previous study used that without separation. In addition, the range of donor's age in the present study (70–101 years) seemed to be older than that in the previous study (34–88 years) (Byl et al., 2002). We speculated that those factors might influence on measurements of the nerve strain.

In several previous studies, carpal tunnel pressure was lowest in the neutral position (Gelberman et al., 1981; Weiss et al., 1995). Another clinical study, which compared the effects of splinting in the neutral position with those in the extended position, also recommended neutral immobilization (Burke et al., 1994). Then, we think that immobilization in the neutral wrist position may be useful not only in reducing carpal tunnel pressure, but also in reducing nerve strain. We believe that the current study may provide further information regarding the effectiveness of orthotic fixation in the neutral wrist position for the treatment of carpal tunnel syndrome.

A study measuring the ulnar nerve strain using cadavers showed that simple decompression of the cubital tunnel does not change nerve strain (Hicks and Toby, 2002). In accordance with that finding, our study also demonstrated that there was no significant difference in the strain on the median nerve in the carpal tunnel before and after release. On the other hand, in patients with cubital tunnel syndrome, it has been reported that simple decompression of the cubital tunnel improves nerve strain (Ochi et al., 2013). Although it is controversial whether carpal tunnel release improves nerve strain, we believe that the current study could provide new information regarding changes in nerve strain in the carpal tunnel. The biomechanical factors of peripheral nerve entrapment neuropathies such as carpal tunnel and cubital tunnel syndrome are nerve compression and strain (Gelberman et al., 1981; Gelberman et al., 1998; Iba et al., 2006; Ochi et al., 2013). We, therefore, think that regarding the pathogenesis of carpal tunnel syndrome, increase of nerve compression might be more important factor than that of nerve strain.

In this study, we found no significant difference in the degree of median nerve excursion during wrist extension due to direct measurement of values within the carpal tunnel. Similar to the present study, a previous study using cadavers reported that carpal tunnel release did not produce an apparent significant difference in median nerve excursion (Szabo et al., 1994). In a clinical study of patients with carpal tunnel syndrome, it has been reported that carpal tunnel release did not affect excursion change (Tuzuner et al., 2008). However, another study demonstrated that the amount of gliding of the median nerve is significantly decreased in affected patients compared to healthy subjects (Ellis et al., 2017). To clarify this point, we are planning to measure nerve strain by capacitive sensor and excursion within the carpal tunnel before and after transverse carpal ligament release in patients with carpal tunnel syndrome in future studies.

There are several limitations to this study. First, the specimens were harvested from aged cadavers (mean, 84.8 years), and the strain properties of nerves in old specimens might differ from those in younger people. Second, the specimens were separated from the whole body. Third, the medical informantion based on the application form at the study enrollment and the medical certification of death might not be enough to be listed as exclusion criteria in several donors. Fourth, we measured the nerve strain within the carpal tunnel using cadaver models, which might not reflect pathological conditions in patients with carpal tunnel syndromes. We, therefore, need to evaluate the strain of the median nerve during the surgery in patients with carpal tunnel syndrome. However, the sterilization technique for the C-stretch device is not yet available, and there is no appropriate technique for fixing it to the median nerve in the patient. We think those issue are tasks to be solved in a future study.

5. Conclusions

Quantitative evaluation of median nerve strain using a C-stretch sensor showed that the nerve strain within the carpal tunnel was significantly higher than that at a site proximal to the carpal tunnel during the wrist extension. These changes tended to be unaffected by carpal tunnel release and excursion of the median nerve. We believe this result might help us understand the pathogenesis of carpal tunnel syndrome.

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Ethical approval

Informed consent was obtained before death or from the respective families before enrollment in this study and the study was approved by the institutional review board of the University.

The manuscript contains original material. Neither the article nor any part of its essential substance or figures has been or will be published elsewhere.

All the named authors actively involved in the planning, enactment and writing up of the study.

CRediT authorship contribution statement

Kenichi Takashima: Data curation, Formal analysis, Investigation, Visualization, Writing – original draft. **Atsushi Teramoto:** Methodology. **Mitsuhiro Aoki:** Methodology, Supervision. **Hiroki Miyamoto:** Data curation, Methodology. **Egi Hidaka:** Data curation, Investigation. **Rikiya Shirato:** Investigation, Formal analysis. **Yasuhiro Ozasa:** Methodology, Investigation. **Akira Saito:** Investigation. **Makoto Emori:** Data curation, Methodology. **Toshihiko Yamashita:** Supervision, Writing – review & editing. **Kousuke Iba:** Conceptualization, Project administration, Supervision, Writing – review & editing.

Declaration of Competing Interest

Kousuke Iba has an endowed chair at Department of Musculoskeletal Anti-aging Medicine, Sapporo Medical University. The other authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Thumb pronation efficacy of Camitz tendon transfer with insertion on the ulnar capsule of the metacarpophalangeal joint: a cadaver study

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Abstract

Several studies have indicated that Camitz transfer for severe carpal tunnel does not adequately restore thumb opposition. The aim of this study was to determine whether modification of the distal insertion of the transferred palmaris longus tendon could provide more effective opposition. We used 12 fresh-frozen upper extremity specimens. For spatial analysis, we used a three-dimensional motion-tracking device. At 0 N and 5 N of traction force, the pronation angle was significantly larger for the modified procedure than for the conventional procedure. There was no significant difference in the palmar abduction angle between the two groups. The modified palmaris longus tendon insertion on the ulnar side of the thumb metacarpophalangeal joint provides more effective thumb pronation than conventional Camitz opponensplasty in a cadaver model.

Keywords

Carpal tunnel syndrome, Camitz opponensplasty, cadaver study, pronation, abduction

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Introduction

Advanced carpal tunnel syndrome causes significant thenar muscle atrophy, resulting in the impairment of thumb opposition. Opposition requires palmar abduction and thumb pronation so that the thumb pulp faces the finger pulps (Cooney et al., 1984; Lee et al., 2003). Opponensplasty with carpal tunnel release is often required for the surgical treatment of advanced carpal tunnel syndrome. The Camitz opponensplasty involves transfer of the insertion of the palmaris longus (PL) tendon with a strip of the palmar aponeurosis to the insertion of the abductor pollicis brevis (APB) (Camitz, 1929). However, several studies have indicated that the Camitz transfer does not restore true opposition as the radial axis of the transferred tendon means that it is unable to provide pronation of the thumb while providing good abduction (Braun, 1978; Foucher et al., 1991; Kato et al., 2014; Park et al., 2010). There are a number of modifications to the Camitz transfer that aim to restore pronation, but most have focused on the incorporation and placement of pulleys (Rymer and Thomas, 2016). Previous studies have indicated that the optimal PL insertion is on the dorsoradial aspect of the metacarpophalangeal (MCP) joint (Camitz, 1929; Terrono et al., 1993; Wan et al., 2007).

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Several studies have reported other insertion sites for the Camitz transfer (Brand, 1970; Bunnel, 1938; Littler, 1949; Riordan, 1964). Recently, Takayama et al. (2002) demonstrated that transfer of the insertion of the abductor digiti minimi tendon to the ulnar capsule of the MCP joint was effective in restoring thumb pronation in Huber's procedure, in which pinch impairment of the hypoplastic thumb is reconstructed by abductor digiti minimi transfer (Littler and Cooley, 1963). We hypothesized that transfer of the insertion of the PL tendon to the ulnar capsule of the MCP joint would also be effective in restoring thumb pronation. The aim of the present study was to determine biomechanically whether transfer of the insertion of the PL tendon to the ulnar capsule of the MCP joint without modification of the transferred tendon routes by pulley creation could improve thumb pronation.

Methods

The study was approved by the Institutional Review Board of the university hospital (No. 2-1-34) and carried out in compliance with the Declaration of Helsinki. We obtained informed consent before death or from the respective families and stored the cadavers until use. We used 12 fresh-frozen upper extremity specimens from four female and eight male cadavers (mean age 82 years; range 71–96). These specimens were amputated at the upper one-third of the humerus and were thawed at room temperature before testing. Specimens with a history of surgery on or trauma to the thumb, or with scarring and limitation of range of motion in the digits or wrist were excluded. Room temperature was maintained at 22°C during the experiment and physiological saline was sprayed on to the specimens every 30 min to prevent drying.

Surgical technique

We carried out two surgical procedures (conventional and modified Camitz opponensplasty) on each cadaver. The order in which the two procedures were done was randomized using the RAND function in Microsoft Excel 365. All operations were done by the first author (KT). To obtain the maximum length of the transferred PL tendon, a distal skin incision was started on the distal palmar crease of the middle finger. The incision continued radially at the level of the proximal palmar crease and then curved along the thenar crease to the distal wrist crease. The longitudinal fibres of the palmar aponeurosis in continuity with the PL tendon were dissected up to the flexor retinaculum. The fibres of the detached palmar aponeurosis were drawn together with 4-0 nylon and used as a transferred tendon attached to the PL tendon (Figure 1(a)). A 1 cm transverse incision was made at the proximal wrist crease, and the PL tendon and palmar aponeurosis were pulled out at the palmar side of the wrist. The flexor retinaculum was incised to replicate the carpal tunnel release (Figure 1(b)). A suture was placed at the distal end of the transferred tendon with 4-0 nylon to allow traction, and the tendon was then passed through a subcutaneous tunnel in the direction of the thumb MP joint (Figure 1(c)). No pulleys were created.

To define the insertion sites for the two surgical procedures, a second longitudinal incision was made on the dorsal side of the thumb MCP joint. In the conventional Camitz opponensplasty, the distal tendon was sutured to the APB tendon insertion or the radial capsule at the base of the proximal phalanx with 4-0 nylon sutures (Figure 2(a)). In the modified procedure, the PL tendon was passed under the APB and extensor pollicis longus (EPL) tendons and anchored to the medial capsule at the base of the proximal phalanx and the adductor pollicis insertion on the ulnar side of the thumb MP joint (Figure 2(b)). As the transferred tendon passed under the APB and EPL in the modified procedure, it was inserted into the ulnar aspect of the MP joint at an angle more in line with the long axis of the thumb than in the conventional procedure. When suturing to the insertion site, in both procedures the thumb was placed opposite to the palm, and a traction force of 50 g was applied in the distal direction when anchoring the transferred tendon.

Experimental set-up

The experimental set-up was based on that of previous studies with some modifications (Duymaz et al., 2013; Iwase et al., 2021; Lee et al., 2003; Skie et al., 2010). First, 3.0 mm and 2.4 mm K-wires were inserted into the ulna, radius and humerus, and the specimen was placed in a custom-made aluminium jig with the elbow at 90°, the forearm in a supinated position and the wrist in a neutral position (Figure 3). Radiographs were used to ensure the radiocarpal joints and the wrist complex were maintained in anatomical alignment in the jig. Next, a number of small transverse incisions were made on the palmar side of the forearm to identify the run of the PL and flexor pollicis longus (FPL) tendons. The muscle-tendon junctions of the two tendons were sutured with No. 1 silk thread. Similarly, the EPL tendon was identified on the dorsal aspect of the wrist joint and sutured with silk thread. The sutured silk thread

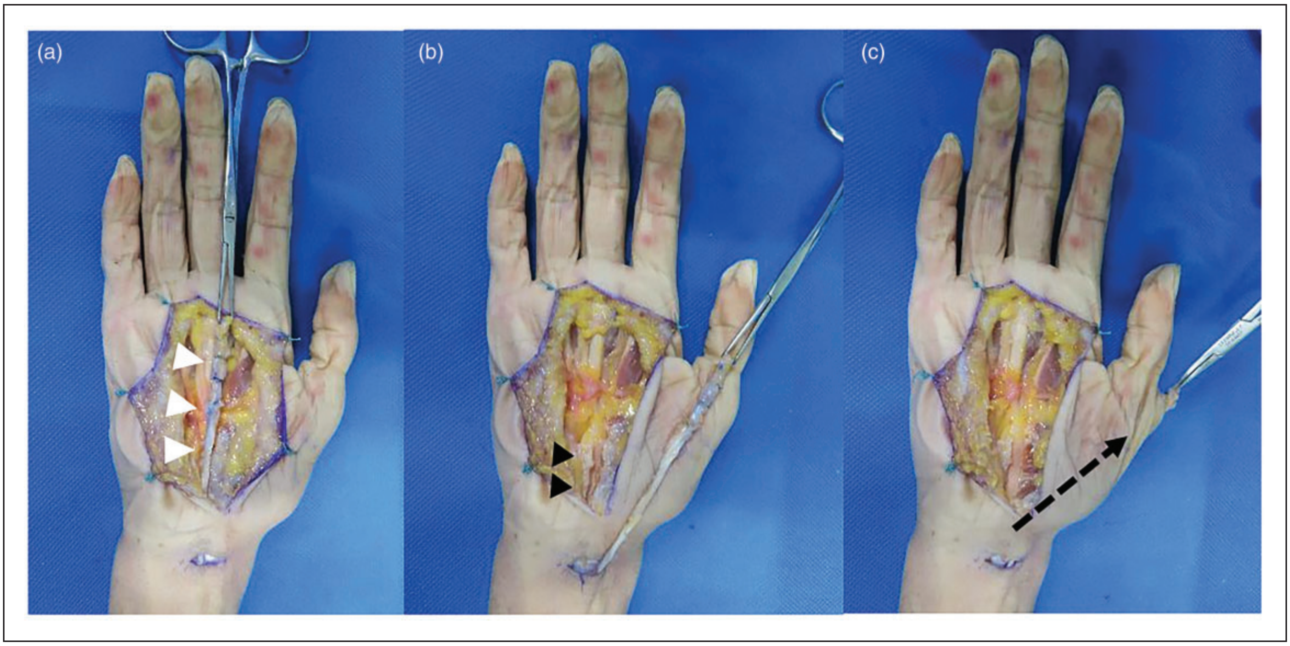

Figure 1. Preparation of the transferred tendon. (a) The longitudinal palmar aponeurosis fibres were separated and drawn back together using 4-0 nylon to create the transferred tendon (white arrowheads). (b) The tendon was pulled out at the palmar aspect of the wrist and the flexor retinaculum released (black arrowheads) and (c) The tendon was then passed through a subcutaneous tunnel in the direction of the thumb metacarpophalangeal joint without pulley creation (dotted black arrow).

was passed under the skin of the forearm and through the lateral or medial humeral skin, and the FPL and EPL tendons were each pulled at 100 g to reproduce the direction of tendon traction.

For spatial analysis, we used a FASTRAK (Polhemus, Colchester, VT, USA) three-dimensional (3-D) motion-tracking device. This system can measure and record the sensor position and orientation in a reliable 40 Hz electromagnetic field. With a root-mean-square precision of 0.76 mm for the x, y or z coordinates and 0.15° for receiver orientation within 76 cm, the system can locate and calculate the angular orientation of each sensor in relation to the source by sensing its electromagnetic field. The dorsal aspects of the thumb and index metacarpals were exposed, and a wooden jig was placed on the bone. The microsensors were placed on the thumbnail, and on the wooden jigs placed on the thumb and index metacarpals (Figure 4). The rotational angle of the microsensor placed on the thumbnail was defined as the thumb pronation angle. A 3-D digitizer was used to set the long axis of the thumb and index metacarpals, and the angle between the two metacarpals in the sagittal plane was defined as the palmar abduction angle. The 3-D data were collected using Medis-3D software (MediSens, Saitama, Japan). Thumb opposition was reproduced by pulling the silk thread sutured to the PL tendon in the direction of the medial condyle of the humerus and the angles of palmar abduction and thumb pronation were measured (Figure 5). The loading forces were measured with a digital tension gauge (Digital push-pull gauge 9550B type; Aikoh Engineering, Osaka, Japan). Loading forces were increased in increments of 5 N to a maximum of 20 N with reference to a previous study (Iwase et al., 2021). We defined the thumb pronation angle and palmar abduction angle as 0° under the conditions before tendon transfer. We measured the angles before and after PL tendon transfer with increasing traction force.

Statistical analysis

All measured data were analysed using EZR (Saitama Medical Center, Jichi Medical University, Saitama, Japan), a graphical user interface for R (The R Foundation for Statistical Computing, version 1.54). The Shapiro–Wilk test was used to determine the normality of outcome data. As all outcome data had a normal distribution, repeated-measures analysis of variance (ANOVA) was used to study the interactions between the pull traction force and the angles for each surgical technique. Post hoc analyses of differences between the data were carried out using Bonferroni's test. For comparison between groups at each traction force, a matched pair Student's *t*-test was used to identify any differences between the conventional Camitz procedure and the modified method. A *p*-value of 0.05 was chosen as the level of significance. Means and two-sided 95% confidence intervals (CIs) were calculated from the measurement results. G-power software version 3.1.9.6 (Universität Düsseldorf, Germany) with a sample size of 12 for each group was used to calculate the effect size from the mean and standard deviation between each matched group. From the

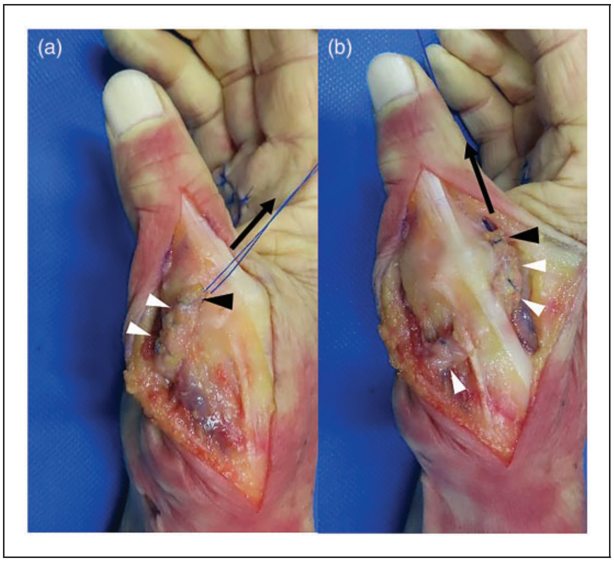

Figure 2. Surgical procedures. (a) In the conventional Camitz opponensplasty, the distal transferred tendon (white arrowheads) was sutured to the APB tendon insertion or the radial capsule at the base of the proximal phalanx with 4-0 nylon sutures (black arrowhead) under a traction force of 50 g (black arrow) and (b) In the modified procedure, the PL tendon (white arrow heads) was passed under the APB and extensor pollicis longus tendons and anchored to the medial capsule at the base of the proximal phalanx and the adductor pollicis insertion on the ulnar side of the thumb metacarpophalangeal joint (black arrowhead) under a traction force of 50 g (black arrow). APB: abductor pollicis brevis; PL: palmaris longus.

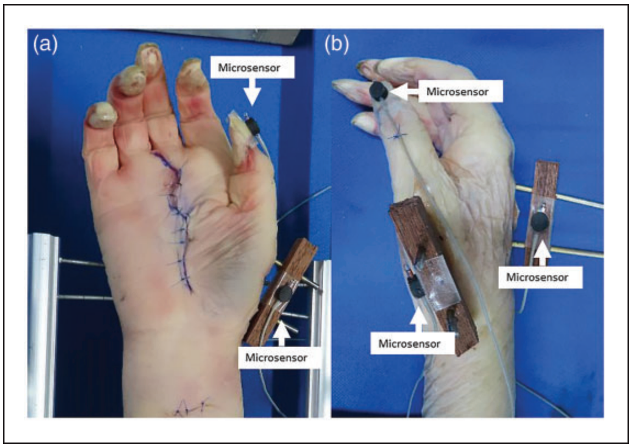

Figure 4. Microsensor installation. A wooden jig was set by pin fixation to the bone on the dorsal side of the index and thumb metacarpals. The microsensors were placed on the thumbnail and on the wooden jigs on the dorsal side of the metacarpals.

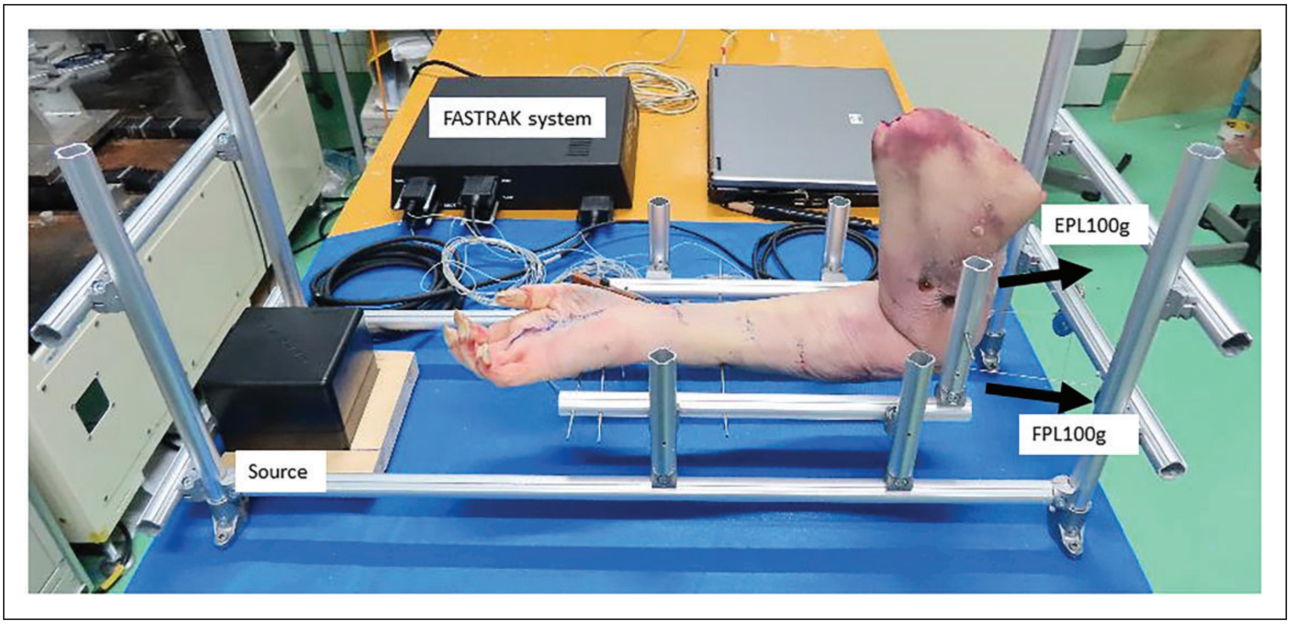

Figure 3. Experimental set-up. The specimen was mounted with the elbow at 90°, the forearm fully supinated and the wrist in a neutral position on a customized aluminium jig. The identified pollicis longus, FPL and EPL muscle-tendon junctions were stitched together using No. 1 silk thread. The FPL and EPL tendons were each pulled at 100 g to replicate the direction of tendon traction (black arrow). EPL: extensor pollicis longus; FPL: flexor pollicis longus.

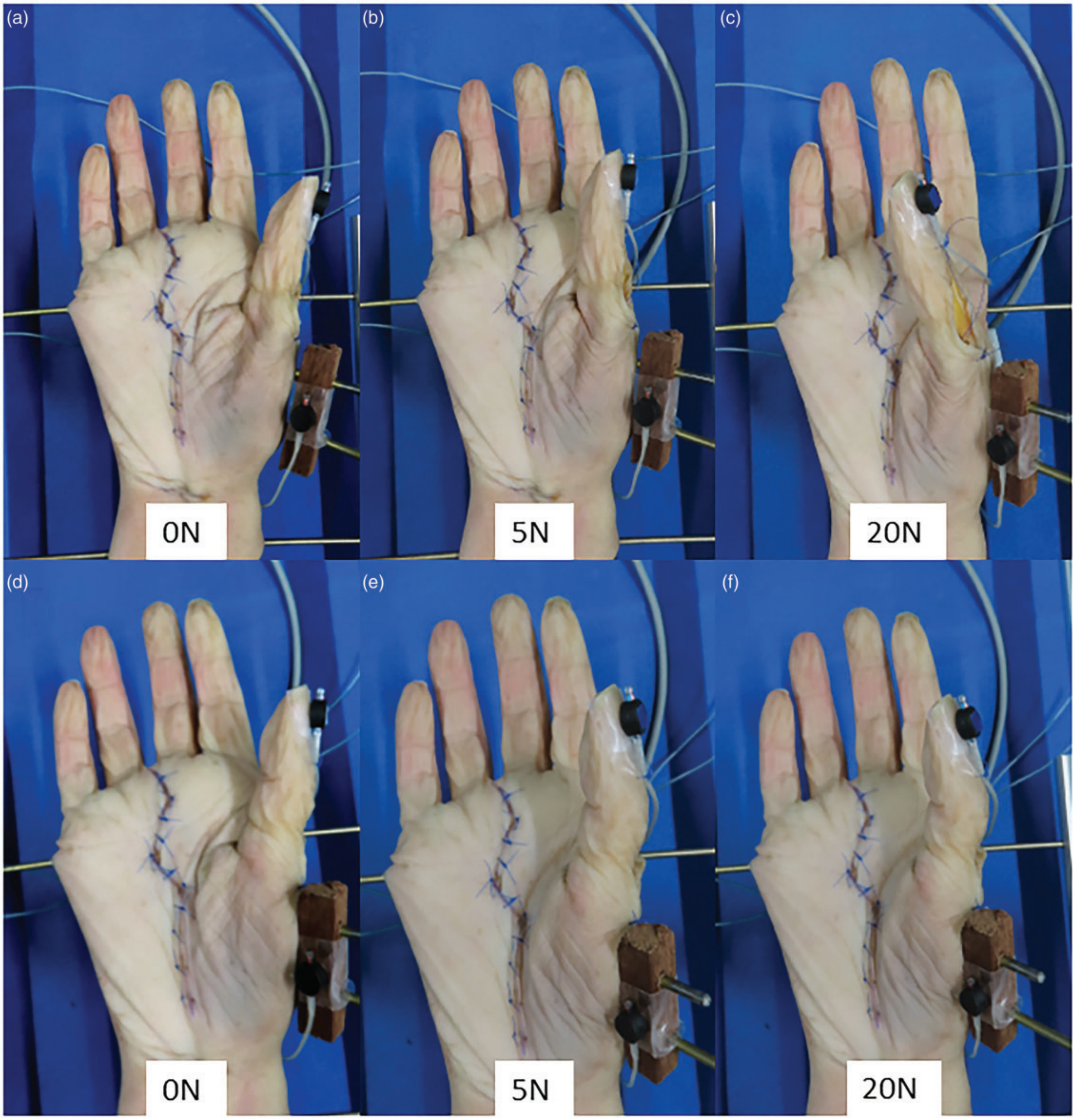

Figure 5. Thumb opposition during transferred tendon traction. (a–c) The conventional Camitz procedure and (d–f) the modified Camitz procedure with traction forces 0–5 N.

calculated effect sizes and significance levels, we confirmed that the power was greater than 0.9.

Results

Pronation angle

The thumb pronation angle was increased with increases in traction force in both the conventional and modified Camitz opponensplasty groups (ANOVA, $p < 0.01$). As traction force was increased from 0 to 15 N, the pronation angle increased significantly in both groups but there was no significant change in angle with increases in force from 15 to 20 N. The pronation angles before the application of traction (0 N) and at 5 N of traction force were significantly larger in the modified Camitz opponensplasty group than in the conventional opponensplasty group (Figure 6; Table 1).

Palmar abduction angle

The palmar abduction angle increased significantly with increases in the traction force from 0 to 20 N in both the conventional and modified Camitz opponensplasty groups (ANOVA, $p < 0.01$). There were no significant differences in the palmar abduction angles between the two groups at any traction force (Figure 7; Table 1).

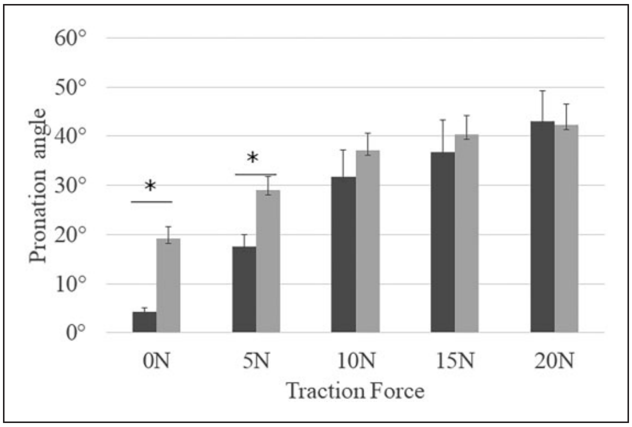

Figure 6. Pronation angle. The pronation angles for the modified opponensplasty (grey bar) were significantly larger than those for conventional Camitz opponensplasty (black bar) when the traction force was 0 N and 5 N. There were no significant differences between the surgical procedures at traction forces of 10 N or more (matched pair Student's *t*-test; $*p < 0.05$).

Discussion

Opposition is a complex motion involving palmar abduction, thumb pronation and MP joint flexion. Thumb palmar abduction is needed to grasp larger objects, whereas pinch function to hold smaller objects requires thumb pronation to approximate the thumb pulp to the finger pulps. A number of studies have reported the efficacy of modified tendon transfer techniques to restore thumb opposition in patients with advanced carpal tunnel syndrome (Bunnel, 1938; Kang et al., 2012; Kato et al., 2014; MacDougal, 1995; Matsumura et al., 1999; Naeem and Lahiri, 2013; Park et al., 2010). However, it is difficult to determine the outcomes of these procedures since various clinical evaluation criteria have been used (Rymer and Thomas, 2016). It is also difficult to accurately assess the functional outcome of Camitz opponensplasty accurately using patient-reported outcomes such as the Disabilities of the Arm, Shoulder and Hand, and Carpal Tunnel Syndrome Instrument scores as these rely on both sensory and motor recovery. In this study, we focused on a Camitz opponensplasty with a modified PL tendon insertion in a cadaver model and showed that a modified insertion on the ulnar side of the thumb MCP joint enabled more effective thumb pronation than did conventional insertion on the radial side.

Takayama et al. (2002) reported that in a modified abductor digiti minimi opponensplasty in the congenital hypoplastic thumb the transferred tendon runs across the ulnar side of the thumb MP joint and acts as if it were an ulnar collateral ligament. In addition,

Table 1. Pronation angles and palmar abduction angles.

	CC ($n = 12$)		MCC ($n = 12$)		
Traction force (N)	Mean (°)	95% CI	Mean (°)	95% CI	*p*-value
Pronation					
0	4.2	2.4 to 6.1	19.2	13.6 to 24.7	**<0.01**
5	17.5	11.8 to 23.2	29.0	22.6 to 35.5	**<0.01**
10	31.8	19.2 to 44.4	37.1	28.9 to 45.3	0.14
15	36.7	21.7 to 51.8	40.3	31.3 to 49.3	0.40
20	43.1	28.9 to 57.3	42.3	33.0 to 51.7	0.89
Palmar abduction					
0	23.3	15.5 to 31.0	25.7	17.1 to 34.2	0.22
5	28.6	20.0 to 37.3	31.8	24.6 to 39.0	0.10
10	34.2	26.0 to 42.3	38.3	31.9 to 44.8	0.13
15	36.0	27.9 to 44.1	40.1	33.6 to 46.6	0.20
20	37.3	29.2 to 45.4	41.2	34.5 to 47.8	0.25

Matched pair Student's *t*-test was used to demonstrate differences between the conventional Camitz procedure and the modified procedure. Statistically significant *p*-values are shown in bold font.

CC: conventional Camitz procedure; CI: confidence interval; MCC: modified Camitz procedure.

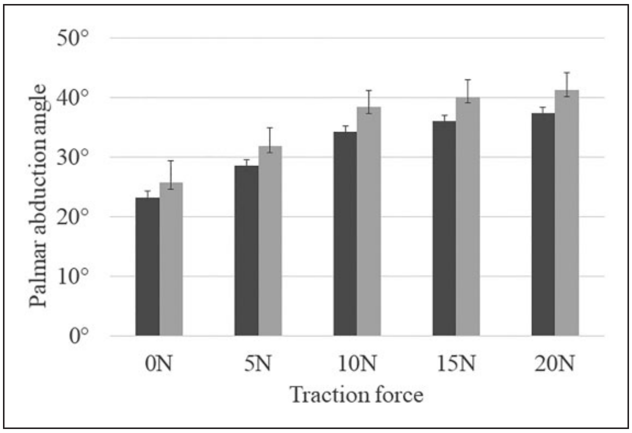

Figure 7. Palmar abduction angle. There was no significant difference in palmar abduction angle between the conventional (black bar) and modified Camitz procedure (grey bar) at traction forces from 0 to 20 N.

this change in the anchoring point contributes to it acting not only as an abductor but also as a pronator of the thumb, which is an important movement for pinching actions with the pulps or tips of the digits. Our cadaver study demonstrated that a transfer of the insertion of the PL tendon to the ulnar side of the thumb improves thumb pronation in comparison with the conventional Camitz opponensplasty.

Previous biomechanical studies have demonstrated excellent abduction of the thumb with a Camitz opponensplasty (Lee et al., 2003) but thumb abduction is not the only movement involved in opposition (Lee et al., 2003). In the present study, the pronation angle in the modified method was significantly larger than that in the conventional method when the PL tendon was pulled by traction forces of 0 N and 5 N but there was no significant difference in pronation angle when the force applied was 10 N or more. The palmar abduction angle was also increased with increases in the traction force in both the conventional and modified Camitz opponensplasties, and the palmar abduction angle reached approximately 35° to 40° at forces exceeding 10 N. We speculate that at approximately 40° of palmar abduction the axis of the tendon force with the modified insertion might not provide any mechanical advantage in pronation in comparison with the conventional insertion.

A previous study on finger flexion demonstrated that a traction force of 0.5 N on the flexor tendon enabled flexion to start, and 2 N enabled flexion of 58°, 102° and 52° at the DIP, PIP and MP joints, respectively (Ueba, 1976). Another in vivo study indicated that the flexor tendon force is less than 10 N during active hand grip (Kursa et al., 2006). The present study showed that a traction force at 5 N could provide 30° of palmar abduction of the thumb, which seems to be sufficient for thumb opposition. Based on these results, a muscle tension of as little as 0.5 to 5 N at finger flexion and thumb palmar abduction might be sufficient for thumb pinch in holding smaller objects in common activities of daily living, such as fastening buttons, leafing through sheets of paper and writing. We speculate that a mean pronation force of the thumb less than 10 N, might enable pinch function for such common activities of daily living.

Previous studies have indicated that the Camitz opponensplasty does not provide restoration of true opposition, including thumb pronation, with the radial axis of the transferred tendon being the main drawback (Braun, 1978; Foucher et al., 1991; Naeem and Lahiri, 2013; Park et al., 2010; Rymer and Thomas, 2016). Subsequently, various procedures have focused on pulley modifications to improve pronation of the thumb and were found to be more effective (Bunnel, 1938; Kang et al., 2012; Kato et al., 2014; MacDougal, 1995; Matsumura et al., 1999; Naeem and Lahiri, 2013; Park et al., 2010; Rymer and Thomas, 2016). However, such pulley modifications have the potential to loosen over time owing to widening of the pulley, to permit the formation of adhesions at the contact points between pulley and tendon, and to result in median nerve compression by the transferred PL tendon when using an ulnar pulley (Naeem and Lahiri, 2013; Park et al., 2010). Although a recent review article reported that the Camitz transfer with pulley creation is an effective surgical technique for improving thumb pronation (Coulshed, et al., 2023), we examined whether a simple, minimal modification of the tendon insertion of the Camitz opponensplasty might improve thumb pronation. However, we did not compare the effect of pulley modifications on thumb pronation with that of insertion modifications and this is a limitation of the study. We also need to confirm the clinical effectiveness of the technique in restoration of thumb pronation in patients with advanced carpal tunnel syndrome.

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Ethical approval We obtained informed consent before death or from the respective families and stored the cadavers until use. The study was approved by the institutional review board of Sapporo Medical University (No. 2-1-34).

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