1 Introduction
With the development of the sports and health industry, the number of recreational tennis players has increased internationally. [1–3] The incidence of tennis injuries ranges from 0.05 to 2.9 per player per year, and upper limb injuries are more likely to become chronic than lower limb injuries. [1] Therefore, it is important to prevent recurrence by providing treatment and guidance, especially for upper limb disorders. Lateral epicondylitis (tennis elbow), a typical tennis disorder, is a painful condition of the extensor tendons attached to the lateral condyle of the humerus. The extensor carpi radialis brevis (ECRB) muscle is the affected tendon in almost 90% of cases. [4–5] Over 30 treatments are described for the tennis elbow; therefore, many of them are used routinely such that there is no single optimum treatment. [6] Patient education is provided as part of the treatment, [7] including instructions on using the elbow band and gripping the racket. The four traditional single-handed hand grip positions are the continental, Eastern, semi-western, and Western. [8] Tagliafico et al. investigated the grip styles of tennis players and found the damage caused by different grip styles. It has been reported to be related to the Eastern grip with radial-sided injuries and the Western or semi-western grip with...
ulnar-sided injuries. [9] In addition to the grip position, information on the pressure distribution (PD) of the finger being applied is important. Studies using grip strength devices have reported that the involvement of the ulnar fingers, such as the ring finger and little finger, was useful for exerting grip strength. [10] Furthermore, the force of the index finger before impact reportedly affects the force after impact. [11] It was suggested that a weaker index finger is desirable to suppress excessive contraction. However, the relationship between forearm muscle activation and the grip pressure distribution has not been clarified.

As there have been studies examining the PD of each finger using various test devices (cylinder of various sizes with sensors, [12] dynamometer with pulley assembly, [13] and digital dynamometer [14] with force sensor), it was found that the PD of the index finger and the middle finger is more involved in the grip strength. Recently, qualitative and quantitative data on the whole-hand PD have been reported using a cylinder with surface-pressure sensors. Mühldorfer et al. measured the load in each anatomical hand region during a grip task and reported similar results in previous studies. [15] Similarly, the same authors studied changes in load distribution that accompanied changes in grip strength and use for wrist fusion patients. [16] Since these techniques can quantitatively confirm information on gripping and PD, converting qualitative information, such as guidance on gripping, into quantitative information for comparison has become possible. It is necessary to consider whether the flexor grip (centered on the index finger and middle finger) or the ulnar grip (centered on the index finger and little finger) is better to transmit force and prevent injury efficiently. Our research question was how PD relates to forearm muscle activation when the radial or ulnar fingers are predominantly gripped (radial grip or ulnar grip) during a power grip compared to when all fingers are gripped evenly (power grip).

Surface electromyography (EMG) is commonly used as a non-invasive tool for evaluating muscle function in clinical settings and research institutions. Several studies have used EMG to document muscle activation during a power grip task to assess the relationship between grip strength and activity in forearm muscles, [17–18] while others have documented muscle activation in styles other than the power grip. [19–20] These latter studies only observed the relationship between muscle activation and total grip strength, and no study has examined the simultaneous relationship between regional forces in the hand and the activity of muscles involved in the grip task. Understanding the regional distribution of forces during hand grasping and their relationship with the activity of the muscles responsible for the task will lead to a better overall understanding of grasping and its disorders. In a systematic review of EMG studies of the tennis elbow, representative of both the extensor carpi radialis (ECR) brevis and longus combined or selective for the ECRB alone, extensor digitorum communis (EDC), flexor carpi ulnaris (FCU), flexor carpi radialis, flexor digitorum superficialis (FDS), pronator teres, and triceps brachii have been selected. [21] Since we focused on the main movement of the wrist joint and finger muscles during grip, we acquired the muscle activities of the EDC, ECR, FDS, and FCU muscles. This study aimed to: (1) quantify the load distribution in the hand during various styles of the gripping task and (2) investigate the relationships of these distributions with muscle activation. We hypothesized that the grip force of the radial grip is associated with the activity of the extensor muscles, such as the ECR and EDC, and the ulnar grip is associated with the activity of the flexor muscles such as the FDS and FCU. Furthermore, we predicted that ECR activity in the flexor grip was significantly higher than that in the ulnar grip.

2 Methods

2.1 Participants

The participants of this cross-sectional study were 15 healthy students from a national university. They were all informed about the experiments, and those who provided informed consent were included. The exclusion criteria were as follows: (1) persistent pain that leads to an inability to grip, (2) a history of musculoskeletal disorders, (3) severe neurological or cardiovascular disease, and (4) hand deformity. The study was approved by the Ethics Review Committee of University Graduate School and Faculty of Medicine (approval number R2018). Written informed consent was obtained from the patients for the publication of their anonymized information in this article.

2.2 Equipment

2.2.1 Measurement of grip force and load distribution

Grip force and load distribution were measured using a cylinder-shaped device with an embedded pressure sensor, allowing the capture of qualitative and quantitative data during grip tasks. The sensor sheet (200 × 300 mm) with an embedded pressure sensor (173 × 288 mm, pitch 1.2 mm) was wrapped around a hard cylinder (60 mm diameter) to record the load in various hand regions. Pressure sensor data were transferred to a computer at a frequency of 10 Hz (Figure 1). This
technology is useful for printing high-definition and high-precision electronic circuits on a flexible sheet substrate and the PD system incorporated into the sensor. This device exhibits high sensitivity and selectivity against various types of pressure. [22–24]

2.2.2 EMG

Muscle activities were recorded using the TeleMyo 2400 system (Noraxon, Scottsdale, AZ, USA) with a sampling rate of 1000 Hz. Surface electrodes were placed to record from the EDC, ECR, FDS, and FCU muscles of the forearm. These muscles were strategically selected because they represent key extrinsic hand locations and for their ease of accessibility to surface EMG recordings. We confirmed the crosstalk between each EMG recording in advance and visually confirmed that individual muscle activation did not affect other muscle activations. The skin at the electrode sites was shaved and cleaned using scrubbing gel and alcohol. Bipolar surface electrodes (Ambu A/S, Ballerup, Denmark) were placed with a 2 cm interelectrode distance on these muscles.

2.3 Experimental protocol

The participants performed the following three grip tasks using the cylindrical device: a radial grip, a power grip, and an ulnar grip, as described previously. They gripped the cylindrical device (placed vertically on a platform) with their right hand while sitting on a chair, with both shoulders in a neutral position, their right elbow flexed at 90°, and their right wrist dorsiflexed at 0° to 15°, similar to a conventional grip test. [25] They were given verbal instructions and demonstrations on gripping the device as follows: for the radial grip: hold it primarily with the index and middle fingers; the power grip: hold it around all your fingers; and the ulnar grip: hold it primarily with the ring and little fingers. Before starting each task, the participants practiced how to grasp. Subsequently, looking at the data displayed, they performed a maximum force grip of 3 seconds twice on the device. Load distribution and EMG data were recorded while gripping the device.

2.4 Data analysis

The sensor loads within the sensor matrix are displayed as a two-dimensional raster diagram. This distribution map represents the contact regions of the hand grasping the cylinder. After calculating the force value from each sensor in the sheet, their values were summed to determine the total force of the hand-contact area. The forces were calculated based on seven anatomical regions (thumb, index finger, middle finger, ring finger, little finger, thenar, and hypothenar) as previously described to analyze load distribution. [16] Setting the
force applied across the entire contact area to 100%, each region’s percentage contribution was calculated (Figure 2).

For EMG data, a 10 Hz high-pass filter and a 450 Hz low-pass filter were applied, and the root mean square method was used for signal rectification. After this waveform processing, the average amplitude (during the 3-second task) for each muscle was calculated, and the average values from two trials of each grip task were calculated for all parameters. Normalization was performed by dividing the average amplitude data by the amplitude at the time of maximum muscle strength (% maximum voluntary contraction = %MVC).

2.5 Statistical analysis

All statistical analyses were conducted using IBM SPSS Statistics version 26 (IBM, Armonk, NY, USA). The data were normalized to analyze the relationship between grip forces applied from each grip pattern and EMG, and Pearson’s correlation analysis was performed. In addition, the relationships between extensors and flexors due to different grip patterns were evaluated using repetitive one-way analysis of variance (ANOVA), with post hoc comparisons performed when significance was determined using ANOVA. Furthermore, the partial

Table 1. Muscle activities and pressure distribution in each grip style

| Variable | Radial grip | Power grip | Ulnar grip |
|----------|-------------|------------|------------|
| Grip force (kgf) |             |            |            |
| Thumb     | 2.6 (0.6)   | 2.0 (0.8)  | 2.1 (1.0)  |
| Index finger | 7.0 (2.2)   | 4.5 (1.8)  | 1.3 (0.7)  |
| Middle finger | 7.6 (3.8)   | 5.3 (3.9)  | 0.9 (0.8)  |
| Ring finger | 1.1 (1.1)   | 4.4 (2.7)  | 3.6 (1.7)  |
| Little finger | 0.6 (0.7)   | 2.7 (1.5)  | 5.0 (2.4)  |
| Thenar    | 3.9 (2.0)   | 2.4 (1.4)  | 2.1 (1.1)  |
| Hypothenar | 0.2 (0.5)   | 0.5 (1.0)  | 0.4 (0.7)  |
| Normalized (%MVC) |            |            |            |
| EDC       | 100.6 (31.7)| 111.4 (33.5)| 91.0 (28.2) |
| ECR       | 78.5 (19.7) | 83.8 (11.66)| 71.4 (16.5) |
| FDS       | 67.1 (21.6) | 51.9 (14.94)| 56.1 (15.1) |
| FCU       | 61.1 (40.4) | 76.4 (34.8) | 94.8 (27.5) |

Variables are expressed as mean standard deviation (SD). Abbreviations: EDC, extensor digitorum communis; ECR, extensor carpi radialis; FDS, flexor digitorum superficialis; FCU, flexor carpi ulnaris; and %MVC, % maximum voluntary contraction.
η square ($\eta^2$) was calculated to investigate the effect size.

### 3 Results

Of the participants, eight were female, the mean age was $27.8 \pm 8.2$ years, and all participants were right-handed. Table 1 shows the EMG and PD data for each of the three grip patterns. The forces applied differed with grip patterns in each of the anatomical regions; however, almost no force was observed in the hypothenar region using any grip. Figure 3 shows the relative contributions of the seven anatomical regions of each grip pattern. For the radial grip, the contributions of the index finger ($31.6 \pm 6.0\%$) and the middle finger ($31.9 \pm 9.1\%$) were larger than for the other grips. Forces during the power grip were distributed across the fingers as follows: index finger ($23.4 \pm 11.1\%$), middle finger ($22.5 \pm 9.6\%$), ring finger ($18.7 \pm 6.7\%$), and little finger ($12.3 \pm 5.0\%$). For the ulnar grip, the ring finger ($23.2 \pm 7.6\%$) and little finger ($33.4 \pm 9.8\%$) regions tended to have stronger grips than the other grips. The relationships between the grip forces and EMG are shown in Table 2. Grip force was correlated with EDC in both the radial grip ($r = 0.52$, $p = 0.03$) and power grip ($r = 0.47$, $p = 0.04$), while it was correlated with FDS activity in the ulnar grip ($r = 0.55$, $p = 0.02$). Figure 4 shows the comparison results of %MVC with different grip patterns. As a result of repeated one-way ANOVA, the EDC was less activated in the ulnar grip than in the power grip ($p = 0.007$, 95% confidence difference inter-

### Table 2. The relationship between the grip pressure and electromyography in each grip style

|                  | Radial grip | Power grip | Ulnar grip |
|------------------|-------------|------------|------------|
| EDC              | 0.52*       | 0.47*      | 0.23       |
| ECR              | 0.15        | -0.1       | 0.04       |
| FDS              | 0.31        | 0.32       | 0.55*      |
| FCU              | 0.09        | 0.14       | 0.37       |

Abbreviations: EDC, extensor digitorum communis; ECR, extensor carpi radialis; FDS, flexor digitorum superficialis; and FCU, flexor carpi ulnaris.

* $p < 0.05$. 

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Fig. 3. The percentage contribution of the seven anatomical areas in each grip type

The (A) radial grip, (B) power grip, and (C) ulnar grip are shown in order from the top. The left side of the figure in each grip style shows the contribution of each anatomical area on the total pressure. The right side shows the pressure distribution in grey scale, wherein the darkening of color indicates the increase in pressure.

Fig. 4. Results of comparing %MVC with different grip patterns

White, radial grip; grey, power grip; and black, ulnar grip. * $p < 0.05$. % MVC=% maximum voluntary contraction
val [CI] = 6.0–34.9, ηp2 = 0.44). Furthermore, the FCU was activated to a greater extent in the ulnar grip than in the radial grip (p = 0.004, 95%CI = 10.6–56.8, ηp2 = 0.49). The ECR showed a similar trend to the EDC, but no significant difference was found (p = 0.08).

4 Discussion

Our study findings showed that grip force was correlated with the EDC in both the radial grip and power grip, while it was correlated with FDS activity in the ulnar grip. The EDC was less activated in the ulnar grip than in the power grip. Furthermore, the FCU was activated to a greater extent in the ulnar grip than in the radial grip. This study found that the PD changed due to the differences in grip patterns. This information on PD confirms that the participants properly performed the grip patterns based on our purpose.

In the present study, the index and middle finger PDs were large during the power grip. Additionally, a previous study reported that when using a glove with embedded pressure sensors, the contribution of the middle finger was the largest in lifting a metal object from a desk. [26] Power grip studies of load distribution have similarly reported the index or middle finger contributions to be the largest, followed by the ring finger and little finger forces. [16] Finger length is involved in the PD of the hand, and it is reasonable that the PD of the middle finger is the largest in healthy adults. [15] Correlation analysis showed that the power grip and radial grip were associated with EDC activity, and the ulnar grip was associated with FDS activity. In a pathological autopsy of the tennis elbow, the abnormal region of the elbow contains the lateral ECRB-EDC complex, and the EDC also originates from the lateral epicondyle, which is considered a factor in the development of tennis elbow. [27] Both the radial and power grips have a large PD between the index and middle fingers, suggesting that extensor muscle activation increases when the radial side fingers are dominant. Moreover, unless the participants were instructed to grip with the ulnar fingers, the power grip tended to have a high-PD on the index and middle fingers, similar to the radial grip. Therefore, the EDC may be excessively active in amateur players who do not receive proper guidance. Furthermore, when the radial grip is performed, the racket’s tip is raised more than when the ulnar grip is used; therefore, a compensatory action is required to correct it. The ECR showed a tendency to show similar muscle activity as the EDC, but there was no correlation with grip strength. Previous studies have reported that the ECR shows higher activity during the groundstroke [28]. However, in this study, the participants performed the task of gripping the device without changing the dorsiflexion angle of the wrist joint, which may have resulted in force adjustments occurring mainly in the fingers. Therefore, we considered that there was no difference in the ECR activity. The PD of the ring finger and little finger was high in the ulnar grip, suggesting that this is related to the flexor muscle groups such as the FDS and FCU. The FCU has been reported to be a major stabilizer for elbow valgus stability, [29] and the ulnar grip may be of teaching significance. Furthermore, our results suggest that the ulnar grip can increase the FCU activity and decrease the EDC activity and is considered an effective teaching method to prevent the development of tennis elbow. However, excessive flexion poses a risk of injury to the lateral wrist ulna; therefore, the degree should be considered. This study's characteristic is that the qualitative index of the difference in grip was quantified using the grip sensor. By quantification, the values of the PD of the index finger and middle finger in the power grip and radial grip were both high. Therefore, in treating tennis elbow, in addition to physical treatment, such as massage, teaching the patient how to hold the racket and properly applying force are necessary.

This study had some limitations that should be noted. First, the number of muscles was limited. Representative muscles involved in finger movements were selected based on previous studies. However, this muscle selection may be biased owing to the setup requirements. Second, there are limitations to the shape and size of the equipment used to analyze the PD. Here, the size of 60φ was adopted to prevent finger overlap. Previous studies have confirmed that different racket sizes do not affect muscle activity. [30] However, the influence of the shape and weight of the racket is predicted. Thus, in future studies, it will be necessary to measure PD and muscle activation during groundstroke, such as wrapping a sensor around a tennis racket. Moreover, the number of target muscles, such as the ECU and FCR, should be increased while focusing on muscle crosstalk. Finally, the age of onset of tennis elbow is between the 30s and 50s, and muscle activity characteristics during this period may be different than that in younger individuals. Therefore, future studies that take age into account are needed.

5 Conclusions

This quantitative study revealed different load distributions during various grip patterns, and it was clarified that the pressure distribution of the index and middle fingers was associated with the EDC activity.
Moreover, the pressure distribution in the ring finger and the little finger, such as in the ulnar grip, is related to flexor muscle activity such as that of FDS and FCU. Considering these results, the ulnar grip may be useful for preventing lateral epicondylitis.

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