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Grip Force Modulation on Median Nerve Morphology Changes

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ABSTRACT

Compression on the median nerve can lead to carpal tunnel syndrome (CTS), and median nerve indicators measured from ultrasound images can be used for CTS diagnosis. The aim of this study was to investigate the relationship between grip force modulation and dynamic morphological changes of the median nerve. We used a digital grip dynamometer to measure grip force while simultaneously conducting ultrasound examinations. Ultrasound images were sampled for both the dominant and nondominant hands of all participants ($n = 20$) during a baseline condition at approximately 0% maximum voluntary force (MVF), during sustained grip force conditions at 25%, 50%, 75%, and 100% MVF, and during the return to a relaxed state (≈0% MVF) directly following each grip force condition. Regardless of hand dominance, grip force level, and grip force modulation, median nerve cross-sectional area (MNCSA) during the grip tasks was smaller relative to the initial baseline condition without grip force. With respect to shape change, the median nerve became more flattened, including increased longitudinal diameter (D1) and decreased vertical diameter (D2), when grip force was relaxed compared to the preceding sustained grip force condition for the dominant hand; however, there were no significant shape changes for the nondominant hand. As morphological changes to tissue result in strain, our results indicate that median nerve injury development may be associated with more hand usage (dominant hand, grip exertion, and grip force modulation), and further suggests the evaluative potential for median nerve dynamics within the carpal tunnel.

1 | Introduction

Median nerve morphology has received much attention in recent years due to its relationship with the onset of carpal tunnel syndrome (CTS), which is widely recognized as the most common upper limb nerve compression syndrome [1]. The median nerve is a major nerve in the human body that originates from the brachial plexus (C5–T1), runs along the upper arm and forearm, passes through the carpal tunnel formed by the carpal bones and the transverse carpal ligament (TCL), and branches throughout the hand; it is responsible for transmitting both sensory and motor signals. In the narrow and structurally complex carpal tunnel, the median nerve is prone to compression or damage, which can lead to CTS, causing numbness, tingling, and weakness in the hand [2–4]. In CTS patients, an increase in the cross-sectional area of the median nerve and its flattening can be observed, which tend to normalize after carpal tunnel release surgery [5–7]. To screen and diagnose this neuropathy, median nerve cross-sectional area (MNCSA) obtained through ultrasound imaging has been used as a simple and practical clinical indicator [8–10]. However, MNCSA as a sole indicator is not without limitations, as it does not specifically describe morphological characteristics of the median nerve, and the reference range of MNCSA reported in previous studies varies with age, geographical location, and gender [11, 12].

In addition to quantifying MNCSA, one approach in the literature is to include complementary indicators that further describe morphological characteristics of the median nerve. Even with the same MNCSA, using the longitudinal diameter and the vertical diameter of the median nerve as indicators can quantify the flattening of the median nerve [13, 14]. Specifically, flattening of the median nerve is characterized by a greater longitudinal diameter and a smaller vertical diameter, which indicates stress on the nerve caused by compression, and can serve as a key feature in understanding the pathophysiology of CTS. Additionally, circularity of the median nerve can describe whether the median nerve is circular or angular [15, 16]. However, the variability in the reference ranges of median nerve indicators across different studies remains unresolved, as this variability is still largely attributed to demographic characteristics [12, 17]. Therefore, median nerve evaluation should further consider how morphological changes relate to environmental factors, such as injury development caused by frequent hand usage. Compared to static median nerve indicators under a specific single condition, analyzing the dynamic processes of the median nerve formed at multiple time points during hand activities may be more meaningful [18]. Repetitive hand use can cause damage to the subsynovial connective tissue (SSCT), and the accumulation of such damage may result in different outcomes for the median nerve during hand activities [19–21].

Previous research has provided limited insights into median nerve morphology during this dynamic process of gripping, particularly during the relaxed phase. Given this gap in knowledge, we hypothesized that the measurements of MNCSA, longitudinal diameter (D1), vertical diameter (D2), and circularity of the median nerve would show significant changes under increasing maximum voluntary force (MVF) and using the dominant hand compared to the nondominant hand. Therefore, the main objective of this study was to investigate dynamic morphological changes of the median nerve in both wrists under different force exertions.

2 | Methods

This study was approved by the Research Ethics Committee of the Faculty of Design, Kyushu University (approval no. 555).

2.1 | Participants

Twenty healthy undergraduate and graduate students (male = 10, female = 10) were recruited by convenient sampling and provided written informed consent before their participation. The only inclusion criteria were ability and willingness to provide informed consent and above 20 years of age. The exclusion criteria for participation were: (1) previous CTS, (2) wrist injury history by self-report, and (3) positive results from Phalen's Test or Tinel's Sign. Physical anthropometry characteristics were recorded (height and weight), and the 10-item Edinburgh Handedness Inventory was used to identify participant handedness [22]. Table 1 presents the participants' demographic data.

We initially calculated that a sample size of $n = 15$ by G*Power software (version 3.1.9.7, Heinrich Heine University Düsseldorf, North Rhine-Westphalia, Germany) would achieve a statistical power of 0.80 to detect an effect size of $f = 0.3$ at a significance level of 0.05. To enhance the study's sensitivity, we increased the sample size to $n = 20$. This adjustment raised the statistical power to 0.92 for the same effect size or allowed for the detection of a smaller effect ($f = 0.25$) while maintaining a power of 0.80.

2.2 | Experimental Setup

A digital grip dynamometer (T.K.K.5710b; Takei Scientific Instruments, Japan) secured to a table was used to measure grip force. Participants were seated at the table facing the dynamometer and placed their distal forearm and hand on a support, which stabilized their wrist in a neutral position (i.e., 0° wrist flexion/extension and radioulnar deviation). Grip force was measured within the same test apparatus for both the dominant and nondominant hand. Electrical signals obtained by the digital grip dynamometer were amplified (T.K.K.1268; Takei Scientific Instruments, Japan), sampled by an A/D converter at 1000 Hz (PowerLab PL3508; ADInstruments, Sydney, Australia), and visually displayed in LabChart software (v7.3.8; ADInstruments, Sydney, Australia) by a display monitor, which was placed on the table to show each participant their real-time grip force measured from the digital grip dynamometer (Figure 1). The current study involved ultrasound scans and analysis of two grip states and five force levels to measure median nerve morphological changes. The grip states were selected as: (1) the moment when grip force was sustained (grip condition) and completely relaxed (real time grip force ≈0 N for the first time, relaxed condition) (Figure 2).

2.3 | Experimental Procedure

Each participant took part in one experimental session, which started with a familiarization protocol within the experimental setup, including wrist position, gripping movements, and observation of real-time grip force showed by the monitor. The experimental session included ultrasound examination without

TABLE 1 | Mean (± SD) demographic data of the participants ($n = 20$).

Variable		All ($n = 20$)	Male ($n = 10$)	Female ($n = 10$)
Age (years)		25.3 ± 4.2	25.2 ± 3.7	25.2 ± 5.1
Height (cm)		167.6 ± 12.0	177.0 ± 8.1	158.1 ± 6.4
Weight (kg)		63.5 ± 11.7	72.8 ± 7.7	54.1 ± 6.1
BMI (kg/m^2)		22.5 ± 2.1	23.2 ± 1.6	21.7 ± 2.4
Handedness	Right-handed	20	10	10

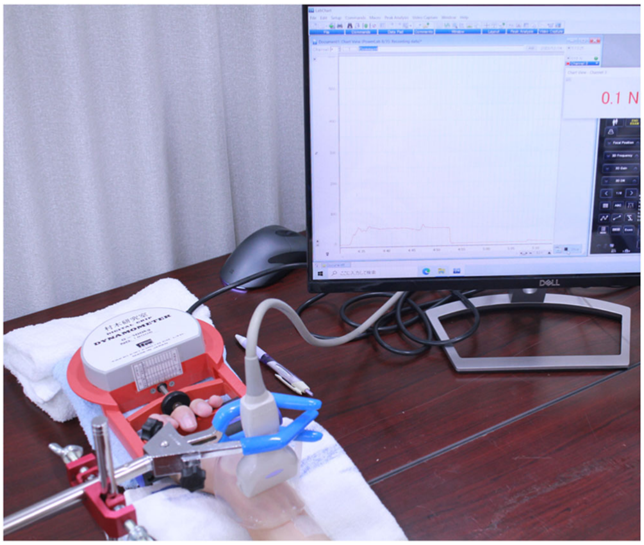

FIGURE 1 | Grip force measurement with the digital grip dynamometer. When participants were asked to hold the dynamometer without grip force, the display monitor showed real-time grip force of 0.1N (relaxed ≈0N).

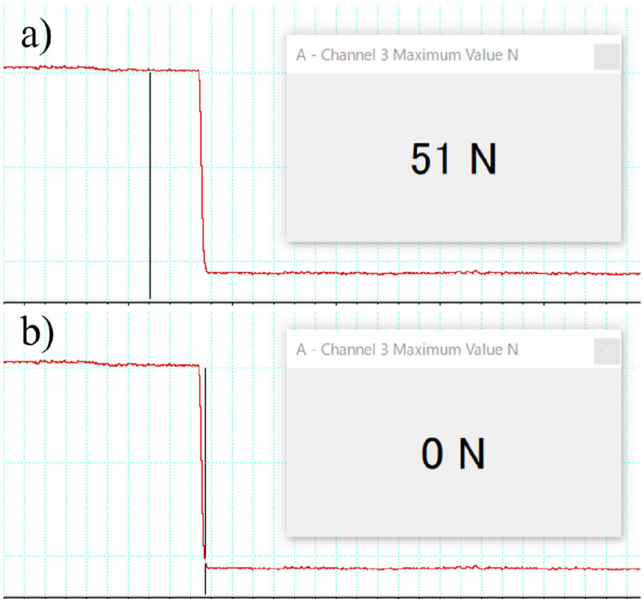

FIGURE 2 | Determination of grip and relaxed conditions in a grip task record: (a) grip condition when the target grip force was sustained; (b) relaxed condition when grip force was completely relaxed (real time grip force ≈0N for the first time). Red line, grip force record; Black line (horizontal), timeline; Black line (vertical), sampling point.

grip force (baseline ≈0% MVF) as well as ultrasound examinations at specified target grip forces (25%, 50%, 75%, and 100% MVF), including at both grip state time points (grip condition followed by relaxed condition) as previously described above. All grip tasks and ultrasound examinations (baseline ≈0%, 25%, 50%, 75%, and 100% MVF) were repeated three times. Among the specified target grip forces, participants were first required to perform their MVF trials, with the average of the three trials recorded as 100% MVF. The subsequent target force sequence was set to 25%, 50%, and 75% MVF, with a 1-min rest period following each grip task to prevent fatigue development due to sustained high grip force levels. For each experimental session, all grip tasks and ultrasound scans were duplicated, once for the dominant hand and wrist, and once for the nondominant hand and wrist.

2.4 | Ultrasound Image Acquisition

Ultrasound examinations were performed with the Viamo Portable ultrasound system (Canon Medical Systems, Tochigi, Japan) equipped with a PLT-1204ST linear transducer. During each ultrasound exam, in addition to ultrasound gel, a 7.0 mm thick sonar pad (Nippon BXI Inc., Tokyo, Japan) was used as a coupling agent to ensure good acoustic coupling between the transducer and the skin while minimizing compressive force from the transducer (Figure 1). The ultrasound transducer was set in place via a 3-prong adjustable clamp attached to the testing apparatus, with the transducer fixed parallel to the distal wrist crease to identify the median nerve in the transverse plane at the proximal carpal tunnel. The ultrasound scanning parameters in this experiment included a scanning acquisition frequency of 12 MHz and video framerate of 20 fps. The total scanning depth was set to 30.0 mm, with the scanning depth of interest set to the median nerve (usually 10.0 mm) to best observe median nerve morphological changes (both depths include the 7.0 mm thick sonar pad).

In each task, once the specified target force was achieved, the participant was required to continue sustaining the target force for at least 3 s. During this time, a 3-second video was collected while the participant sustained the target force. Afterwards, participants were asked to relax their grip force, and during this time another 3-second video was collected, which included the moment when the grip force became completely relaxed. Due to the synchronous collection of the grip dynamometer and ultrasound system, image samples were taken in the videos at the time points closest to the specified target force (Figure 2a) and complete relaxation (Figure 2b), which were used as the ultrasound images for subsequent analysis.

2.5 | Ultrasound Image Analysis

For all collected ultrasound images (Figure 3a), the examiner traced the median nerve along its hyperechogenic border using ImageJ (version 1.53t, National Institutes of Health, Bethesda, MD, USA) to measure the MNCSA and median nerve circularity (defined as 4π (MNCSA/median nerve perimeter^2); values ranging from 0 to 1; 1 = perfect circle) (Figure 3b) [23, 24]. After tracing the median nerve, the OpenCV library (version 4.7.0) accessed with a Python (version 3.11.4) script was used to quantify the longitudinal diameter (D1) and vertical diameter (D2) using the minimum bounding rectangle method (Figure 3c) [25]. The average of the three images was calculated for MNCSA, D1, D2, and circularity for each task.

2.6 | Statistical Analyses

Statistical analysis was performed using SPSS version 24.0 software (IBM Corporation, Chicago, IL, USA). One-way repeated

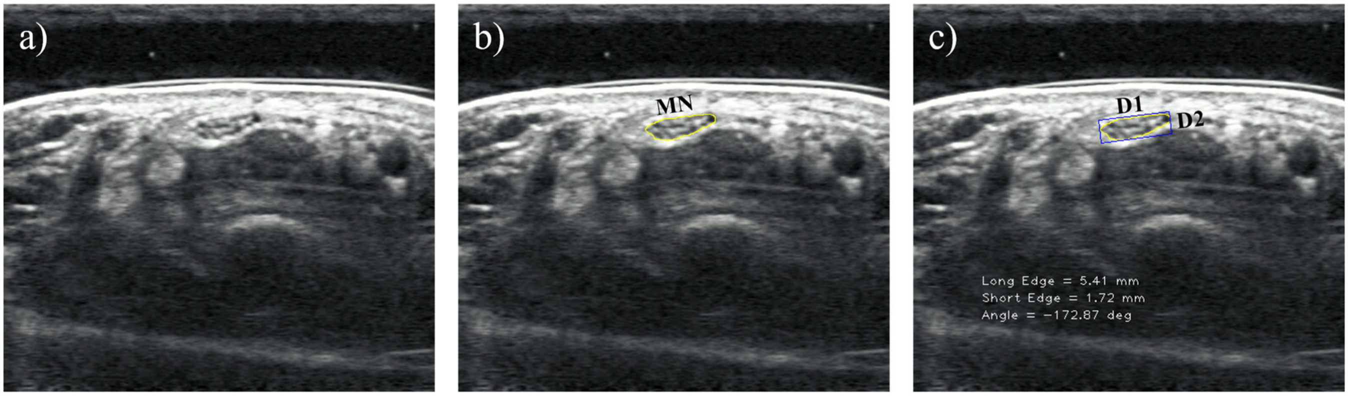

FIGURE 3 | Ultrasound images in this study: (a) original ultrasound image; (b) outline traced by ImageJ; (c) minimum bounding rectangle quantified by Python.

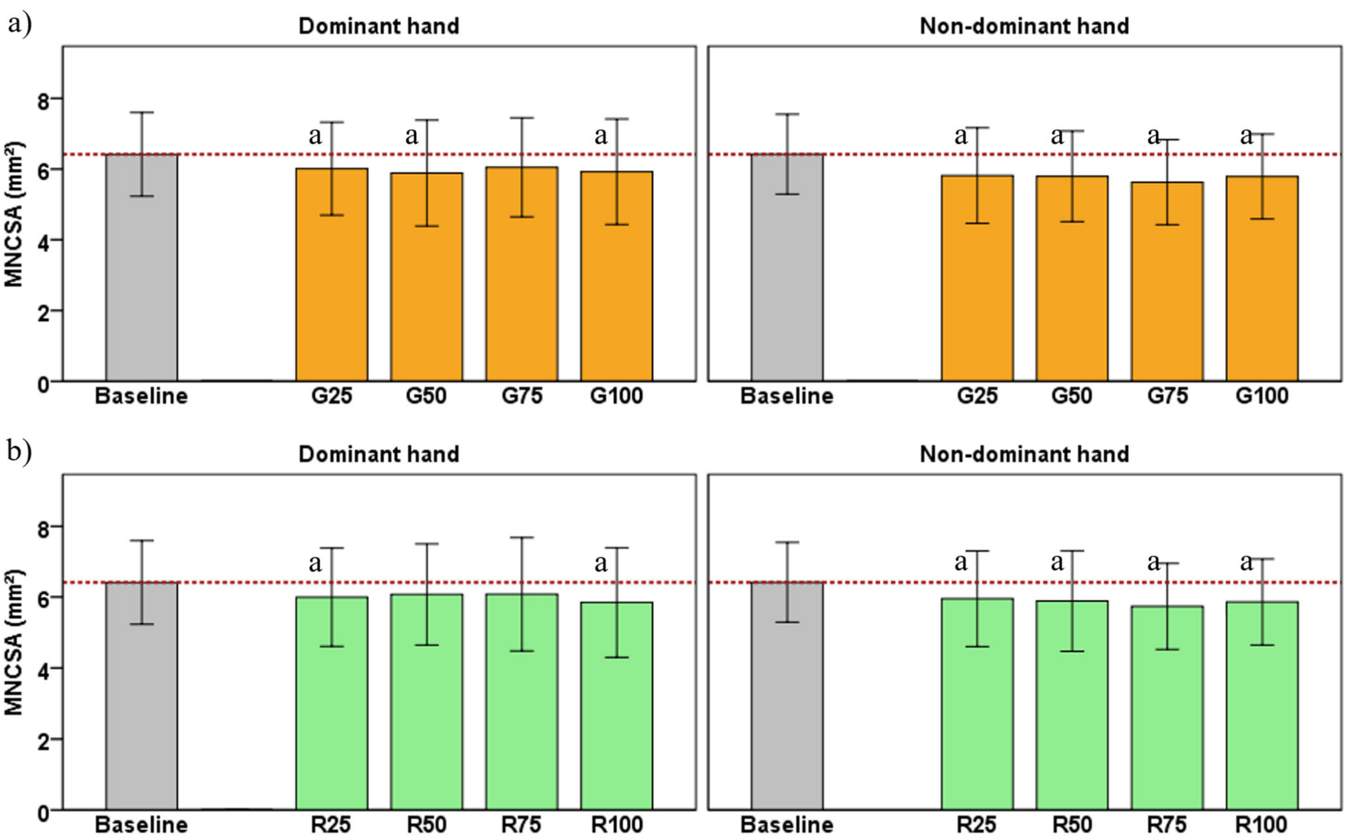

FIGURE 4 | Comparison of MNCSA with baseline: (a) grip condition; (b) relaxed condition. a = MNCSA < baseline condition ($p < 0.05$), G = grip condition, R = relaxed condition.

measures ANOVA was used to evaluate changes from baseline under gripping and relaxed conditions separately. Furthermore, two-way repeated measures ANOVA, with grip states (grip and relaxed) and force levels (25%, 50%, 75%, and 100% MVF) as independent variables, was conducted to investigate the differences in MNCSA, D1, D2, and median nerve circularity during and after the grip task. All analyses were conducted separately for the dominant and nondominant hands. When Mauchly's test indicated a violation of the sphericity assumption, Greenhouse-Geisser correction was used in the analysis of variance. Bonferroni pair-wise comparisons were used for post-hoc testing at a significance level of 95% ($p < 0.05$). All data were expressed as the mean ± SD.

3 | Results

3.1 | Median Nerve Cross-Sectional Area

MNCSA results are presented in Figures 4 and 5; Table 2. Overall, MNCSA was lower at specified target force levels (25%–100% MVF) compared to the initial baseline condition (≈0% MVF). As depicted in Figure 4, these reductions with the target force levels relative to the baseline were observed during both the sustained grip condition (dominant, F [2.8, 52.5] = 5.692, $p = 0.002$, nondominant, F [4.0, 76.0] = 12.013, $p < 0.001$) and during the following relaxed condition (dominant, F [2.6, 49.1] = 5.743, $p = 0.003$, nondominant, F [4.0, 76.0] = 10.281, $p < 0.001$).

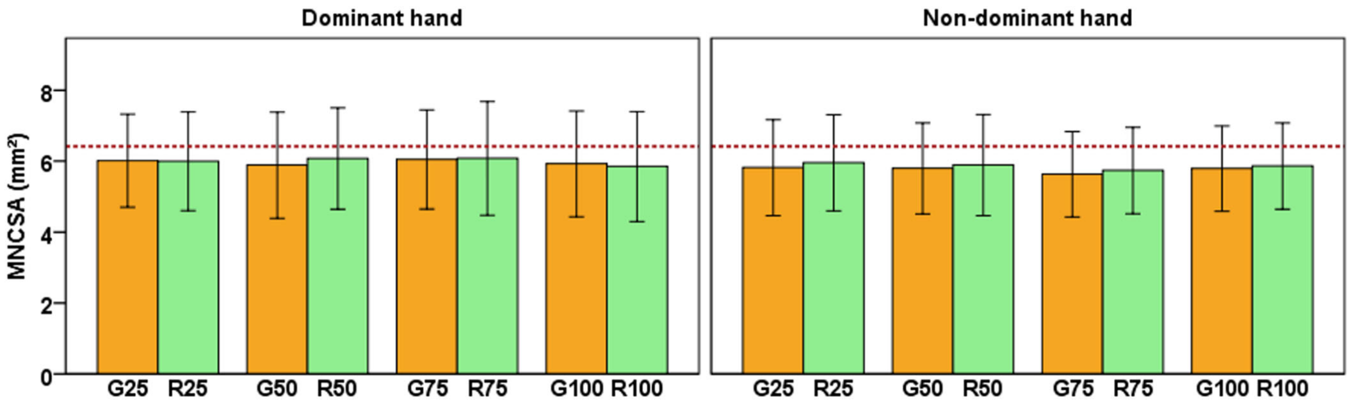

FIGURE 5 | Differences in MNCSA during and after the grip task. G = grip condition, R = relaxed condition.

TABLE 2 | Median nerve cross-sectional area (MNCSA) (mm^2) at different force levels.

Hand	Force level	All relaxed	Grip	Relaxed
Dominant	Baseline (0%)	6.41 ± 1.18	—	—
($n = 20$)	25%		6.01 ± 1.31	6.00 ± 1.39
	50%		5.89 ± 1.50	6.07 ± 1.43
	75%		6.05 ± 1.40	6.08 ± 1.60
	100%		5.92 ± 1.49	5.85 ± 1.55
Nondominant	Baseline (0%)	6.42 ± 1.13	—	—
($n = 20$)	25%		5.82 ± 1.35	5.95 ± 1.35
	50%		5.80 ± 1.28	5.89 ± 1.42
	75%		5.63 ± 1.20	5.73 ± 1.22
	100%		5.79 ± 1.20	5.86 ± 1.22

However, no significant differences were observed between during and after the grip tasks at different force levels for both the dominant and nondominant hands (Figure 5). Specifically, there were no significant main effects of grip state (dominant, F [1.0, 19.0] = 0.168, $p = 0.687$, nondominant, F [1.0, 19.0] = 1.591, $p = 0.222$), or force level on MNCSA (dominant, F [2.0, 37.8] = 1.365, $p = 0.268$, nondominant, F [3.0, 57.0] = 1.497, $p = 0.225$). Finally, the grip state × force level interaction term was not significant for either hand (dominant, F [3.0, 57.0] = 1.588, $p = 0.202$, nondominant, F [3.0, 57.0] = 0.145, $p = 0.933$).

3.2 | Longitudinal Diameter (D1)

D1 results are presented in Figures 6 and 7; Table 3. Compared to baseline, D1 was smaller under both grip and relaxed conditions, but generally these differences did not reach significance. For example, while the 1-way ANOVA achieved statistical significance for the dominant hand under the grip condition (F [4.0, 76.0] = 4.274, $p = 0.004$), post-hot testing did not reveal any significant differences between each target force in comparison to baseline (Figure 6). Furthermore, no significant effects were found for the dominant hand under the relaxed condition (F [2.5, 48.1] = 0.522, $p = 0.639$) or the nondominant hand (grip condition, F [4.0, 76.0] = 2.214, $p = 0.075$, relaxed condition, F [4.0, 76.0] = 1.720, $p = 0.154$).

For the dominant hand, there was a significant main effect of grip state (F [1.0, 19.0] = 8.364, $p = 0.009$) on D1, while a force level main effect (F [3.0, 57.0] = 1.011, $p = 0.394$) and a grip state × force level interaction (F [1.6, 31.2] = 0.503, $p = 0.574$) were not found. With respect to grip state, D1 increased significantly in the relaxed versus sustained grip condition, returning to the same value as baseline ≈0% MVF (Figure 7). Conversely, for the nondominant hand, there were no significant main effects for grip state (F [1.0, 19.0] = 2.122, $p = 0.162$) and force level (F [3.0, 57.0] = 0.234, $p = 0.872$) on D1; likewise, the grip state × force level interaction term was not significant (F [3.0, 57.0] = 1.066, $p = 0.371$).

3.3 | Vertical Diameter (D2)

D2 results are presented in Figures 8 and 9; Table 4. While the one-way ANOVA with the baseline condition and the specified target force conditions achieved significance for the dominant hand under the relaxed condition (F [2.2, 41.5] = 4.157, $p = 0.020$), post hoc testing again showed no significant differences between any of the target forces compared to baseline (Figure 8). In addition, no significant effects were found for the dominant hand under the grip condition (F [4.0, 76.0] = 0.417, $p = 0.796$) or the nondominant hand (grip condition, F [2.4, 46.0] = 2.186, $p = 0.114$, relaxed condition, F [4.0, 76.0] = 2.495, $p = 0.050$).

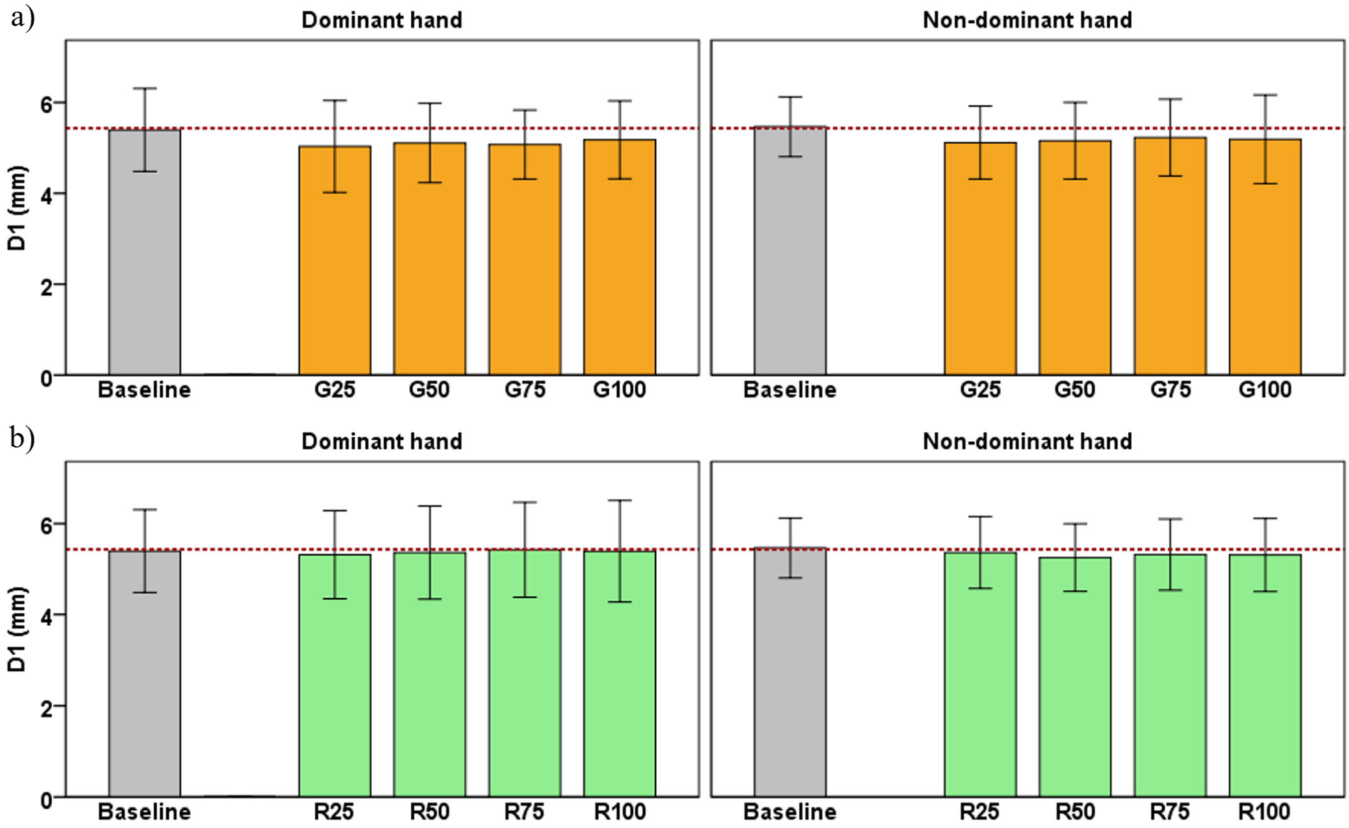

FIGURE 6 | Comparison of D1 with baseline: (a) grip condition; (b) relaxed condition. G = grip condition, R = relaxed condition.

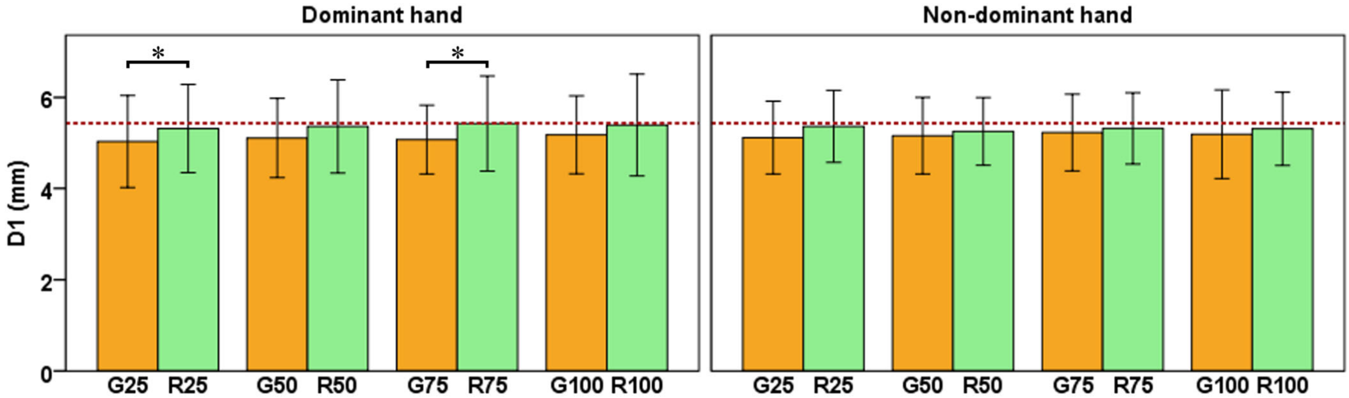

FIGURE 7 | Differences in D1 during and after the grip task. G = grip condition, R = relaxed condition, *, significant difference ($p < 0.05$).

For the dominant hand, there was a significant main effect of grip state on D2 (F [1.0, 19.0] = 5.528, $p = 0.030$); however, the main effect of force level was not significant (F [3.0, 57.0] = 1.425, $p = 0.245$). Likewise, the grip state × force level interaction was not significant (F [1.7, 33.2] = 0.238, $p = 0.760$). With respect to grip state in the dominant hand, D2 became smaller when grip force was relaxed at any force level; however, a significant difference was only achieved at 100% MVF (Figure 9). In contrast, for the nondominant hand, there was no significant main effect of grip state on D2 (F [1.0, 19.0] = 0.022, $p = 0.884$). The main effect of the force level on D2 in the nondominant hand was not significant (F [1.6, 30.8] = 1.883, $p = 0.175$). Once again, for the nondominant hand, there was no significant grip state × force level interaction (F [3.0, 57.0] = 0.348, $p = 0.791$).

3.4 | Median Nerve Circularity

Median nerve circularity (defined as 4π [MNCSA/median nerve perimeter^2]; values ranging from 0 to 1; 1 = perfect circle) results are presented in Figures 10 and 11; Table 5. Similar to results for D2, 1-way ANOVA with the baseline and the force level conditions achieved statistical significance, but only for the dominant hand under the relaxed condition (F [4.0, 76.0] = 5.083, $p = 0.001$, Figure 10). In contrast, no significant effects were found for the dominant hand under the grip condition (F [4.0, 76.0] = 0.963, $p = 0.433$) or the nondominant hand (grip condition, F [2.7, 51.6] = 0.837, $p = 0.470$, relaxed condition, F [4.0, 76.0] = 2.149, $p = 0.083$).

TABLE 3 | Longitudinal diameter (D1) (mm) at different force levels.

Hand	Force level	All relaxed	Grip	Relaxed
Dominant	Baseline (0%)	5.40 ± 0.91	—	—
($n = 20$)	25%		5.03 ± 1.01	5.31 ± 0.97
	50%		5.11 ± 0.87	5.36 ± 1.03
	75%		5.07 ± 0.76	5.42 ± 1.05
	100%		5.18 ± 0.86	5.39 ± 1.12
Nondominant	Baseline (0%)	5.46 ± 0.66	—	—
($n = 20$)	25%		5.12 ± 0.80	5.36 ± 0.79
	50%		5.16 ± 0.84	5.25 ± 0.75
	75%		5.23 ± 0.84	5.32 ± 0.78
	100%		5.19 ± 0.97	5.31 ± 0.81

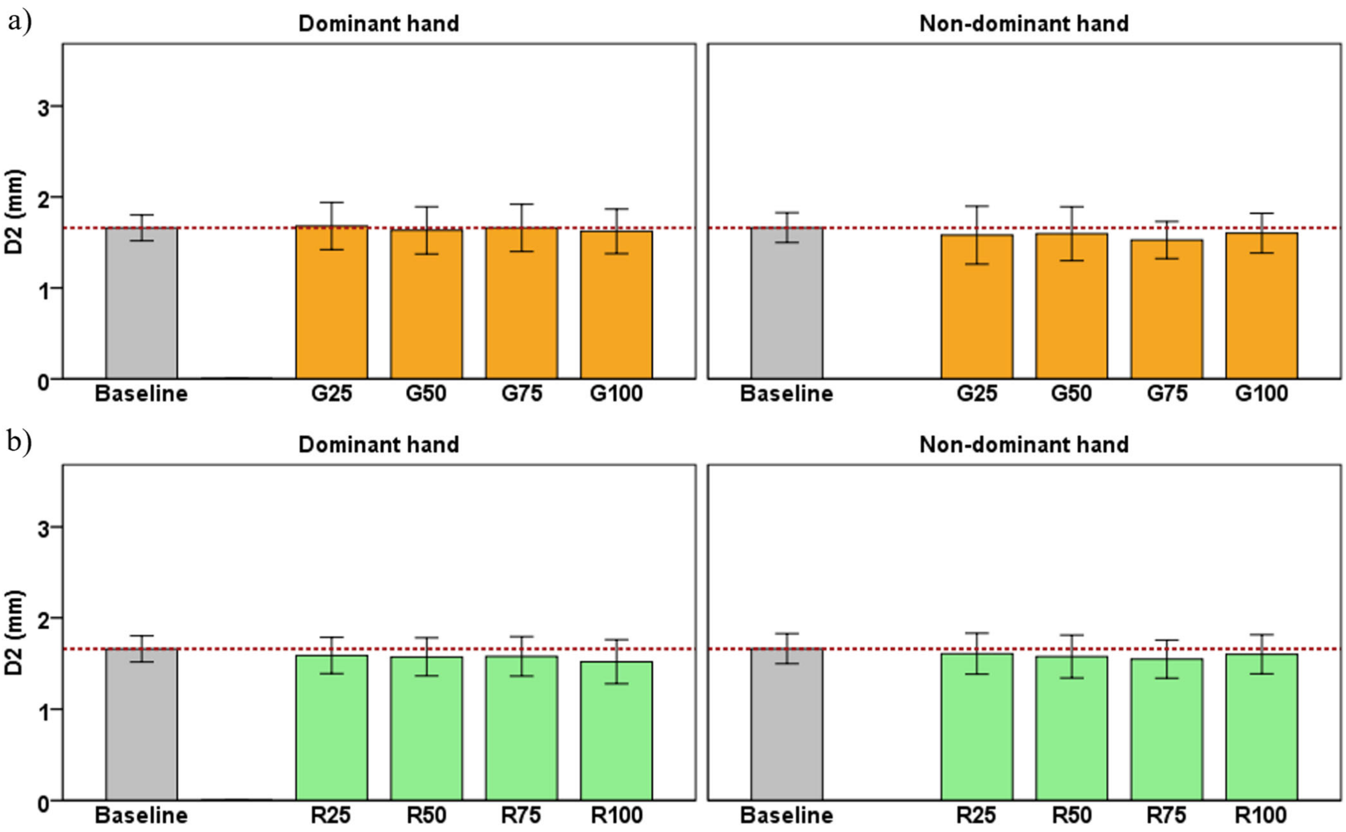

FIGURE 8 | Comparison of D2 with baseline: (a) grip condition; (b) relaxed condition. G = grip condition, R = relaxed condition.

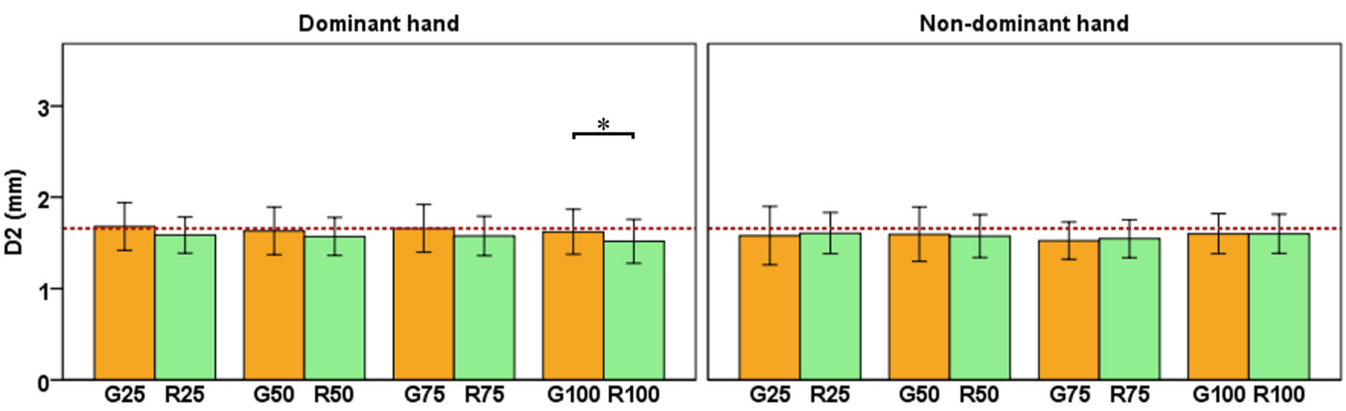

FIGURE 9 | Differences in D2 during and after the grip task. G = grip condition, R = relaxed condition, *, significant difference ($p < 0.05$).

TABLE 4 | Vertical diameter (D2) (mm) at different force levels.

Hand	Force level	All relaxed	Grip	Relaxed
Dominant	Baseline (0%)	1.66 ± 0.14	—	—
($n = 20$)	25%		1.68 ± 0.26	1.59 ± 0.20
	50%		1.63 ± 0.26	1.57 ± 0.21
	75%		1.66 ± 0.26	1.58 ± 0.22
	100%		1.62 ± 0.25	1.52 ± 0.24
Nondominant	Baseline (0%)	1.66 ± 0.16	—	—
($n = 20$)	25%		1.58 ± 0.32	1.61 ± 0.22
	50%		1.60 ± 0.30	1.58 ± 0.23
	75%		1.53 ± 0.20	1.55 ± 0.21
	100%		1.60 ± 0.22	1.60 ± 0.21

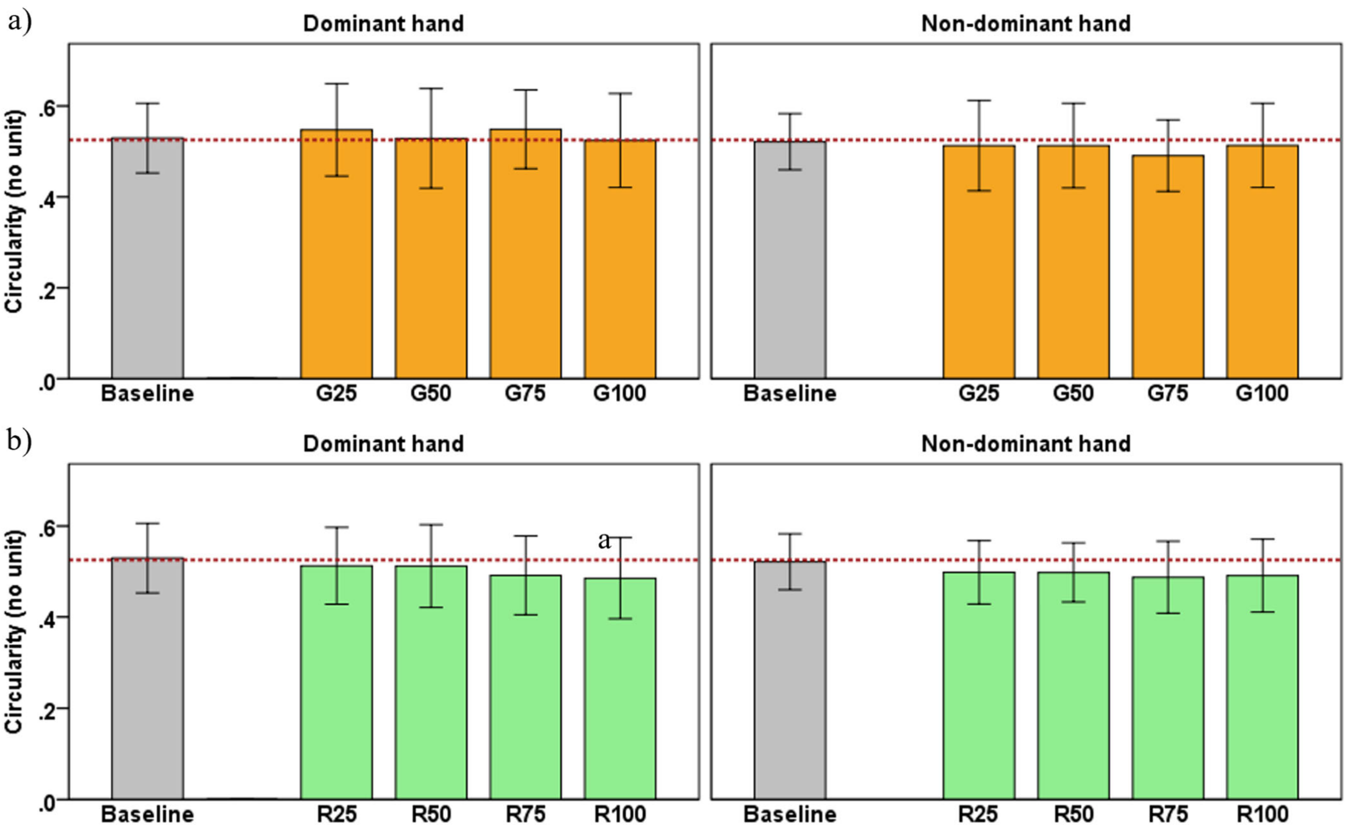

FIGURE 10 | Comparison of circularity with baseline: (a) grip condition; (b) relaxed condition. a = MNCSA < baseline ($p < 0.05$), G = grip condition, R = relaxed condition.

For the dominant hand, grip state had a significant main effect on circularity (F [1.0, 19.0] = 6.409, $p = 0.020$). While force level did not affect circularity (F [3.0, 57.0] = 2.607, $p = 0.060$), and there was no significant grip state × force level interaction on median nerve circularity (F [3.0, 57.0] = 1.691, $p = 0.179$). More specifically, the relaxed grip state resulted in lower circularity (i.e., the median nerve was flatter) compared to the preceding sustained force grip state in the dominant hand, but only at the 75% MVF and 100% MVF grip force levels. On the contrary, for the nondominant hand, there were no significant main effects of grip state (F [1.0, 19.0] = 0.989, $p = 0.333$) and force level (F [2.0, 38.9] = 0.872, $p = 0.429$), and no significant interaction between grip state × force level (F [3.0, 57.0] = 0.591, $p = 0.623$) on median nerve circularity.

4 | Discussion

Previous work has demonstrated the effectiveness of MNCSA in diagnosing CTS. Specifically, it has been found that the average MNCSA at the proximal carpal tunnel is less than 9 mm^2 in healthy wrists, while a threshold of 9–10.5 mm^2 is considered to have adequate diagnostic performance in the general population [17, 26]. However, the reference range for MNCSA is

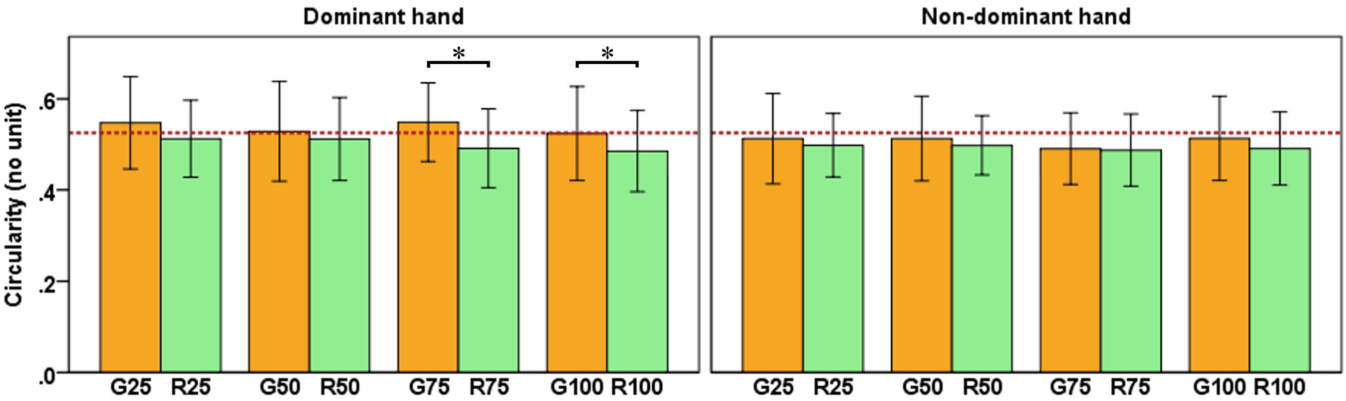

FIGURE 11 | Differences in circularity during and after the grip task. G = grip condition, R = relaxed condition, *, significant difference ($p < 0.05$).

TABLE 5 | Median nerve circularity (no unit) at different force levels.

Hand	Force level	All relaxed	Grip	Relaxed
Dominant	Baseline (0%)	0.53 ± 0.08	—	—
($n = 20$)	25%		0.55 ± 0.10	0.51 ± 0.08
	50%		0.53 ± 0.11	0.51 ± 0.09
	75%		0.55 ± 0.09	0.49 ± 0.09
	100%		0.52 ± 0.10	0.49 ± 0.09
Nondominant	Baseline (0%)	0.52 ± 0.06	—	—
($n = 20$)	25%		0.51 ± 0.10	0.50 ± 0.07
	50%		0.51 ± 0.09	0.50 ± 0.07
	75%		0.49 ± 0.08	0.49 ± 0.08
	100%		0.51 ± 0.09	0.49 ± 0.08

influenced by demographic characteristics [12]. In fact, a 20.7 mm^2 MNCSA at the proximal carpal tunnel has been observed in healthy individuals, which is nearly twice the aforementioned threshold [27].

In this study, we compared the changes in MNCSA, median nerve diameters (D1 and D2), and median nerve circularity between different grip force levels, including when the specified grip force was sustained followed by when the grip force became relaxed. The obtained parameter values were consistent with previous study on gripping, demonstrating the repeatability of these parameters [28]. For both the dominant and nondominant hands, at all force levels (25%–100% MVF), we found that MNCSA decreased relative to the baseline condition ≈0% MVF. However, for diameters and circularity, only the dominant hand showed significant changes.

4.1 | Bilateral Asymmetry of the Median Nerve Throughout the Grip Task

The significant differences in results between the dominant and nondominant hands expand the findings on bilateral asymmetry of the median nerve. It is well known that bilateral asymmetry is common in various parts of the human body, particularly in the upper limbs [29]. Due to the usage of the dominant hand in daily activities, the dominant hand also typically exhibits greater grip force and faster nerve conduction velocity [30, 31]. This suggests that similar bilateral asymmetry may result from differences in workload between the two hands. Previous studies quantifying static MNCSA showed significant differences between the two hands, particularly in a repetitive hand work group, with MNCSA being larger in the dominant hand than the nondominant hand [11, 32]. Our study results showed significant bilateral asymmetry in the diameters and circularity of the median nerve during grip tasks. In addition, our findings suggest that the median nerve exhibits bilateral asymmetry not only in static conditions, but also shows more pronounced deformation patterns in the dominant hand during dynamic conditions, such as the grip tasks in this study due to long-term hand usage.

4.2 | Relationship Between Median Nerve Compression and Grip Force

This study is consistent with the deformation pattern of the median nerve under similar grip tasks as reported in previous studies. As grip force increases from baseline to a specified target force relative to MVF, the MNCSA and D2 become smaller due to the transverse compressive stress exerted by the tendons [28, 33]. Furthermore, although the median nerve experiences transverse compressive stress in all directions of its cross-section, the radial-ulnar compressive stress appears to be significantly greater than the palmar-dorsal compressive stress. Evidence from this and other studies has observed greater circularity of the median nerve under grip conditions as the D2 (i.e., vertical) diameter decreased [33, 34]. The finger flexor tendons displace palmarly during gripping tasks, thereby occupying the space where the median nerve was previously located, subsequently necessitating the median to migrate in the radial-ulnar axis within the carpal tunnel [16]. In turn, the median nerve exhibits smaller MNCSA and greater circularity, generating greater elastic force to balance the compressive stress during sustained gripping.

In addition, grip tasks cause the finger flexor tendons and median nerve to glide proximally from the distal carpal tunnel, where the median nerve may have a larger cross-sectional area compared to the proximal carpal tunnel, and may potentially cause lumbrical muscles incursion into the carpal tunnel [12, 17, 35, 36]. However, in this study, there was no significant difference in MNCSA between specified grip forces, indicating that even the elastic force generated by median nerve deformation is not sufficient to counteract the transverse compressive stress from the flexor tendons. Therefore, the main reason for the compression on the median nerve in the grip tasks was the radial-ulnar stress caused by tendon displacement, followed by dorsal-palmar stress, and then proximal gliding of the median nerve. Nevertheless, this does not mean that proximal gliding is not important. The proximal carpal tunnel exhibits greater pressure than the distal carpal tunnel, and gliding will cause the distal median nerve to displace more proximally [37, 38]. The carpal tunnel during grip tasks has higher pressure, so although there was no observed change in MNCSA, the median nerve likely still experienced greater compressive stress.

4.3 | Difference Between Sustained and Relaxed Grip

The SSCT is a mesh-like tissue consisting of multiple layers of collagenous fibers, which loosely connects the tendons and nerves in a nonpathological state. Flexor tendon movement during hand and finger use cause vertical fibers between adjacent layers of the SSCT to become stretched layer by layer, beginning with the deepest layers closest to the tendons, as a means to reduce gliding friction [5, 39]. During tendon gliding associated with hand usage from a relaxed state to a movement state, accompanying longitudinal gliding and transverse plane displacement of the median nerve were also observed [40, 41]. It is likely that the accompanying median nerve displacement is due, in part, to inter-connections through the SSCT [42]. However, these studies have not focused on the recovery process from hand movement back to the relaxed state, even though this process is inherent in any hand movement. In this study, we established grip and relaxed conditions to reflect the behavior of the median nerve during this recovery process.

We found that for all median nerve diameter and circularity indicators, significant deformation of the median nerve between the sustained grip force condition and the following relaxed condition during the recovery phase only occurred in the dominant hand, and these findings may indicate early changes to the SSCT, including less tissue compliance or greater stiffness. Previous research has noted that changes in connective tissue dynamics and material properties observed in wrists already diagnosed with CTS often begins, or is more pronounced in, the dominant hand [43–45]. In healthy wrists, the SSCT may also be more strained along with more pronounced median nerve deformation caused by greater usage of the dominant hand. Moreover, we observed that the MNCSA in the relaxed state during the recovery process did not immediately return to the same level as the baseline ≈0% MVF condition. In previous research, this recovery process required 2 s or more [33]. Altogether, this suggests that during repetitive hand movements, compression of the median nerve and stretching of the SSCT may not completely dissipate before the next repetitive cycle of compression and stretching occurs. Therefore, during repetitive movements, tissues within the carpal tunnel may be exposed to greater loading, likely expediting pathological changes including median nerve ischemia as well as SSCT shearing damage that ultimately leads to thickening and fibrosis of the SSCT [46, 47]. Accordingly, we believe deformation changes in the median nerve throughout the entire period of active hand exertion, as well as the time required to recover to the original relaxed state, may serve as a stress indicator on the median nerve.

5 | Conclusion

Our study demonstrated that the median nerve undergoes deformation during grip exertion, sustained grip force, and use of the dominant hand. Additionally, varying levels of grip exertion influenced the percentage deformation of median nerve parameters. A notable limitation of this study was the small yet statistically significant difference observed in the 100% MVF between the dominant and nondominant hands (Mean ± SD, dominant hand, 221.8 ± 88.6 N, nondominant hand, 204.4 ± 77.3 N; Paired samples *t*-test, $p = 0.037$). However, we believe this minor difference had a negligible impact on the overall results. Next, pathological changes of CTS may influence the dynamic movements of the structures within carpal tunnel. Future research should investigate these dynamics across diverse age groups and among CTS patients to evaluate long-term changes in median nerve deformation and to explore the applicability of similar assessment methods in predicting nerve compression syndromes.

Author Contributions

Shengwei Li: study design, data acquisition, data analysis, data interpretation, manuscript drafting. **Aaron M. Kociolek:** data interpretation, manuscript editing. **Lizbeth Mariano:** data interpretation, manuscript editing. **Ping Yeap Loh:** study design, data interpretation, manuscript editing. All authors have read and approved the final submitted manuscript.

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