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Tactile sensory abilities in cerebral palsy: deficits in roughness and object discrimination

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Abstract

Motor deficits in cerebral palsy (CP) have been well documented; however, associated sensory impairment in CP remains poorly understood. We examined tactile object recognition in the hands using geometric shapes, common objects, and capital letters. Discrimination of tactile roughness was tested using paired horizontal gratings of varied groove widths passively translated across the index finger. We tested 17 individuals with hemiplegia (mean 13y 9mo [SD 5y 2mo]; 6 males, 11 females), 21 with diplegia (mean 14y 10mo [SD 7y]; 10 males, 11 females), and 21 without disabilities (mean 14y 10mo [SD 5y 1mo]; 11 males, 10 females). All participants with CP fell within level I or II of the Gross Motor Function Classification System and level I or II of the Manual Abilities Classification System. Individuals with CP were significantly less accurate compared with those without disabilities on all tactile object-recognition tasks using their non-dominant hand. Both groups of patients also had significantly higher thresholds for groove-width differences with both hands compared with those without disabilities. Within the group with diplegia, only roughness discrimination differed between hands, whereas within the group with hemiplegia, significant between-limb differences were present for all tasks. Despite mild motor deficits compared with the entire population of individuals with CP, this sample demonstrated ubiquitous tactile deficits.

Cerebral palsy (CP) encompasses non-progressive heterogeneous disorders of the developing central nervous system and is the most prevalent childhood physical disability, affecting 2 to 3 per 1000 live births.¹ The etiologies of diplegic and hemiplegic CP commonly involve pathology of the central nervous system that alters normal development of the somatosensory system. For example, recent diffusion tensor imaging in individuals with diplegic CP showed prominent damage to the thalamocortical projections to the somatosensory cortex, with less frequent severe damage to the corticospinal tracts, despite a history and clinical presentation consistent with motor tract injury.²

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Tactile input is used to localize and characterize the various qualities of touch. Cutaneous input also contributes to proprioceptive information for coordinated motor action.³ Bolanos et al.⁴ proposed that somatosensory testing be an important part of rehabilitation assessments because tactile discrimination and tactile object recognition are necessary for finger dexterity. Decreased somatosensory functioning of the hand (two-point discrimination, stereognosis, and pressure sensitivity) correlates with diminished dexterity of the affected hand in hemiplegic CP.⁵ A series of object manipulation studies found that children with CP inaccurately plan and scale the rate of grip, and that load force increases according to the object being grasped.⁶ The authors related this deficiency to impaired somatosensory perceptions.⁷ Therefore, numerous reports associate motor impairments to somatosensory deficits in CP, providing a rationale for the importance of assessing tactile sensitivity in this population.

With the exception of the studies on quantitative grip force^{6,7} and that by Krumlinde-Sundholm and Eliasson,⁸ which used established and novel measures to assess tactile sensibility and dexterity in children with hemiplegia compared with those without disabilities, most previous studies in CP examined tactile abilities using imprecise, non-standardized, or inadequately parameterized measures, and often failed to include normative data. Additionally, several studies combined data from various subtypes and severities of CP, ignoring the unique brain lesions associated with different CP subtypes. Furthermore, when the sample was narrowed to a single subtype, most studies focused on those with hemiplegia rather than diplegia, despite similar prevalence of both clinical conditions.¹

Previous studies found stereognosis and spatial acuity the most often and significantly impaired tactile modalities in CP.^{4,9} Stereognosis deficits have been identified in CP by using familiar objects and shapes, and spatial acuity deficits have been assessed with two-point discrimination.^{4,5,7-12} In hemiplegia, Semmes-Weinstein monofilaments and the Manual Form Perception Test¹³ have also revealed punctate tactile and stereognostic deficits respectively.^{7,8,12} However, evidence of tactile deficits in CP is largely contradictory, especially between studies that reported data from different types of assessment, but even among studies that used identical assessment tools. For example, Cooper and colleagues¹² reported no significant differences in stereognosis, proprioception, and light touch between hands in hemiplegia, whereas others showed significant differences between hands in these somatosensory modalities.⁵ Furthermore, contradictory reports of tactile deficits in the dominant hand in hemiplegia have included findings of deficiencies¹⁰ as well as intact tactile function.^{5,11} Most previous studies reported deficits in stereognosis and/or two-point discrimination for approximately 30 to 50% of people with CP,⁹ yet others reported much more prevalent tactile deficiencies.^{5,12} A paucity of standardized or sufficiently sensitive psychophysical assessments plausibly underlies the contradictory findings on impaired touch in CP. Tests of two-point discrimination are the most widely assessed tactile ability in many previous CP studies. However, standard two-point discrimination testing can be unreliable because application force varies across trials and testers,¹⁴ non-spatial cues exist from instrument vibration,¹⁵ two points (broad stimulus) versus one (narrow stimulus) stimulate different areal extents,¹⁶ and stimulation from pressure points can be non-synchronous.¹⁴

Johnson, Van Boven, Phillips (JVP) domes assess spatial discrimination with varying grating dimensions, while addressing the above limitations of two-point discrimination.¹⁷ Sanger and Kukke¹⁷ revealed spatial discrimination abnormalities in individuals with diplegia using JVP domes. However, half of the participants with diplegia in that study were unable to detect the largest grating, suggesting that commercially available JVP domes do not sensitively measure tactile abilities in diplegia. Similarly, our pilot testing showed JVP domes did not have wide enough groove widths to measure tactile abilities accurately in people with CP.

In the present study, we evaluated somatosensory tactile psychophysics in both hands of individuals with diplegia and hemiplegia and compared performance to an age-matched group without disability. We determined somatosensory abilities in individuals with clinically described diplegia or hemiplegia, who were within levels I or II on the Gross Motor Functional Classification System¹⁸ and Manual Ability Classification System.¹⁹ A mild subgroup was tested to differentiate motor from somatosensory deficits, which becomes more difficult as the degree of motor involvement increases. A larger effort will be needed to characterize somatosensory abilities in a wider range of severities and types of CP. Additionally, we obtained functional neuroimaging data from many of these same participants, which was possible in those able to maintain postural stability during scanning owing to fewer motor and tone abnormalities.

We assessed tactile identification of common objects, geometric shapes, raised letters, and discrimination of roughness. The three object recognition tasks were comparable to previous well-studied evaluations of the tactile shape recognition system²⁰ and were selected because of functional relevance to manual dexterity and everyday experience in CP. Collectively the touched objects varied in size, familiarity, and difficulty. Each task probed a different aspect of tactile processing. For example, tactile identification of common objects allows for familiarity to compensate for diminished sensations because the objects touched in the current study are commonly experienced haptically. Tactile experience is less with embossed geometric shapes and letters. The geometric shape task probed the effects of object size on tactile abilities parametrically with the hypothesis that haptic identification of smaller versus larger shapes would be more difficult. Finally, we hypothesized that the letter identification task would most sensitively reveal group differences because this task is the most novel by touch and requires integration of multiple tactile shape features before correctly naming the letter. Most people have little or no experience with touching embossed letters, where the tactile shape features of each letter must be felt, stored, and integrated before accessing sublexical brain centers to identify the letter.

A previously described sensitive assay of texture perception was a roughness discrimination task based on horizontal gratings of varying dimensions.^{21,22} This task minimizes the effects of application force variance with repeated applications and non-spatial cues, thereby avoiding the aforementioned limitations of classical two-point discrimination testing. Here, roughness perception is proportional to groove width, with larger groove widths perceived as being rougher.²³ Therefore discrimination thresholds are determined by varying felt groove-width differences to assess potential sensitivity differences between limbs and among groups. Groove widths chosen for this study were based on pilot testing in participants with CP and without disabilities and were aimed at approximating 75% performance accuracy for both hands, which is the Weber threshold commonly used for two-alternative forced choice tasks.²²

All tactile tests compared performance between dominant and non-dominant hands and among hemiplegia, diplegia, and control groups. We hypothesized that individuals with diplegia would be less proficient in tactile object recognition and exhibit higher thresholds for discrimination of differences in groove width compared with those without disabilities, and that participants with hemiplegia would be less proficient on their non-dominant hand compared with their dominant hand, and on both sides compared with those without disabilities.

Method

PARTICIPANTS

Fifty-nine individuals participated in this study. We examined 17 individuals with hemiplegia (i.e., unilateral involvement; mean age 13y 9mo [SD 5y 2mo]; 6 males, 11 females), 21 individuals with spastic diplegia (i.e., leg-dominated bilateral involvement; mean age 14y

10mo [SD 7y]; 10 males, 11 females), and 21 age-matched individuals without neurological or orthopedic disabilities (mean age 14y 10mo [SD 5y 1mo]; 11 males, 10 females). Participants either were recruited from the Pediatric Neurology Cerebral Palsy Center at St. Louis Children's Hospital or responded to a research study advertisement. All participants with CP ambulated independently, which indicated level I or II on the Gross Motor Function Classification System.¹⁸ All participants with diplegia or hemiplegia were level I or II on the Manual Ability Classification System.¹⁹ Additionally, school-age participants were in grade levels appropriate within two years of their age; all those over 21 were in or had completed college; and all reliably followed instructions and responded appropriately. Exclusion criteria included individuals with athetoid or quadriplegic CP, a history of selective dorsal rhizotomy, any upper or lower extremity surgery in the year before testing, botulinum toxin injections in the upper or lower extremities in the 6 months before testing, marked visual impairment, or damage to the inner ear.

All participants provided informed consent following guidelines approved by the Human Studies Committee of Washington University. Responses to a modified Edinburgh handedness inventory²⁴ assessed proportional hand dominance for each participant (a score of 100 indicates complete right-handedness, and a score of 0 indicates complete left-handedness). The hand with higher proportion of usage was considered the participant's dominant hand for all testing and analyses. All tactile sensitivity tests were administered in a single session.

TACTILE OBJECT RECOGNITION

Participants first identified groups of five common objects, followed by four embossed geometric shapes, and finally eight embossed capital letters. The test order followed probable decreasing prior familiarity with the touched objects. Objects touched within a group were presented in random order. The common objects were a key, penny, pencil, spoon, and button, and each was presented once. Common objects were individually mounted to a smooth, solid subsurface that constrained haptic explorations to the exposed object surface and sides. Embossed geometric shapes were a triangle, square, circle, and star. Shapes were replicated in varying sizes (15, 20, 30, 40mm in the longest axis); each shape/size object was presented twice. The embossed block capital letters were A, O, W, J, U, L, T, I, which previously were shown to be least confusable through touch.²⁵ The long axis of the Arial font letters was 8mm, and width varied by letter shape. Each letter was presented once. The geometric shapes and letters were raised about 0.8mm through photoetching a flexible, photopolymer subsurface. Therefore, all tactile objects were secured to a smooth, flat subsurface in an attempt to minimize the motor dexterity and exploratory strategy differences across sides and participants. The limb order (dominant vs non-dominant) for testing was determined randomly. Participants were allowed to touch an object actively and freely for 5 seconds before naming it. A curtain occluded vision of the tested hand and object. The number of correctly identified objects for each hand was recorded for analyses.

ROUGHNESS DISCRIMINATION

Participants judged whether paired horizontal grating stimuli were the 'same' or 'different' in roughness.²² Each grating surface was 22mm wide × 38mm long and had ridge widths of 0.25mm that were approximately 0.5mm high. Grating patterns were constructed through photoetching polyamide plastic on a metal backing (Nyloprint; Process Color Plate, Chicago, IL, USA). A 10mm space separated the paired grating surfaces. Roughness perception is proportional to groove width, with larger groove widths perceived as being rougher.²³ Groove widths were 2000, 1750, 1500, 1300, and 1100µm. Four paired grating surfaces had groove-width differences (GWDs) of 450, 500, 700 and 900µm, and four had paired grating surfaces with no GWDs (Table I). Thus, there were an equal number of trials with matched and unmatched groove widths for grating pairs. The dominant hand was tested first for each

participant. An examiner manually translated paired gratings in a direction perpendicular to grating ridge–groove orientation, proximal to distal across the index finger at a rate of about 30mm/s so that successive grating strips contacted and passed over the fingertip. Each paired grating was presented ten times in a random order with replacement. Among paired surfaces that differed in groove width, half of the trials were presented in the rough to smooth direction and half in the reverse direction. Participants sat with the elbow resting on a table and the tested hand and forearm in a neutral position with respect to pronation/supination; and the index finger was isolated by the examiner's thumb gently supporting the dorsal aspect of the proximal phalanx of the index finger. A curtain occluded vision of the tested hand. Mean performance was calculated and used to estimate the GWD that would yield 75% accuracy, as linearly interpolated from the slope of the acquired data. Post hoc analyses examined performance only on GWDs of 700µm and 900µm because of near chance accuracy for the patient groups on smaller GWDs.

STATISTICAL ANALYSES

One-tailed Mann–Whitney *U* tests examined pairwise differences within and between groups for each task. Each CP group was compared with those without disabilities but not with each other. Differences were significant when $p \leq 0.008$ (Bonferroni corrected for multiple comparisons, based on six comparisons per task).

Results

The analysis of performance on all tactile tasks revealed significantly more errors by individuals with CP on any task involving the non-dominant limb and several tasks involving the dominant limb even in hemiplegia (Fig 1–Fig 3). These results revealed sizeable tactile deficits in people with CP, even in presumed less-affected limbs. The following text describes findings for each CP subtype separately.

DIPLEGIA

Individuals with diplegia were significantly less accurate than those without disabilities when identifying any touched object with the non-dominant hand (Fig. 1; Table II). Group magnitude differences revealed lower median percentage accuracy in diplegia compared with those without disabilities by 20.0%, 12.5%, and 37.5%, on identification of common objects, geometric shapes, and letters, respectively. With the dominant hand, individuals with diplegia were significantly less accurate compared with those without disabilities when identifying geometric shapes and letters, with median accuracy differences of 6.25% and 25.0% respectively (Fig. 1b and c; Table II). A separate Kruskal-Wallis test of the effects of size and type of geometric shape for each group found no significant effect of these factors.

All groups performed at near chance level (50% accuracy) when judging whether gratings matched or differed when groove widths differed by 450µm (data points to the left of 500 in Fig. 2). Starting with gratings that differed by 500µm, the control group showed successively more accurate identification of non-matching gratings with progressively larger GWDs when using either hand (Fig. 2a). With the dominant hand, individuals with diplegia also showed better performance with larger GWDs, exceeding chance level with 500, 700, and 900µm GWD. Yet accuracy was always less than those without disabilities at every tested GWD (Fig. 2). Performance in diplegia with the non-dominant hand was at chance with all tested GWDs (not shown in Fig. 2). Possibly larger groove widths might have identified the 75% accuracy threshold for the non-dominant hand. Linear interpolation for results between 500 and 900µm GWD intersected the 75% accuracy threshold in those without disabilities at 733µm and 763µm for both hands and at 994µm GWD for the dominant hand in individuals with diplegia. A 75% threshold for the non-dominant hand could not be estimated. The group with diplegia performed

similarly to those without disabilities on the 500 μ m GWD, with accuracy at near chance level with both hands (Fig. 3a). Mann–Whitney *U* tests indicated that the group with diplegia was significantly less accurate compared with the control group for the non-dominant hand with the 700 μ m GWD (Fig. 3b; Table II) and for both hands with the 900 μ m GWD (Fig. 3c; Table II). On 900 μ m GWD, median percentage accuracy was lower in diplegia compared with those without disabilities by 10% and 40% with the dominant and non-dominant hand respectively. In the group with diplegia, median accuracy was 30% lower with the non-dominant compared with the dominant hand on 900 μ m GWD.

HEMIPLEGIA

Individuals with hemiplegia were significantly less accurate than those without disabilities when identifying any touched object with the non-dominant hand (Fig. 1a–c; Table II). Group magnitude differences revealed lower median percentage accuracy with the non-dominant hand in hemiplegia compared with those without disabilities by 40.0%, 37.5%, and 56.25%, on identification of common objects, geometric shapes, and letters respectively. With the dominant hand they also made significantly more errors when identifying letters (Fig. 1c; Table II), with a median accuracy 12.5% lower than those without disabilities. However, performance accuracy with the dominant hand was comparable to those without disabilities with common objects and geometric shapes (Fig. 1a, b; Table II). Like diplegia, the size and type of geometric shape were not significant factors in performance.

With the dominant hand, individuals with hemiplegia showed better performance with larger GWDs, but were always less accurate than those without disabilities at every tested GWD; accuracy exceeded chance levels only with the tested 700 μ m and 900 μ m GWD (Fig. 2). Performance with the non-dominant hand was below chance with all tested GWDs (not shown in Fig. 2). The linear extrapolated 75% accuracy threshold was 1008 μ m for the dominant hand and could not be determined for the non-dominant hand. The group with hemiplegia performed less accurately than those without disabilities on the 500 μ m GWD with both hands, but these differences did not reach significance (Fig. 3a). Mann–Whitney *U* tests indicated the hemiplegia group was significantly less accurate compared with the control group bilaterally with the 700 μ m and 900 μ m GWD (Fig. 3b, c; Table II). On the 900 μ m GWD, median percentage accuracy was lower in hemiplegia compared with those without disabilities by 20% and 50% with the dominant and non-dominant hand respectively. Accuracy with the dominant hand was also significantly better than with the non-dominant hand on the 700 and 900 μ m GWDs (Fig. 2). Within the group with hemiplegia, median accuracy was 30% lower with the non-dominant compared with the dominant hand on the 900 μ m GWD.

It is improbable that these between- and within-group differences arose from motor difficulties while performing the roughness discrimination task, because the task was passively administered and there were no significant group or limb differences on roughness discrimination when groove widths of paired gratings were the same (GWD=0).

Discussion

Individuals with CP exhibited tactile sensory deficits in both hands. The observed deficit magnitudes were surprising, especially for the dominant hand, given mild motor impairments in all participants with CP. For example, in diplegia, roughness discrimination and tactile object recognition of geometric shapes and embossed letters were deficient bilaterally; and in hemiplegia, haptic identification of embossed letters and roughness perception deficits were present bilaterally. The clinical significance of these findings on the dominant side in hemiplegia and the relation between somatosensory and motor deficits in all groups and limbs warrants further study.

Previous investigations of upper extremity touch in diplegia did not separate analyses by side of limb dominance but instead grouped results from both limbs or strictly by side (left and right), irrespective of predominant use. Examinations based on combined assessment of both upper limbs may overlook possible bilateral asymmetries in diplegia owing to asymmetrical brain injuries or differences in use. In contrast, studies of hemiplegia usually grouped data by limb dominance, typically using the clinical motor symptoms to determine affected side(s); (e.g., see Krumlinde-Sundholm and Eliasson⁸). We indexed hand dominance using a modified Edinburgh Handedness Inventory,²⁴ which indicates the limb (left or right) predominantly used during 12 common motor tasks (e.g., writing, throwing, and kicking). The Edinburgh Handedness Inventory validity in individuals with CP has not been established. However, the categorization of each participant's dominant side matched their reported or diagnosed less affected side. Limb dominance, however, does not imply normality, but simply identifies the limb used most successfully on motor tasks.

The non-dominant arm showed greater sensory impairments, but the dominant hand also was affected in diplegia. Observed deficits were consistent with previous reports of problems in identifying shapes, common objects, or in two-point discrimination thresholds.^{4,10,11} However, there were subtle differences between hands in diplegia. The non-dominant hand in diplegia was significantly less sensitive on all tactile tasks compared with those without disabilities. The dominant hand exhibited significant deficits on the geometric shapes, letters, and roughness discrimination tasks compared with those without disabilities. These findings suggest that the tests used were more sensitive than those used previously.

Individuals with hemiplegia have pervasive touch deficits of the non-dominant hand, as reported previously using clinically oriented tests.^{4,5,7–12} Previous reports are equivocal on touch deficits with the dominant hand in hemiplegia. Some investigators reported comparable touch sensitivity of the dominant hands in hemiplegia and control groups,^{8,11} whereas others found tactile perception deficits.¹⁰ In the present study, the letter identification and roughness discrimination tasks revealed significant deficits of the dominant hand in hemiplegia. Possibly these findings reflected that both tasks required attending to and remembering multiple tactile features, again emphasizing considerably heightened sensitivity over standard clinical assessments in revealing even bilateral upper limb touch deficits in hemiplegia.

The tasks used in the present study have been extensively vetted with neurologically normal individuals in studies involving recognition of shapes and common objects,²⁰ raised letters,²⁵ and surface roughness.²¹ Tasks using shapes and common objects probed recognition based on identifying a few contours that linked tactile input to extended prior experience and memory. Differences in object size or shape had no effect on performance on the geometric shapes task. The letter identification task most effectively revealed differences between limbs and among groups. The sensitivity of the letters task possibly reflected less familiarity with touching embossed letters and with its inherent complexity, which involves perceiving, remembering, and integrating multiple shape features (e.g. points, line orientations, spaces) before assembling a composite image that is compared against a sublexical memory. Similarly, using horizontal gratings to examine roughness perception provides an especially sensitive, parametric method for assessing tactile sensory abilities. It is a tactile test in which increasing the grating groove width increases perception of surface roughness.²³ Exposure to tactile gratings and judgments about surface roughness are probably atypical experiences with consequent infrequent categorization; therefore discrimination of roughness differences is relatively untainted by everyday lexical categories.

CLINICAL IMPLICATIONS

The tactile sensory impairments in both upper limbs of individuals with CP probably impact tactile guidance of the hands, especially in haptics, and possibly contribute to awkward

dexterity owing to diminished sensory information when touching objects. Thus a clinical presentation of diminished motor coordination might be considered a combined sensorimotor deficit. The effects of diminished somatosensory input on motor function in CP require further examination. These results recommend that clinical assessments be broadened to include psychophysical somatosensory testing of all limbs in CP. The tasks used here can be adapted for clinical use to detect differences between individuals and between limbs for an individual. Letter identification and roughness discrimination tasks sensitively detected subtle tactile deficits, even in individuals with mild diplegia or hemiplegia. The functional relevance of tactile deficits, particularly for individuals with CP with greater motor involvement who are likely to have even more pronounced sensory impairment, warrants further investigation.

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Figure 1. Performance accuracy median and 95% confidence intervals on (a) common object, (b) geometric shape, and (c) letter identification tasks. Bar graphs are plotted separately by group for dominant (filled) and non-dominant (hatched) hands. p values have been Bonferroni corrected for six comparisons.

Figure 2.

Mean percentage correct on roughness discrimination. Intersection of vertical lines with the 75% accuracy level indicates the GWD 75% threshold for each group. For the control dominant (CD) and non-dominant (CN) hands, interpolated thresholds were 733μm and 763μm respectively. For the dominant hands in diplegia (DD) and hemiplegia (HD), extrapolated 75% thresholds were 994μm and 964μm respectively. Seventy-five percent thresholds could not be extrapolated for the non-dominant hands in diplegia (DN) and hemiplegia (HN) because performance with these hands was near chance level; therefore these data are not shown.

Figure 3.

Group differences in roughness discrimination. Performance accuracy median and 95% confidence intervals on the roughness discrimination task with groove-width difference (GWD) of (a) 500, (b) 700, and (c) 900µm. Bar graphs are plotted separately by group for dominant (filled) and non-dominant (hatched) hands. p values have been Bonferroni corrected for six comparisons.

Table 1
Roughness discrimination groove widths and corresponding groove-width differences

Groove width (μm)	2000	1750	1500	1300	1100
2000	0	—	500	700	900
1750	—	0	—	450	—
1500	—	—	0	—	—
1100	—	—	—	—	0

Table II
Pairwise differences in accuracy within and between groups on each tactile task examined with Mann–Whitney *U* tests

	CD-DD		CN-DN		DD-DN		CD-HD		CN-HN		HD-HN	
	% diff*	p	% diff	p	% diff	p	% diff	p	% diff	p	% diff	p
Common objects	0.0	0.359	20.0	<0.001	20.0	0.202	0.0	0.181	40.0	<0.001	40.0	<0.001
Geometric shapes	6.25	<0.001	12.5	<0.001	6.25	0.308	0.0	0.158	37.5	<0.001	37.5	<0.001
Letters	25.0	<0.001	37.5	<0.001	12.5	0.587	12.5	<0.001	56.25	<0.001	43.75	<0.001
Roughness (700µm)	10.0	0.050	20.0	0.045	10.0	0.999	10.0	0.544	30.0	0.028	20.0	<0.001
Roughness (900µm)	10.0	<0.001	40.0	<0.001	30.0	0.002	20.0	<0.001	50.0	<0.001	30.0	0.003

% diff, median percentage accuracy differences; *p* values are Bonferroni corrected for multiple comparisons.

Group and hand dominance: DD, diplegia dominant hand; DN, diplegia non-dominant hand; HD, hemiplegia dominant hand; HN, hemiplegia non-dominant hand; CD, control dominant hand; CN, control non-dominant hand.