Anatomical correlates of proprioceptive impairments following acute stroke: A case series

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A B S T R A C T

Background: Proprioception is the sensation of position and movement of our limbs and body in space. This sense is important for performing smooth coordinated movements and is impaired in approximately 50% of stroke survivors. In the present case series we wanted to determine how discrete stroke lesions to areas of the brain thought to be critical for somatosensation (thalamus, posterior limb of internal capsule, primary somatosensory cortex and posterior parietal cortex) would affect position sense and kinesthesia in the acute stages post-stroke. Given the known issues with standard clinical measures of proprioception (i.e. poor sensitivity and reliability) we used more modern quantitative robotic assessments to measure proprioception.

Methods: Neuroimaging (MRI, n = 10 or CT, n = 2) was performed on 12 subjects 2–10 days post-stroke. Proprioception was assessed using a KINARM robot within the same time frame. Visually guided reaching was also assessed to allow us to compare and contrast proprioception with visuomotor performance.

Results and Conclusions: Proprioceptive impairments were observed in 7 of 12 subjects. Thalamic lesions (n = 4) were associated with position sense (n = 1) or position sense and kinesthesia (n = 1) impairments. Posterior limb of the internal capsule lesions (n = 4) were associated with primarily position sense (n = 1) or kinesthesia (n = 2) impairments. Lesions affecting primary somatosensory cortex and posterior parietal cortex (n = 2) were associated with significant position sense and kinesthesia impairments. All subjects with damage to hypothesized structures displayed impairments with performance on the visually guided reaching task. Across the proprioceptive tasks, we saw that position sense and kinesthesia were impaired to differing degrees, suggesting a potential dissociation between these two components of proprioception.

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1. Introduction

Proprioception is a term used to describe the knowledge of the location and movement of our limbs in space [1]. Classically, it has been considered to have two subcomponents: position sense and kinesthesia. Position sense is the perception of static limb location, whereas kinesthesia is the sensation of limb or joint motion [2].

Proprioceptive impairment following stroke has been reported to occur in approximately 50% of patients [3–5]. While many post-stroke studies focus on motor function, impairments in proprioception have been linked to postural instability [6], impaired motor recovery [7], safety concerns, as well as longer hospital stays and decreased functional independence at discharge [8,9]. Proprioception can also predict long-term motor recovery after stroke [10,11] and has been strongly correlated with motor recovery of the hemiplegic arm after stroke [12]. However, the relationship between lesion location and specific proprioceptive impairment remains poorly understood.

Prior studies attempting to link neuroimaging and proprioception in stroke have relied on finger position sense or proprioception measured by standard clinical assessment [13–17]. These studies have reported proprioceptive impairments following thalamic lacunar stroke [14,15,17], posterior limb of the internal capsule stroke [16] and cortical stroke [13,16].

Most clinical tests of proprioception involve a patient’s ability to discriminate between the upward or downward position of a digit when passively moved [18]. This test and other clinical assessments of proprioception such as the thumb localizing test [19], are based on ordinal scales, show relatively poor inter-rater reliability and lack sensitivity.

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Further, these tools were not designed to differentiate between impairments in position sense and kinesthesia following stroke.

Robotic assessments have recently been developed to quantitate sensorimotor impairments following stroke [24,22,23]. These robotic assessments are relatively quick to administer and can quantitate position sense reliability [5], while also providing insight into other aspects of proprioception, such as kinesthesia [24]. Further, subjects can easily complete a brief battery of robotic tasks to assess various aspects of behavior, including motor function. This allows the observer to compare and contrast differences in sensory versus motor performance after a stroke. Pairing these assessment methods with lesion analysis after stroke may allow for an improved ability to interpret the behavioral consequences of a particular stroke lesion location.

The present study examined twelve stroke survivors with acute lesions to structures believed to be involved with proprioception and evaluated their performance on three different robotic tasks. Comparisons were made of the subjects’ performance on tasks measuring position sense, kinesthesia and a standard motor task (visually guided reaching). We hypothesized that damage to the following structures: ventral posterior lateral (VPL) nucleus of the thalamus, the posterior limb of the internal capsule (PLIC), the post-central gyrus (S1) and posterior parietal cortex (PPC) would produce measureable impairments in sensorimotor function. Further, we made comparisons to two acute stroke subjects without damage to these brain areas to demonstrate a behavioral dissociation based on lesion location.

2. Methods

2.1. Subjects

A total of 12 subjects with first diagnosis of clinical stroke were recruited from the Foothills Medical Centre (FMC) or the Dr. Vernon Fan ning Centre (VFC) in Calgary, Alberta, Canada. Ten cases were chosen based on lesions identified on neuroimaging to VPL thalamus, PLIC, S1 or PPC. Two cases were chosen because they had no damage to these regions. Subjects had no other neurological diagnoses (including previous stroke) and cognition and language were sufficient to follow the instructions required to complete the assessments. Neuroimaging was conducted a mean of 1.5 days (SD 2.2) post-stroke and clinical magnetic resonance imaging (MRI) or computed tomography (CT) scans were obtained according to the standard acute stroke protocol at the Foothills Medical Centre for use in the present study. Axial T2-weighted FLAIR (fluid attenuated inversion recovery) images were used to depict lesion location. Subjects participated in both a clinical and robotic assessment a mean of 7.3 days (SD 3.7) post-stroke. This study was approved by the University of Calgary Research Ethics Board.

2.2. Lesion Delineation

Although we based inclusion in the study on the appearance of the stroke lesions on the clinical neuroimaging scans, in order to accurately quantify the burden of lesion in our hypothesized areas we performed a region of interest (ROI) analysis. Regions of interest for each area (thalamus, posterior limb of the internal capsule, post-central gyrus and superior parietal lobe) were first drawn on the T1 Montreal Neurological Institute (MNI) template brain with MRICron [25] (www.mricron.com) using both a white matter atlas [26] and Myeloarchitectonic Atlas [27]. Lesion location of each subject was then demarcated directly on corresponding slices of the T1-weighted MNI template brain in MRICron by closely examining the FLAIR and diffusion weighted imaging (DWI) for those with MRI and CT for those without. This procedure is consistent with previously reported methods [28–30]. ROI analysis was performed using Non-Parametric Mapping (NPM) software (available with the MRICron software package). This provided the percentage of each ROI that was damaged in each subject and the percentage of an individual’s lesion that was located within the borders of each ROI. Lesion volume was also obtained through NPM.

2.3. Robotic Assessment

Robotic assessment was performed using a KINARM robotic exoskeleton (BKIN Technologies Ltd., Kingston, Ontario, Canada) (see Fig. 1A). Subjects were seated in the wheelchair base with both arms supported against gravity by the robotic exoskeleton in the horizontal plane (~80° shoulder flexion) and the exoskeleton was adjusted to fit each subject’s body dimensions (height, limb segment length) by the study therapist. The robot allowed subjects to move freely in the horizontal plane with flexion and extension movements of the elbow joints and shoulder joints. The KINARM monitored and recorded arm movement, and applied mechanical loads to the shoulder and elbow joints during passive movements used in the position matching and kinesthesia tasks.

2.4. Arm position matching task

The arm position matching task (Fig. 1B) was used to quantify position sense of the upper extremities. This task was performed without vision, as previously described in detail by Dukelow and colleagues [5]. The position matching task required the subject to move his/her unaffected/less affected arm (active arm) to mirror match the end position of the stroke affected arm that was passively moved by the KINARM (passive arm). The robot moved the subjects’ passive arm to nine different spatial locations pseudorandomly, with the subject matching each location with the active arm before moving onto the next trial. The passive arm was moved to each target 6 times for a total of 54 trials. Three parameters were derived from the end point position of the active hand for all trials. Variability in the x and y direction (varxy) measured trial to trial consistency of the end position of the active arm. Spatial contraction/expansion (cont/exprxy) measured the ratio of the total area of workspace matched by the active arm relative to the passive arm. Systematic shifts (shiftxy) measured consistent errors between active and passive arms. Consistent errors were measured as the mean error between passive and active hands for each target location across all trials in the x direction, y direction and combined xy. The average of these mean errors in the combined xy coordinate then denoted the magnitude of systematic shift. Normal ranges for each parameter were derived from the 95% confidence interval from 170 control subjects with consideration for age, sex and handedness [31]. Overall, we found that 95% of controls failed 1 or fewer parameters on the arm position matching task. Thus, we created a task failure threshold for subjects with stroke of 2 or more parameters [31].

2.5. Arm kinesthesia task

This kinesthesia task (Fig. 1C) was used to examine kinesthesia of the upper extremities. This task (also previously described) [24] was administered without vision of the upper extremities. This task required the subjects to use their active (unaffected/less affected) arm to mirror match the movement of their passive (stroke affected) arm that was being moved by the KINARM. Prior to the start of each trial, the subject’s hands were moved to one of three pre-set mirrored locations in the workspace. The passive arm was then moved to one of two other target locations by the robot and subjects were instructed to use their active arm to mirror match the speed, direction and distance of the movement as soon as they felt the robot move, thereby attempting to mimic the passive movement in real time. A total of 6 movement directions were performed 6 times each for a total of 36 trials.

Four parameters were used to measure the temporal and spatial (x,y) aspects of movements of each subject [24]: Response Latency (RL) — the time between movement initiation (point where subject reached 10% of hand speed maximum) of the passive arm and active arm. Peak Speed Ratio (PSR) — the ratio of maximum passive arm speed...
and maximum active arm speed. Initial Direction Error (IDEKIN) — the absolute angular deviation between passive and active hands at the point of hand speed maximum. Path Length Ratio (PLR) — the ratio between total movement length of the subject’s active arm and passive arm. The end of active movement was the point where the subject’s arm slowed to 10% of maximum hand speed after reaching maximum speed. Variability for all four of these parameters was also calculated as the standard deviation across all movements (RL variability (RLv), PSR variability (PSRv), IDEKIN variability (IDEv KIN), PLR variability (PLRv)) producing a total of eight parameters. Normal ranges for each measure were determined from the 95% confidence interval of 74 healthy control subjects [24]. Overall, we found that 95% of controls failed 2 or fewer parameters on the arm kinesthesia task. Thus, we created a task failure threshold for subjects with stroke of 3 or more parameters [24].

2.6. Visually Guided Reaching

Motor behavior was assessed with a visually guided reaching task (Fig. 1D) that has been previously described [23]. With full vision of arms and hands, subjects made movements with their stroke-affected arm from a central target located at approximately the centre of the arm’s workspace to one of eight peripheral visually presented targets as quickly and accurately as possible (Fig. 1D). All targets were red circles with a 1 cm radius. For the duration of the task, a white circle was used to represent the subjects’ index finger. To start each trial the subject placed the tip of their index finger in the central target for 1250 to 1750 ms. One of the eight peripheral targets was then illuminated and subjects were given 3000 ms to complete the reach (central target extinguished when hand exits target). Targets were presented in a random-block design along with two catch trials where no peripheral target was illuminated. This was repeated 8 times for a total of 80 trials for each arm.

Five movement parameters were recorded. These parameters have previously been described in detail [23]. Postural control was determined based on postural hand speed (PS) for 500 ms prior to target illumination. Reaction time (RT) was the time between peripheral target illumination and movement onset. Initial movement direction error (IDEVGR) was the angular deviation between subject’s initial movement path (point of first hand speed minimum) and the straight path to the target. The number of corrective movements was counted as the number of speed peaks per reach (NSP). Finally, total movement time (MT) was used as the total movement parameter. Normal control ranges for each parameter were determined as the 95% confidence interval derived from 231 healthy controls [32]. Overall, we found that 95% of controls failed 2 or fewer of these parameters on the visually guided reaching task. Thus, we created a task failure threshold for subjects with stroke of 2 or more parameters [32].

2.7. Clinical Assessment

Clinical assessments were performed by a trained study therapist. The Thumb Localizing Test (TLT) [19] was used to test upper extremity position sense of the stroke affected arm. It has been used previously in a number of studies on individuals with stroke [5,33,34]. During this test the subject’s eyes were closed and the therapist manipulated the
some lesion extension into surrounding structures in some cases. For example, the lesion in subject 4 primarily involved the thalamus yet there is some extension into the internal capsule as seen in Fig. 2. We also present two subjects with lesions outside of the areas hypothesized to be involved in proprioception (Fig. 5) for comparison.

Fig. 1 presents exemplary healthy, non-stroke control data for all 3 robotic tasks. Note the relatively small variability in errors made by the control subject in the position matching task as denoted by the standard deviation ellipses (Fig. 1B). The control subject easily mirrors the direction and path of movement in the kinesthesia task (Fig. 1C). The control exemplar also demonstrates relatively straight line reaching movements to all eight targets (Fig. 1D).

3.2. Thalamus

Fig. 2B displays performance for those subjects with lesions primarily involving the thalamus on the position matching task. The ROI analysis revealed both the percentage of the thalamus that was damaged (subject 1 = 1.6%, subject 2 = 12.1%, subject 3 = 21.7%, subject 4 = 54.5%) and the percentage of lesion that was located within the thalamus (subject 1 = 94.3%, subject 2 = 82.8%, subject 3 = 42.0%, subject 4 = 43.4%). Subject 1 was within normal ranges for all parameters tested. Subject 2 was found to contract the workspace (cont/exp_{xy} = 0.41) yet fell within normal ranges for the other two parameters. Subject 3 fell outside the normal range for variability between trials (var_{xy} = 10.6 cm) and contraction/expansion (cont/exp_{xy} = 0.12) whereas shift fell within the normal range (Fig. 2B). Finally, Subject 4 had increased variability (var_{xy} = 8.8 cm) and contracted the workspace (cont/exp_{xy} = 0.03) with little evidence of a significant systematic shift. In summary, although abnormalities were observed in three subjects, only two of the four subjects with primarily thalamic lesions were considered to have failed the position matching task.

Fig. 2C displays performance on the kinesthesia task. Subject 1 fell within normal ranges for all measurements. Subject 2 had an increased response latency (RL = 970 ms) and fell within normal ranges on all other parameters of the kinesthesia task. Subject 3 had increased initial direction error (IDE_{lin} = 22.5°) yet fell within normal ranges for all other parameters. Subject 4 reported he was unable to feel the robot moving his arm during this task, therefore no subject movement is displayed. In summary, although 3 subjects demonstrated some abnormalities, subject 4 was the only subject with a thalamic lesion that failed the kinesthesia task.

Fig. 2D displays performance on the visually guided reaching task. Subject 1 was outside the normal range on PS (0.79 cm/s), RT (0.5 s)
and MT (1.26 s). Subject 2 was outside the normal range on IDE (9.4°), NSP (3.25) and MT (1.4 s). Subject 3 was outside the normal range on PS (1.26 cm/s), RT (0.5 s) and IDE (4.5°). Finally, subject 4 failed all parameters. Since all 4 of these subjects failed 2 or more parameters, they were all considered to have failed the visually guided reaching task [32].

3.3. Posterior Limb of the Internal Capsule

Subjects 5 to 8 presented with lesions primarily involving the posterior limb of the internal capsule. ROI analysis of these subjects revealed percentage of PLIC damage (subject 5 = 19.3%, subject 6 = 29.0%, subject 7 = 8.3%, subject 8 = 19.6%) and the percentage of lesion located within the PLIC (subject 5 = 29.5%, subject 6 = 45.0%, subject 7 = 22.8%, subject 8 = 42.1%). For position matching (Fig. 3B), subject 5 demonstrated increased variability (\(\text{var}_{xy} = 7.8 \text{ cm}\)) with a shift away from midline (\(\text{shift}_{xy} = 10.8 \text{ cm}\)). Subject 6 also had increased variability (\(\text{var}_{xy} = 6.5 \text{ cm}\)) between trials while falling into normal ranges for the other measurements. Subject 7 was only found to have an increased contraction/expansion ratio (\cont/exp_{xy} = 1.38\). Subject 8 fell within normal ranges for all parameters of this task. Thus, while abnormalities were noted in three of the four subjects in this group, subject 5 was the only subject with a lesion to the internal capsule that failed the position matching task.

On the kinesthesia task (Fig. 3C), subject 5 had increased response latency (RL = 1007 ms). Subject 6 had increased IDE (35.2°) with large IDE (34.1°), PLR (0.3) and PSR (0.4). Subject 7 had increased PLR (1.6) and PSR (1.7) with increased variability on both of these parameters (PLRv = 0.3, PSRv = 0.4). Subject 8 had increased IDE (28.9°) and was variable on this parameter (IDEv = 40.3°) with all other parameters falling within normal ranges. In summary, although some abnormalities were seen on all subjects, only two subjects [67] with lesions of the internal capsule failed the kinesthesia task.

During visually guided reaching (Fig. 3D), subject 5 demonstrated abnormalities in PS (1.0 cm/s), RT (0.5 s) and IDE (9.8°). Subject 6 fell outside the range of normal in RT (0.5 s), IDE (11.2°), NSP (3.6) and MT (2.4 s). Subject 7 was impaired all 5 parameters. Subject 8 was impaired on IDE (10.5°), MT (1.9 s) and NSP (2.98). Thus, all 4 subjects were considered to have failed this task.

3.4. Somatosensory Cortex and Posterior Parietal Cortex

Subjects 9 and 10 experienced the largest impairments in motor and proprioceptive function of all the subjects with stroke (Fig. 4). ROI analysis informed us of the percentage of both post-central gyrus and superior parietal lobule damage (subject 9 = 24.3%, subject 10 = 42.4%) and percentage of lesion located within these two regions (subject 9 = 15.9%, subject 10 = 8.6%). During the position matching task, subject 9 had increased variability between trials (\(\text{var}_{xy} = 7.3 \text{ cm}\)) and severely contracted the workspace (\cont/exp_{xy} = 0.02\) (Fig. 4B). Subject 10 had the highest variability of all subjects (\(\text{var}_{xy} = 26.9 \text{ cm}\)) and was also found to contract the workspace (\cont/exp_{xy} = 0.23\).

On the kinesthesia task subject 9 was outside the normal range on IDE (59°), PLR (0.8) and PSR (0.35) as well as had increased IDE (27.5°), PLR (0.4) and RLV (0.7 s). Subject 10 had abnormal IDE (90.1°) and IDEv (42.2°), PLRv (0.7), RL (0.9 s) and RLv (0.8 s) and PSRv (0.5).

Both subjects 9 and 10 showed impaired visually guided reaching performance (Fig. 4A). Subject 9 fell outside the normal range on all 5 parameters (PS = 0.3 cm/s, RT = 0.6 s, IDE = 9.2°, NSP = 4.23, MT = 1.9 s) and subject 10 performed abnormally on 3 parameters (PS = 0.8 cm/s, IDE = 9.6°, NSP = 3.1). In summary, both subject 9 and 10 failed all three tasks.

3.5. Superior Temporal Gyrus and Lingual Gyrus

We present two subjects as acute stroke controls, one with a lesion centered on the left superior temporal gyrus and another with a lesion centered on the right lingual gyrus. Both of these subjects, with lesions in brain areas presumed not to be involved in proprioception, performed within the normal range across all three robotic tasks (Fig. 5). Only subject 12 was impaired on one parameter of the visually guided reaching task (IDE = 3.79°).

4. Discussion

We examined 10 subjects in the acute stage after stroke with lesions to areas traditionally thought to be involved in somatosensory processing. The majority of these 10 subjects demonstrated some impairment of position and/or kinesthetic sense as measured by the KINARM but not always by standard clinical assessment. The two subjects with lesions to somatosensory and posterior parietal cortex demonstrated the most significant impairments in proprioception. Interestingly, position sense and movement sense were impaired to differing degrees in four subjects (subjects 3, 5, 6 and 7). These subjects only failed either the position sense or kinesthesia tasks. All 10 subjects with lesions to somatosensory structures demonstrated some difficulty performing visually guided reaching. The 2 subjects we examined with lesions outside of our hypothesized somatosensory areas performed normally on all three robotic tasks.

In our sample, lesions to the thalamus produced impairments in position sense, kinesthetic matching and visually guided reaching to varying degrees. Pure sensory strokes resulting from thalamic lesions have been previously reported [14,15,40]. These results are not surprising as the VPL nucleus of the thalamus is known to project somatosensory information from the extremities to the cortex [41,42]. Therefore, lesions to the VPL would directly disrupt transmission of proprioceptive information. The impairments observed in visually guided reaching are consistent with the known importance of sensory feedback from the limb to cortex for the control of voluntary movement [43]. However, it may also reflect that the area of infarct affected the descending corticospinal tracts which run adjacent to the thalamus. We suspect the variability of the performance on the three robotic tasks likely results from both the inter-subject differences in lesion location and size, but also in variability in the individual neuroanatomic representation of given neurological function [44,45].

Damage to the PLIC resulted in impairments in visually guided reaching with less significant impairment of position sense and kinesthetic sense in our sample. The internal capsule is known to transmit both ascending sensory signals [46,47] from the thalamus as well as descending motor commands from the cortex [42,48,49]. Interestingly, subject 7 presented with almost exclusively motor impairments while preserving position sense in the upper extremities. Similarly, subject 8 showed impaired visually guided reaching of his affected arm with relatively intact position and kinesthetic sensation of the same arm. This is somewhat consistent with “pure” motor strokes having been observed.
Fig. 3. Posterior limb of the internal capsule lesions

A. Axial T2 weighted FLAIR images of subjects with internal capsule damage displayed in the left column. Subject number indicated on the left side of each image. White arrows indicate lesion location. Images are oriented anatomically (left is left, right is right).

B. Position Matching Task.

C. Kinesthesia Task.

D. Visually Guided Reaching.
with lesions involving the internal capsule previously [50,51]. Damage to the posterior limb of the internal capsule in our sample was more indicative of motor impairments rather than proprioceptive impairments, perhaps supporting the well-known division between ascending proprioceptive pathways and descending motor pathways at the level of the internal capsule and into the corona radiata.

Fig. 4. Primary somatosensory cortex and posterior parietal cortex lesions A. Axial computed tomography images of subjects with parietal cortex damage. Subject number is indicated on left side of image, white arrows indicate area of ischemia. B. Position Matching Task. C. Kinesthesia Task. D. Visually Guided Reaching.

Fig. 5. Stroke control subjects with lesions outside of hypothesized somatosensory structures A. Axial T2 weighted FLAIR images of subject 11 with left superior temporal lobe and posterior insula damage and subject 12 with right lingual gyrus and occipital lobe damage B. Position Matching Task. C. Kinesthesia Task. D. Visually Guided Reaching.
It was observed that subjects 7 and 8 had lesions that likely appear to have preferentially damaged motor fibres. This was contrasted by subject 6 who was less impaired in visually guided reaching and position matching, yet demonstrated significant impairments in kinesthetic matching (Fig. 3). While the dissociation between sensory and motor impairments might be predicted based on the anatomy of the PLIC, the dissociation between position sense and kinesthesia is unusual, given both are thought to originate in the same end-organ receptors (mainly muscle spindles [52,53]) and ascend in the dorsal columns through the thalamus and up to somatosensory cortex [41,54]. Anatomically, the pathways for position sense and kinesthesia has not been reported in humans. However, we can see from subject 6 that position sense and kinesthetic sense may be affected separately and therefore, consideration should be given to assessing them separately. Further anatomic mapping in humans is necessary to clarify this separation.

Lesions involving S1 and PPC in this sample appeared to have the greatest impact on proprioceptive and motor function. These two subjects also had the largest volume of lesion (subject 9: 57.3 cm³, subject 10: 118.4 cm³). S1 receives somatosensory information directly via the VPL nucleus of the thalamus [54,55] and Brodmann’s areas 5 and 7 in the posterior parietal cortex are important for integration of multiple sensory signals (i.e., visual, tactile, proprioceptive) in order to perform smooth coordinated movements [43]. These areas of parietal cortex are involved in numerous functions related to sensory processing. In a previous lesion analysis study [56], subjects with damage to primary somatosensory cortex and superior parietal cortex generally demonstrated impairments in proprioception. In a separate study of healthy participants assessed with functional neuroimaging, kinesthetic sensation evoked by muscle tendon vibration was shown to involve the superior parietal cortex [57]. Thus it was, perhaps, not surprising to see the magnitude of the impairments seen in subjects 9 and 10. Another potential contributor to the impairment seen in these two subjects could be the presence of spatial neglect. This is especially apparent in the visually guided reaching performance of subject 10 (Fig. 4) who misses left sided targets on multiple trials. Right parietal cortex lesions have been associated with left sided spatial neglect in the past [58,59], which is consistent with our results. We are unable to draw associations between lesion location, spatial neglect and proprioceptive impairment here due to the small sample size, however this remains an important topic for future research.

Another factor that may have influenced our overall results could be lesion volume. Subjects 1 to 4 had increasing lesion size in the thalamus, which was associated with increasing proprioceptive impairment. This trend was not observed in subjects 5 through 8 (PLIC), as their lesion volumes were quite similar (Table 1). Subjects 9 and 10 (parietal lobe) had substantially larger lesion volumes (57.3 cm³ and 118.4 cm³, respectively) compared with the rest of the sample and also had significant proprioceptive impairment. Interestingly, subject 12 had the second largest lesion volume (77.3 cm³) in our sample yet demonstrated normal proprioception and visually guided reaching. Current literature has disputed whether or not lesion volume is related to upper extremity motor deficits post-stroke [60–62]. However, the exact relationship between lesion volume and proprioceptive deficit post-stroke has yet to be determined. When we look at the percentage of each region that has been damaged in our subjects we see large variability in the amount of damage as well as large variability in their proprioceptive impairment. This suggests that even a small amount of damage to these sensory areas may have large effects on proprioceptive function after stroke.

The two stroke controls (subjects 11 and 12) both had lesions located outside of our predicted somatosensory areas. These subjects had relatively large lesions (subject 11 = 10.3 cm³, subject 12 = 77.3 cm³) compared to the rest of our sample yet performed normally on the position matching, kinesthesia and visually guided reaching tasks (Fig. 5). Subject 11 had damage primarily in the left superior temporal gyrus, which is an area typically thought of as processing auditory information and for language comprehension. Subject 12 had damage primarily to the right lingual gyrus, an area believed to be involved in processing visual information. This strengthens our findings by demonstrating lesion locations that spare our hypothesized areas that are not associated with proprioceptive impairment.

Severity of proprioceptive deficits after stroke may also be hemisphere dependent. Previous studies have observed that right hemisphere damage may result in more severe proprioceptive deficits in the subacute phase post-stroke [5,24]. Additionally, hand dominance may affect processing of proprioceptive feedback, as it has been proposed that the non-dominant hemisphere is involved in processing proprioceptive information [63–66]. This is consistent with our results as we found that only two (subjects 3 and 7) out of seven subjects with dominant hemisphere lesions demonstrated proprioceptive impairment while all five (subjects 4–6, 9, 10) individuals with non-dominant hemisphere lesions had proprioceptive deficits (Table 1).

5. Conclusions

We have used three robotic assessments to systematically evaluate our subjects’ position sense, kinesthesia and visually guided reaching performance acutely after stroke [5,23,24] in order to draw the following conclusions. Firstly, as shown in the individual case examples in the present study, these abilities following stroke can be impaired to differing degrees and as such consideration should be given to assessing them accordingly. Secondly, lesions that appeared very similar in location on neuroimaging presented with different behavioural impairments, indicating the need to utilize a variety of assessment techniques to fully appreciate the extent of injury after stroke. Lastly, while our results only pertain to the acute stages of recovery following stroke future research that monitors changes in performance over time with quantifiable measures, such the ones used in this study, will inform on how specific lesions and sensory impairments impact long-term recovery.

Disclosure

Dr. Scott is cofounder and chief scientific officer of BKN Technologies, the company that commercializes the KINARM robotic device.

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References

Kishi M, Sakakibara R, Nagao T, Terada H, Ogawa E. Thalamic infarction disrupts
Debert CT, Herter TM, Scott SH, Dukelow S. Robotic assessment of sensorimotor
Keith RA, Granger CV, Hamilton BB, Sherwin FS. The functional independence
Bohannon RW. Evaluation and treatment of sensory and perceptual impairments
Lincoln N, Crow J, Jackson J, Waters G, Adams S, Hodgson P. The unreliability of
Older E, Derouesne C, Mas JL, Bolgert F, Castaigne P. Pure sensory stroke caused by a small
Sacco RL, Bello JA, Traub R, Brust JC. Selective proprioceptive loss from a thalamic
Ja Gutrecht, Zamani AA, Deepak NP. Lacunar thalamic stroke with pure cerebellar