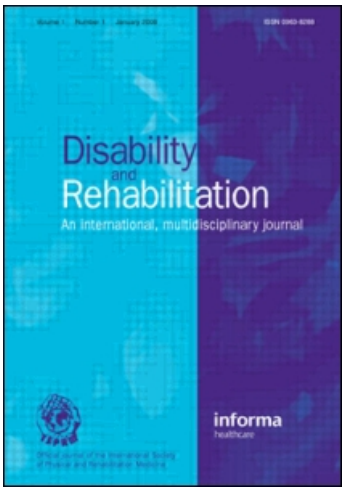

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RESEARCH PAPER

Automated measurement of proprioception following stroke

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Abstract

Background. Proprioception provides feedback which is essential for adequate motor control. Despite having detrimental functional implications, the assessment of proprioception deficits in current clinical practice is mostly qualitative and inadequate for diagnosis and longitudinal monitoring of subtle impairments and their effect on motor function.

Purpose. To evaluate a novel quantitative approach to the assessment of proprioception deficits in stroke patients.

Method. We designed and implemented an automated protocol where a magnetic motion tracking system and a sensor attached to each of the patient's hands, enables registration of trajectories in 3D coordinates. In this protocol the patient's affected and healthy hands are placed respectively below and above a square board. With vision blocked, the subject's affected hand is passively moved to one of four locations, and then the patient is instructed to actively position the healthy hand directly above his/her perceived location of the affected hand. The positional difference between the two hands is automatically recorded by the system. This procedure is repeated several times and the magnitude and direction of errors are used to quantify the proprioception deficit. The data for this pilot study was collected in a sample of 22 stroke patients and an age-matched group of neurologically intact subjects.

Results. Stroke patients had significantly higher *mean distance error* compared with the control group (average values of 7.9 and 5.3 cm, respectively), and showed higher instability (variance) in repeated performance (average values of the standard deviation of errors 3.4 and 1.8 cm, respectively). Significant correlation was found between the *mean distance error* and the results of semi-quantitative clinical tests of proprioception.

Conclusion. The system provides a reliable quantitative measure of upper limb proprioception, offering considerable advantage over the traditional means applied in the clinic.

Keywords: *Proprioception, somatic sensation, measurement, brain damage, stroke*

Introduction

Disturbances of somatic sensation, especially position sense or proprioception, may have detrimental functional implications consequent upon poorly controlled posture and movement. Such disturbances may arise following damage to the sensory pathways anywhere between the peripheral nerve endings and the somatosensory association cortex of the parietal lobe.

Evaluation of somatic sensation, as part of the routine neurological examination, is generally qualitative in nature, and as such precludes accurate and reliable identification of subtle sensory variations. To overcome this limitation, several quantitative tests have been developed. Tactile sensation can be evaluated using calibrated filaments, such as von Frey hairs [1] or Semmes Weinstein monofilaments [2], which allow for the application of quantified amount of pressure on the skin, by using delicate brushes of different textures [3]. The two-point-tactile-discrimination test can be applied to assess quantitatively the minimal distance still allowing discrimination between a pair of stimuli and a single stimulus (for review of the test and its shortcomings see Lundborg & Rosen [4]). Pain sensation can be

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quantified using thermal stimuli or quantifiable pressure [5]. These methods are used mainly for research purposes.

Proprioception is traditionally assessed by a test in which the examiner holds the patient's finger by its sides and gently flexes or extends it. The patient is asked to define the end position of the finger ('*up or down?*' test) [6,7]. Assessment of distal upper limb proprioception by measuring the angular error in the metacarpo-phalangeal joint in a position task has been proposed [8]. However, to our knowledge, there is no simple and reliable method for quantifying proprioception derived from the entire moving upper limb.

We report here on a novel automated approach for measuring upper-limb proprioception deficits following stroke, which is easily applicable in clinical practice and can be used for longitudinal assessment of natural and treatment-induced recovery.

Method

Subjects

Subjects were recruited from a population of patients admitted to the Loewenstein Hospital, Raanana, Israel, for rehabilitation after stroke. Twenty two patients (12 females, 10 males), aged 29 to 79 (mean 62.1) participated in the study. Eleven patients had a right hemisphere damage (RHD; left hand affected), and 11 had a left hemisphere damage (LHD; right hand affected). Five RHD patients (CHA, GD, AC, SS, ZTS) manifested contralesional disadvantage in standardized tests of neglect [9] and/or in visual search tasks [10]. Three patients in the LHD group (RO, IY, MM) had aphasic language disorders. The language deficits in these patients did not preclude full cooperation in the testing procedure. Two patients (CD, MR) had CT evidence of bilateral lesions although the damage was predominantly on one side. The time of testing ranged between 3.5 and 19.6 weeks after the onset of stroke (mean 10.1). A control group of healthy subjects was recruited from patients' spouses and department staff. There were 9 subjects (4 females, 5 males), aged 28 – 80 (mean 53). The difference in age between patient and control groups was not significant. All subjects, in both groups, were right handed. All subjects gave informed consent to participate in the study. Inter-rater and intra-rater (test-retest) reliability of the measurement were assessed in a group of four healthy subjects not included in the above control group.

Apparatus

The apparatus used for measuring the spatial location of the subject's hand is presented in Figure 1. It consists of sensors for recording the

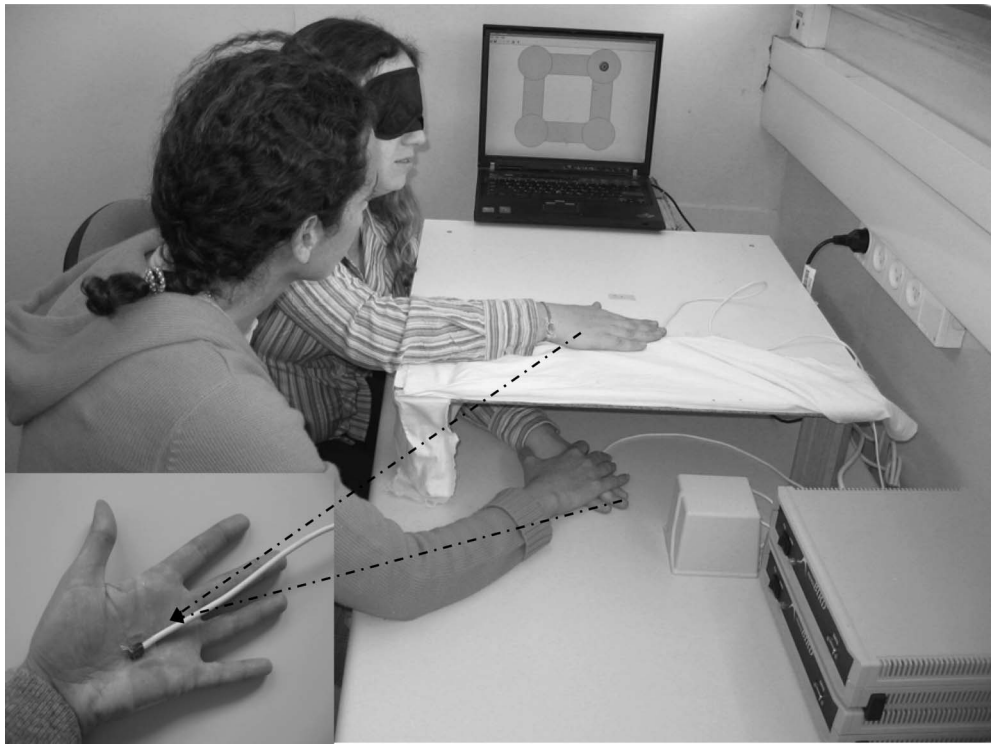

Figure 1. Apparatus. Subject sitting in front of the examination table with sensors attached. The tested (left) hand is moved on the lower surface by the examiner to one of the four target locations, according to visual feedback from a computer screen. The subject is then asked to move the other hand to a point just above the tested hand.

position of the patients' healthy and affected hands, a laptop that displays the hand positions to the examiner, and a miniature table that defines the workspace of the examination. Hand position is sampled at 100 Hz, with a precision of 2 mm, by a MiniBIRD500 magnetic tracking system (Ascension Technologies) comprised of a $10 \times 10 \times 10$ cm transmitter that generates a magnetic field and two tiny 5 mm sensors that transmit their 3D position within the magnetic field and connect to the laptop. A simple application was developed to graphically display the workspace and the sensor positions on the screen. A 60×60 cm wooden miniature table (height 20 cm) was placed on top of a desk. During the examination, the patient's affected hand was passively placed by the examiner in different locations below the miniature table and the patient was asked to bring the healthy hand on the upper surface of the miniature table, exactly above the affected hand. The two sensors, each one attached to one of the patient's hands, enabled recording of the movement trajectories in 3D coordinates.

Experimental protocol

The subject's chair/wheelchair is positioned as close as possible to the desk, and the center of the miniature table is aligned with the subject's mid-sagittal plane. A sensor is taped to the center of the palm of each of the patient's hands. The patient is blindfolded and the affected hand is then passively positioned by the examiner on the surface of the desk, below the center of the miniature table. The unaffected (ipsi-lesional) hand of the patient is placed above the upper surface of the miniature table. During the test, the examiner passively moves the affected (usually paretic or plegic) hand to one of 4 test locations at the corners of a 15×15 cm virtual working area beneath the miniature table. The exact location of the affected hand is displayed on the computer screen by a cartoon hand image and 4 circles mark the four possible testing locations. A target alternating between the 4 circles indicates to the examiner the testing location for each trial. The experiment consists of visiting each of the 4 locations 10 times. The sequence was randomly generated, and was identical for all subjects. The experiment begins with both hands in the center of their corresponding workspaces. A target appears on the screen inside the first circle to visit. The examiner positions the affected hand in the specified testing location, by gently guiding it until the cartoon hand image displayed on the screen coincides with the circle marked with the target. The subject is then asked to reposition his unaffected hand directly above his/her perceived location of the affected hand. When the subject has completed the movement, the examiner presses a key to record the positions of the hands, and the target shifts to the next testing location. Each session is about 15 min long. The patients performed the test only once, with the affected hand being passively guided by the examiner. Neurologically intact control subjects performed the test twice; first, with the right hand being passively guided and the left hand being actively moved to that location, then vice versa.

Computerized data acquisition and analysis

For each trial, a set of parameters was recorded: (i) The *distance error* (DE), the distance between the two hands, computed as the distance between the two sensors in the horizontal plane; and (ii) the *directional error*, computed as the angle formed by the line connecting the hands, to the horizontal axis (e.g., placing the top hand directly to the left of the bottom hand, results in a directional error of 180°). For each patient, and for each hand of the healthy controls, mean and standard deviation were calculated for each of the above parameters.

Clinical evaluation of the sensory-motor deficits

Upper limb proprioception was evaluated after blindfolding the patients, by the traditional '*up-or-down?*' test. Small range ($<20\%$ of the normal range) passive movements at the sagittal plane, starting at mid range, were applied in 4 joints – 2nd metacarpophalangeal, wrist, elbow, and shoulder – with 6 repetitions of the trials in each joint. Since the '*up-or-down?*' is a binary test, the score used to quantify the level of upper limb proprioception deficit was the number of incorrect answers out of a total of 24 questions (6 repetitions by 4 joints). In addition, upper limb tactile sensation and motor deficits were assessed qualitatively on a 0 – 3 scale (where '0' indicates no impairment, '1' indicates mild impairment not leading to any significant upper-limb disability, '2' indicates an impairment that causes mild upper-limb disability, and '3' indicates an impairment leading to significant upper-limb disability).

Results

Clinical evaluation of upper limb proprioception and tactile sensation

In the patient group, the mean number of errors on the '*up or down?*' test was 0.7, 1.0, 1.3 and 1.0 at the shoulder, elbow, wrist and 2nd metacarpophalangeal joint, respectively (out of 6 trials per joint). The mean combined number of errors (out of 24 trials) was 4.04. On a 0 – 3 scale, the impairment in

upper-limb tactile sensation was judged by the treating physician as '0', '1', '2', '3' in 12, 4, 4 and 2 cases, respectively. Thus, no less than 12 of the 22 patients were judged clinically as having no deficit in upper limb tactile sensation. Of these 12 patients, 10 performed the '*up or down?*' test faultlessly in all 4 joints.

Quantitative assessment

In the digital system the *mean distance error* averaged over all subjects of the patient group was 7.9 cm compared with 5.3 cm for the control group (two tailed *t*-test, $p < 0.01$). The standard deviation of the *distance error* averaged over all subjects of the patient group was 3.4 cm compared with 1.8 cm in the control group (two tailed *t*-test, $p < 0.01$). This increase in both the distance error and its standard deviation (i.e., increased scatter) are clearly demonstrated in the results of the digital test for a typical patient versus a typical control subject displayed in Figure 2. For detailed individual data see Table I.

Significant positive correlations were found between the *mean distance error* and the combined number of errors on the '*up or down?*' test (Pearson's correlation 0.647, $p < 0.01$) and between the *mean distance error* and the clinical assessment of sensory impairment (Pearson's correlation 0.752, $p < 0.01$) (see Figure 3). In contrast, there was no correlation with the clinical assessment of the motor impairment (Pearson's correlation 0.097, $p > 0.1$).

Laterality effects

Among the normal control subjects we were able to compare performance based on afferent signals derived from the passively moved left hand and the passively moved right hand. In patients we compared the performance (distance and directional error values) of RHD vs. LHD subjects.

There was no significant laterality effect in the healthy control subjects (average mean distance error 4.2 and 5.3 cm for performance based on passive movement of the left-hand and right-hand, respectively, two tailed paired *t*-test $p = 0.16$; average of standard deviation of distance error 1.7 and 1.8, respectively, two tailed paired *t*-test $p = 0.6$).

In the patient group, there was no statistically significant difference between the RHD and LHD subjects (average mean distance error 8.8 and 7.2 cm, respectively, two tailed *t*-test $p = 0.2$; average of standard deviation of distance error 3.6 and 3.4, respectively, two tailed *t*-test $p = 0.7$).

Directional errors

The histograms of the directional errors show a persistent error pattern: The directions of error of both the patient and control groups, cluster almost entirely in the lower half of the circle (top pane of Figure 4), reflecting a proximal bias (active hand placed closer to the trunk). However, within the control group, when the initial proprioception signal arrives from the passively moved right hand, the directions of the error cluster mainly in the right lower quarter, reflecting a right shifted proximal bias (bottom pane of Figure 4).

Apparatus reliability

In order to assess the intrinsic measurement error of the device and its effect on reproducibility of

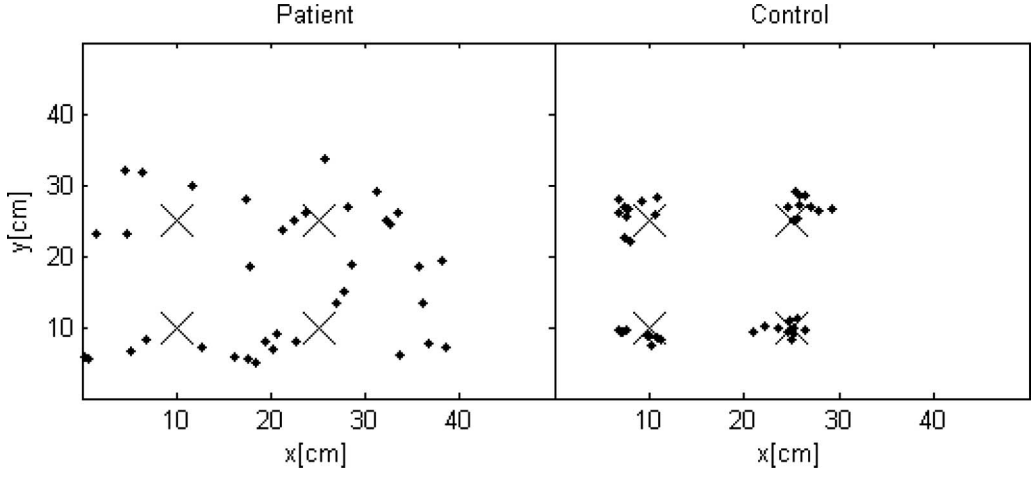

Figure 2. Increased distance error and scatter in a typical patient compared with a typical control subject. The workspace and the results of 40 trials: The targets are marked by four large 'X's. The hand below the workspace was passively moved to these targets. The dots identify the locations in which the subject placed his upper hand when requested to position it directly above his perception of the lower hand while blindfolded.

Table I. Results of patient and control groups on computerized and clinical tests.

Patients		Lesion side	Distance error		'*up or down?*' test				Impairment	
			MDE	SD	Shoulder	Elbow	Wrist	MCP	Tactile sensation	Motor
1	CD	R (L)	3.5	2.1	0	1	0	0	0	2
2	HS	R	8.4	5	0	0	0	0	1	2
3	AN	R	7.1	3.7	0	0	0	0	0	2
4	CY	R	8.6	3.1	0	0	0	6	2	2
5	CHA	R	10.0	3.9	0	0	0	0	0	1
6	RN	R	7.8	2.5	0	0	0	0	0	1
7	GD	R	13.8	5.7	6	5	5	0	3	3
8	EE	R	11.1	1.5	0	0	2	0	1	2
9	EM	L (L)	6.3	3.9	0	0	0	0	1	2
10	DM	L (L)	4.1	2.4	0	0	0	0	0	2
11	AC	R	11.7	4.4	3	3	3	0	2	0
12	MR	L (R)	5.5	1.4	0	0	0	0	0	2
13	SS	R	10.5	5.1	2	3	6	6	3	2
14	AF	L	7.4	2.1	0	0	0	0	0	1
15	IR	L	8.2	3.5	0	0	0	0	0	2
16	RO	L	13.1	5.5	0	2	6	6	2	2
17	ZTS	R	4.8	2.1	0	0	0	0	0	0
18	AKM	L (L)	6.9	3.9	0	0	0	0	0	3
19	FM	L	4.5	2.5	0	0	0	0	0	2
20	AZ	L	7.4	4.6	0	1	0	0	1	1
21	IY	L	5.2	2	1	1	0	0	0	1
22	MM	L	8.8	3.1	4	5	6	6	2	1
Mean			7.9	3.4	0.7	1	1.3	1	0.82	1.64

		Distance error			
		Right hand passive		Left hand passive	
Control subjects		MDE	SD	MDE	SD
1	BTZ	5.1	2.1	4.3	2.3
2	SHN	6.4	1.6	3.2	1.6
3	AE	4.2	1.4	2.4	1.2
4	BI	6.1	1.4	2.8	1.6
5	LB	3.8	1.7	4.8	1.6
6	BS	6.4	1.8	4.8	1.6
7	RA	4.1	1.7	5.9	2.1
8	SG	4.4	1.8	6.2	1.7
9	PY	7.2	2.3	3.2	1.7
Mean		5.3	1.8	4.2	1.7

MDE, Mean of the *Distance Error* (derived from 40 trials); SD, Standard Deviation of the *Distance Error* (derived from 40 trials); MCP, 2nd Metacarpophalangeal joint; '*Up or down?*' test scores are the number of errors in 6 trials at each joint. Upper limb tactile sensation and motor impairments were assessed on a 0–3 scale where '0' indicates no impairment, '1' indicates mild impairment not leading to any significant disability, '2' indicates an impairment that causes mild upper-limb disability, and '3' indicates an impairment leading to significant upper-limb disability. Passive hand specifies that the initial proprioception signals arrive from that hand which was moved passively by the experimenter below the other hand. Lesion side denotes the injured hemisphere (in brackets – old or concurrent minor damage without sensory-motor manifestations, revealed on CT).

testing results, the following procedure was carried out. The location of the four targets was clearly marked. Then a 40-trials exam (10 trials by 4 targets) was performed, taking extreme care to place the top sensor and the bottom sensor exactly on the marking of the targets on the workspace. The *distance error* was averaged across the 40 trials. The test was performed twice, obtaining mean errors of no more than 2.1 and 1.9 mm in subsequent tests.

Test-retest reliability

In order to assess reproducibility of results upon repeated testing by the same examiner on the same subject, four healthy subjects were each tested twice by the same examiner obtaining for each of the four subjects two mean *distance error* scores (the test and the retest scores). The deviations in centimeters of each subject's score between the test and retest were 0.6, 1.9, 0.6, and 0.9, with an average of 1 cm.

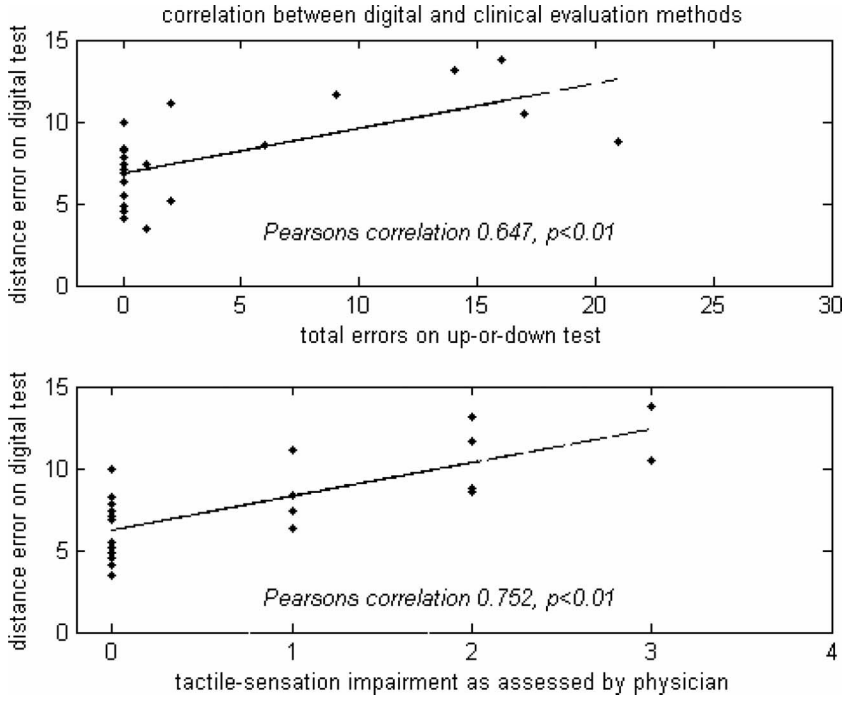

Figure 3. Correlation between digital and clinical evaluation methods. Top pane plots the mean distance error (MDE) per patient vs. patients' combined number of errors in four upper-limb joints (shoulder, elbow, wrist, 2nd metacarpophalangeal) in the sagittal plane, as revealed in the '*up or down?*' test. Bottom pane plots MDE per patient vs. patients' tactile-sensation impairments as assessed by the treating physician on a 0–3 scale (where '0' indicates no impairment, '1' indicates mild impairment not associated with any significant disability, '2' indicates an impairment that is associated with mild upper-limb disability, and '3' indicates an impairment associated with significant upper-limb disability). The line in both panes is the curve fitted linear regression. In both cases, the digital assessment is highly correlated with the traditional semi-quantitative clinical method.

Inter-rater reliability

In order to assess the rater-dependent error, the above four healthy subjects were each tested by two different examiners obtaining for each of the 4 subjects two mean *distance error* scores. The deviations in centimeters of each subject's score between the test and retest were 0.1, 2, 0.8, and 0.2, with an average of 0.8 cm.

Discussion

The aim of the present research was to evaluate a novel approach for quantitative measurement of proprioception deficits in stroke patients. The prototype examined was found to differentiate clearly between patient and control group performance. The method's validity was demonstrated also by the significant correlation that was found between the results of the automated procedure and the sensory deficit (but not the primary motor deficit), as assessed in the traditional neurological examination.

Apart from the advantage of producing quantitative results, the automated method seems to have superior sensitivity to deficits of proprioception compared to the traditional clinical assessment. This possibility is indicated by the fact that no less than 10 of the 22 patients performed faultlessly the '*up or down?*' test, making not a single error in any of the 24 trials (6 per each of the tested 4 upper-limb joints), while the *mean distance error* revealed by the automated assessment in this subgroup of patients ranged from 4.1–10.0 cm (see Table I). The higher sensitivity of the automated method might reflect the fact that the cerebral processing of hand position in space is based on integration of signals arriving actually from all upper-limb joints. In contrast, adequate performance of the clinical '*up or down?*' test necessitates data processing from a single joint at a time. In this sense, the automated method is more akin to proprioception judgements subserving motor control in real-life conditions.

The automated method provides a quantitative measure of patients' proprioception ability at a given point in time, and as such it is suitable for monitoring natural and treatment-related recovery.

Another important advantage relates to the quantitative assessment of performance instability. As shown in this study, patients not only err more, they also show a significant increment in variance with repeated trials, compared to the much more stable and predictable performance of healthy individuals. It has been shown previously in patients with

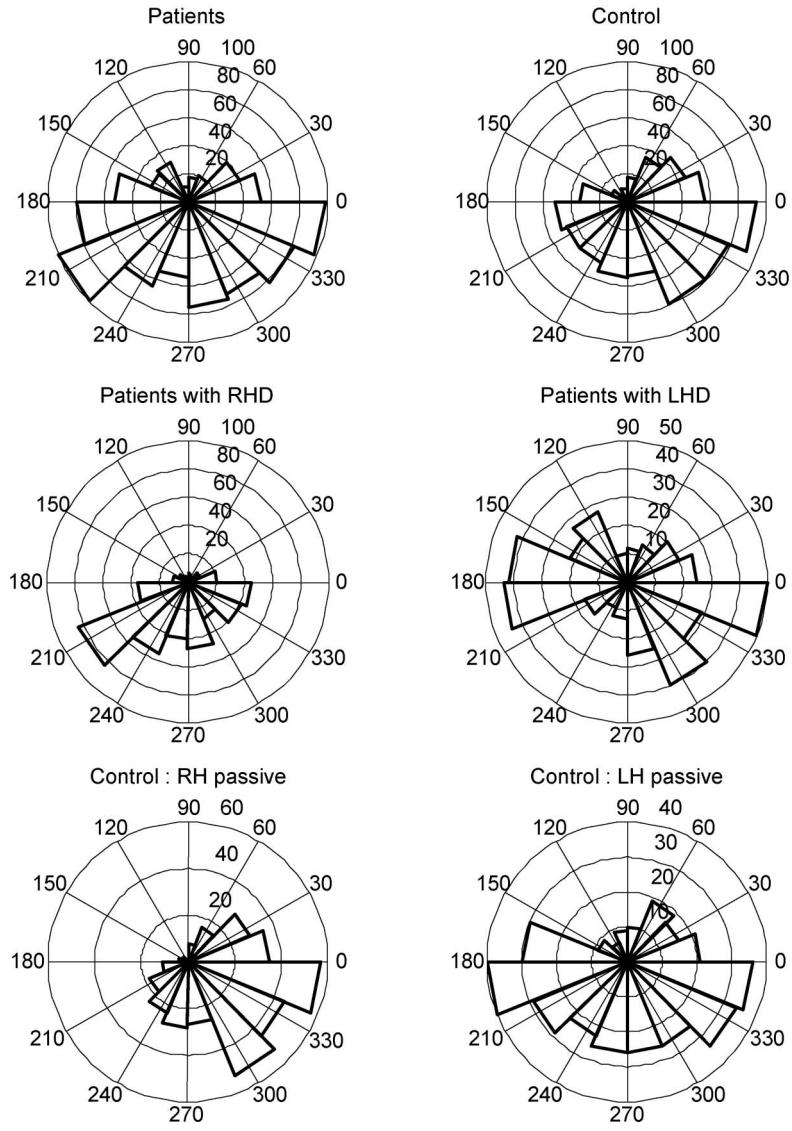

Figure 4. Histogram of the directional error in patients and controls. The histograms present the distribution of the directions of the error: Each bin reflects the errors in the range of directions corresponding to the actual angle of the bin and its length specifies the number of trials with an error in that direction. For instance, the bins pointing downwards specify the number of trials in which the top hand was placed proximally to the correct location. Top pane compares the direction errors between the patient group and the control group. The middle pane compares the patients with RHD and LHD, and the bottom compares the performance of the control subjects when performing with their right hand (RH) passively moved versus with their left hand (LH) passively moved. The histograms reveal that the errors across all groups are almost entirely proximally biased. In addition, the errors in the control subjects with RH passive seem to have a bias towards the right of the actual location.

unilateral neglect performing visual search tasks, that slowed reaction time to contralesional targets is accompanied by significant increment in variance, attributed to the inability to sustain optimal performance over repeated trials (although achieved in some trials) [11]. Likewise, some patients in our group were able to arrive accurately at the specified location, but were unable to do so repeatedly.

It is important to note that the advantage of the quantitative automated assessment over the traditional qualitative method in terms of sensitivity was not counterbalanced by poor reliability. Apparatus reliability assessment, as well as inter-rater and test-retest measurement comparisons in a sample of neurologically intact subjects, disclosed only a small variance (<1 cm on average).

Future research of proprioception deficits in different stroke populations will be able to make advantage of another feature of the system – its ability to provide a quantitative measure of directional errors. It is of interest to evaluate whether lateralized impairments of spatial processing, as in unilateral spatial neglect, are likely to produce systematic and distinct directional errors of upper limb proprioception (e.g., directional hypometria). Due to the small number of neglect patients we were

unable to assess the specific impact of this condition. Likewise, a larger sample will be needed for a proper assessment of the mechanisms underlying the proximal bias shown by many subjects both in the pathological and control groups. These issues are beyond the aims of the present study.

With the recognition of the negative effect of impaired somatic sensation on the ability of stroke patients to control posture and movement, protocols of sensory rehabilitation treatment have been developed and found beneficial [12,13]. A sensitive method for quantitative assessment of proprioception deficits is expected to help clinicians identify patients in need of such treatment, and to facilitate monitoring of treatment efficiency in terms of increased accuracy and reduced performance instability (variance). By adding a simple feedback module able to reflect to the patient the magnitude and direction of the errors performed in real time, the device can be used also as a therapeutic tool. Biofeedback aimed at the motor system has been found beneficial in different areas, such as urinary incontinence [14] and temporomandibular pain disorders [15], and visual feedback was proposed as a treatment in contraversive pusher syndrome [16]. We have not been able to identify studies examining the efficacy of biofeedback on impairments of tactile or proprioceptive sensation.

In conclusion, the results obtained with the prototype apparatus point to clear advantages of using an automated quantitative approach for purposes of diagnosis of proprioception deficits after stroke.

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