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Wrist proprioception in acute and subacute stroke: a robotic protocol for highly impaired patients

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Abstract—Proprioception is a critical component of sensorimotor functions which directly affect recovery after neurological injuries. However, clinical tests of proprioception still lack sensitivity and reliability, while robotic devices can provide quantitative, accurate, and repeatable metrics. This work presents the analysis of the efficacy of a robotic assessment of wrist proprioception in terms of the capability to discern between movements along the different DoFs in a healthy population with a broad range of age. The effect of aging on the proprioceptive matching was analyzed to select an appropriate control group for the comparison with stroke patients, designed to confirm the hypothesis that a high percentage of stroke patients presents proprioceptive impairments in the acute and subacute states. Results show that the protocol is capable of detecting differences in performance along different movement directions, and that wrist proprioception does not deteriorate in the age ranges analyzed. Finally, stroke patients were less accurate in matching the position of their wrist, confirming the hypothesis that proprioceptive performance is often impaired in the acute and subacute phases of stroke.

I. INTRODUCTION

Despite continuous advances in the design of task-specific, repetitive, high-intensity training protocols, stroke remains a leading cause of adult permanent disability. Spontaneous recovery can be usually observed in the first weeks following stroke and motor functions of the arm have been shown to improve and reach the maximum functionality during the first three weeks in 80% of the hospitalized patients [1]. However, improvements show a high heterogeneity across stroke survivors associated with their demographics, behavioral experience, and genetics [2]. While changes in motor functions have been extensively studied, the natural history and neural correlates of spontaneous recovery in somatosensory functions after stroke have received less attention [3], and few studies have targeted the importance of proprioception. The sense of body position is a critical component for motor control and it strongly correlates with motor recovery of the hemiplegic limb [4], [5].

In the study by Winward and colleagues, 18 stroke patients were screened by means of the Rivermead Assessment of Somatosensory Performance over a 6-month period [6].

While none of the participants had fully preserved sensation in the acute stage of stroke, different degrees of recovery were observed in most of the sensory modalities during the study. Among these, proprioception showed the highest recovery. Similarly, among the 56 patients recruited for the study by Semrau et al., almost half of the patients who presented deficits in proprioception after one week from stroke improved during the first 6 months of recovery [7]. Kattenstroth et al. analyzed the recovery of the proprioceptive submodality joint position sense of the fingers of 10 patients (mean weeks post stroke = 2.3) before and after 2 weeks of hospital-based rehabilitation. The authors found significant improvements in performance, which, however, were below those of a healthy age-matched control group (10 individuals) [8]. In another study, the assessment of wrist position sense of 51 patients (mean days post-stroke = 49.5), revealed that 49% of the patients showed impairments of the affected wrist, and that also the ipsilesional wrist (on the same side of the brain lesion) presented a less severe impairment in 20% of participants [9]. In this latter study, the protocol chosen to test the wrist matching performance involved the assessment of the error between the wrist angle, passively reached with the help of the experimenter, and a pointer aligned with the other hand by the patient to match the imagined line between the middle of the wrist to the index finger.

Robotic devices can provide a more objective and reliable mean for monitoring proprioception [10] and can be employed in different protocols addressing its various subcomponents. The estimation of the psychophysical thresholds, or Just Noticeable Difference (JND) between two perceived positions, performed by the wrist robot, was found to be precise and reliable in proprioceptive acuity assessment [11]. Unfortunately, the method proposed has practical implementation issues: it is time-consuming making it difficult to be integrated into the conventional clinical assessments. Reproduction of a joint position, or Joint Position Matching (JPM), is a common task used to test position sense. It results to be more accurate when the position is encoded by active movements, which are the predominant movements observed during daily living [12], compared with passive movements. However, active motions may rely on central motor programs rather than a memory of proprioceptive coordinates [13], and the validity of active reproduction is reduced for stroke patients with limited motor functions.

The JPM task has implementation issues in clinics mainly due to the inability of severe patients to actively move the affected limb. In this study, we employed a revised JPM

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protocol, which is an adaptation of the arm proprioceptive assessment previously designed for chronic stroke population [14]. The revised method was found to be fast and easy to use, and as it involves passive movements, it is suitable for testing stroke participants with a wide range of motor impairments and reduced active range of motion (ROM). Our previous study did not find significant differences in proprioceptive functions between healthy and stroke patients in the chronic phase after stroke (> 5 months after the event), with only two patients, out of the nine screened, presenting proprioceptive impairments of the arm. In order to test the hypothesis that sensory dysfunctions may resolve with time, we employed the revised JPM protocol to assess proprioception of a group of acute and subacute patients (0-3 months post stroke) participating to a study designed to determine the incidence of proprioceptive deficits on admission, discharge and follow-up from rehabilitation using standardized clinical tools and the robotic assessment. The main objectives of the ongoing study is to obtain baseline data to increase the understanding of the incidence, evolution and impact of somatosensory and proprioceptive impairments on post-stroke recovery, as well as to test the feasibility of using a wrist robotic device [15] to safely obtain quantitative wrist joint proprioceptive measurements at the three time points within tolerance of stroke subjects.

In this work, we first test the efficacy of the proposed assessment in detecting the anisotropy across wrist DoFs found for both active proprioception [16] and passive proprioception [11]. Secondly, we show preliminary results on the effect of aging on proprioceptive functions by comparing performances of healthy young participants to that of adult individuals. Finally, we test the hypothesis that the assessment of wrist proprioception is able to discriminate between the control and stroke group, as proprioception is expected to be impaired in a higher percentage of the population analyzed at admission.

II. METHODS

A. Apparatus

The WristBot [15], depicted in Fig. 1A, was employed for the experimental procedure. The robot can apply torques to

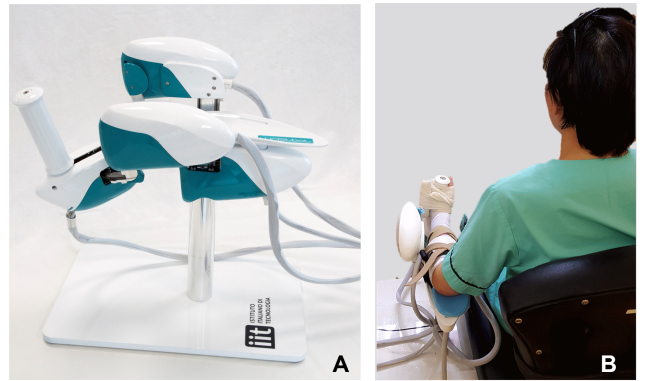


Fig. 1. (A) The WristBot, a three DoFs robotic manipulandum employed in the study; (B) A patient during the experimental procedure in the familiarization phase.

the human wrist across the three DoFs, i.e. flexion/extension (FE), abduction/adduction (AA) and pronation/supination (PS). It is embedded with digital encoders for accurate wrist displacements controlled at 1 kHz by a software running on a laptop computer. Linux Ubuntu version 16.04 was used as the operating system and the software for controlling the robot was developed in C++ and Python.

B. Participants

A group of healthy participants and a group of stroke survivors volunteered for the study.

A total of 13 healthy participants were recruited: eight participants (4 females), whose age was in the range 21 - 33 (mean = 27.2) years formed the *Young* group while the remaining five (2 females), who had an age in the range 43 - 58 (mean = 55) years were included the *Aged* group. All individuals in the *Young* group were right-handed, while one of the five participants in the *Aged* group was left-handed as confirmed by the Edinburgh Handedness Questionnaire. Both groups had no reported neurological, psychiatric, or neuromuscular disorders.

Nine stroke survivors (7 males, mean age \pm std: 54 ± 12.1 years) formed the *Stroke* group. All patients met the inclusion criteria for participating in the study: (1) first clinical stroke

TABLE I

ACUTE AND SUBACUTE STROKE PATIENTS CHARACTERISTICS. FMA REFERS TO THE UPPER-EXTREMITY COMPONENT OF THE FUGL-MEYER MOTOR FUNCTION ASSESSMENT

Subject ID	Age (years)	Gender	Handedness	Time since onset (days)	Nature (Haemorrhagic or Ischaemic)	Paretic Wrist	FMA (0-66)
S1	56	M	R	7	I	L	50
S2	36	M	R	20	H	L	4
S3	70	M	R	10	I	L	4
S4	57	M	R	38	I	L	12
S5	46	M	R	22	H	R	66
S6	51	M	R	9	I	L	64
S7	59	M	R	42	H	R	26
S8	40	F	R	8	I	L	52
S9	71	F	R	14	I	R	61

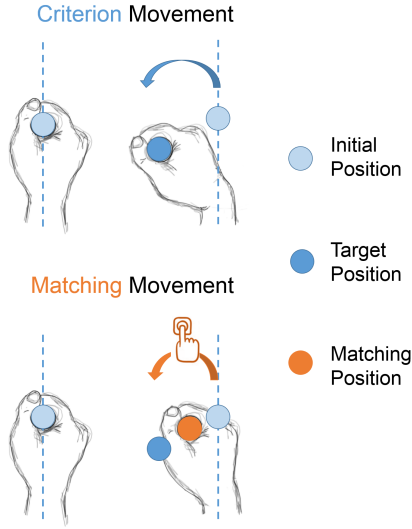


Fig. 2. Experimental protocol: the Criterion movement places the hand on the target position, while the Matching movement is stopped by the participant when they recognize the same position by means of the proprioceptive feedback.

(ischaemic or haemorrhagic) diagnosed by brain imaging CT or MRI; (2) age between 21 years to 85 years; (3) less than 90 days of stroke on admission to rehabilitation; (4) medical and neurological stability; (5) presence of either motor and/or sensory deficit detected by clinical examination; (6) ability to understand simple instructions. Patients were excluded if they presented: concomitant orthopedic conditions limiting the wrist ROM (active arm/wrist fractures, fixed contractures, arthritis and/or wrist fusion), arm or wrist joint pain (Visual Analogue scale VAS $>5/10$), wrist spasticity (modified Ashworth Scale score ≥ 2), instability and/or severe hemispatial neglect. All participants were screened by means of the Montreal Cognitive Assessment (MoCA) [17], which resulted in scores $> 28/30$, indicating the absence of cognitive impairments. Patients' demographic data are reported in Table I. Prior to recruitment, patients signed the informed consent form which conformed to the ethical standards expressed in the 1964 Declaration of Helsinki. The study methodology was approved by the Domain Specific Review Board of the National Healthcare Group (NHG).

C. Protocol

Participants sat comfortably on a height-adjustable chair next to the robotic device, and placed their forearms on the arm support of the robot, holding its handle which was placed in the neutral anatomical position set to 0° in all the three DoFs (Fig. 1B). The height of the chair and the position of the robot, which was placed on a side table on casters, were adjusted so that the participants' shoulder was abducted at $\sim 30^\circ$, their elbow was flexed at $\sim 90^\circ$, and the arm formed $\sim 30^\circ$ from the frontal plane. After visually inspecting the alignment of the affected wrist joint with the center of motion of the robot and making the necessary adjustments, the participants' forearm was secured to the robot using Velcro[®]

strips. All participants were instructed to face forwards, to keep the affected arm and wrist relaxed during the whole duration of the experiment. They were required to hold a Stop button with their non-dominant or unaffected hand which was used by the subjects as explained in the following section.

Wrist proprioception was assessed with an ipsilateral JPM procedure employing only passive movements for the patients. The assessment was carried out for each of the wrist's DoFs within the functional ROM. Participants were blindfolded for all the duration of the test. Each trial consisted of separate phases as shown in Fig. 2: (1) from the initial position, the robot moved one of the three DoF to a preset constant position or proprioceptive target (*Criterion* movement), maintained it for 2 seconds and then moved the joint back to the initial configuration; (2) the robot moved the wrist in the same DoF and the patient was requested to stop the movement by pressing the hand-held button when he felt that the target position was matched (*Matching* movement). Finally, the robot brought the subject's wrist back again to the initial position for the next trial.

Participants did not receive any feedback on their online performance to eliminate the possibility of recalibration of the responses during testing, based on the direct knowledge of performance. *Criterion* and *Matching* movements were displayed by the robot at different velocities so that participants could not rely on the movement duration but had to focus only on proprioceptive information. The *Criterion* movement had a velocity of $8^\circ/s$ while the velocity was set to $5^\circ/s$ for the *Matching* movement. Targets were positioned at $\pm 30^\circ$ for FE, $\pm 20^\circ$ for AA and $\pm 30^\circ$ for PS. Participants performed a total of 6 Target Sets, where a Target Set consisted in a sequence of 6 trials in Flexion, Extension, Abduction, Adduction, Pronation and Supination, resulting in a total of 36 trials. After two target sets, a 1-minute break was provided to avoid drift in the proprioceptive sense. The duration of the complete assessment was ~ 10 minutes.

D. Data analysis

Wrist proprioception was measured in terms of *Absolute error*, *Signed error*, and *Variability*. The *Absolute error* measures the matching accuracy defined as:

$$\text{Absolute Error} = \text{median} |\theta_T - \theta_i| \quad (1)$$

where θ_i is the recognized target position during the i -trial and θ_T is the target position. The median error across N repetitions of the same target in each of the tested DoFs was considered for the statistical analysis, where $N = 6$. The *Signed Error* measures the directional bias of the error and is defined as:

$$\text{Signed Error} = \text{median}(\theta_T - \theta_i) \quad (2)$$

A negative signed error indicates target overshooting, while a positive value indicates undershooting.

The *Variability* reflects the precision of the target matching and is defined as:

$$\text{Variability} = \text{std}(\theta_T - \theta_i) \quad (3)$$

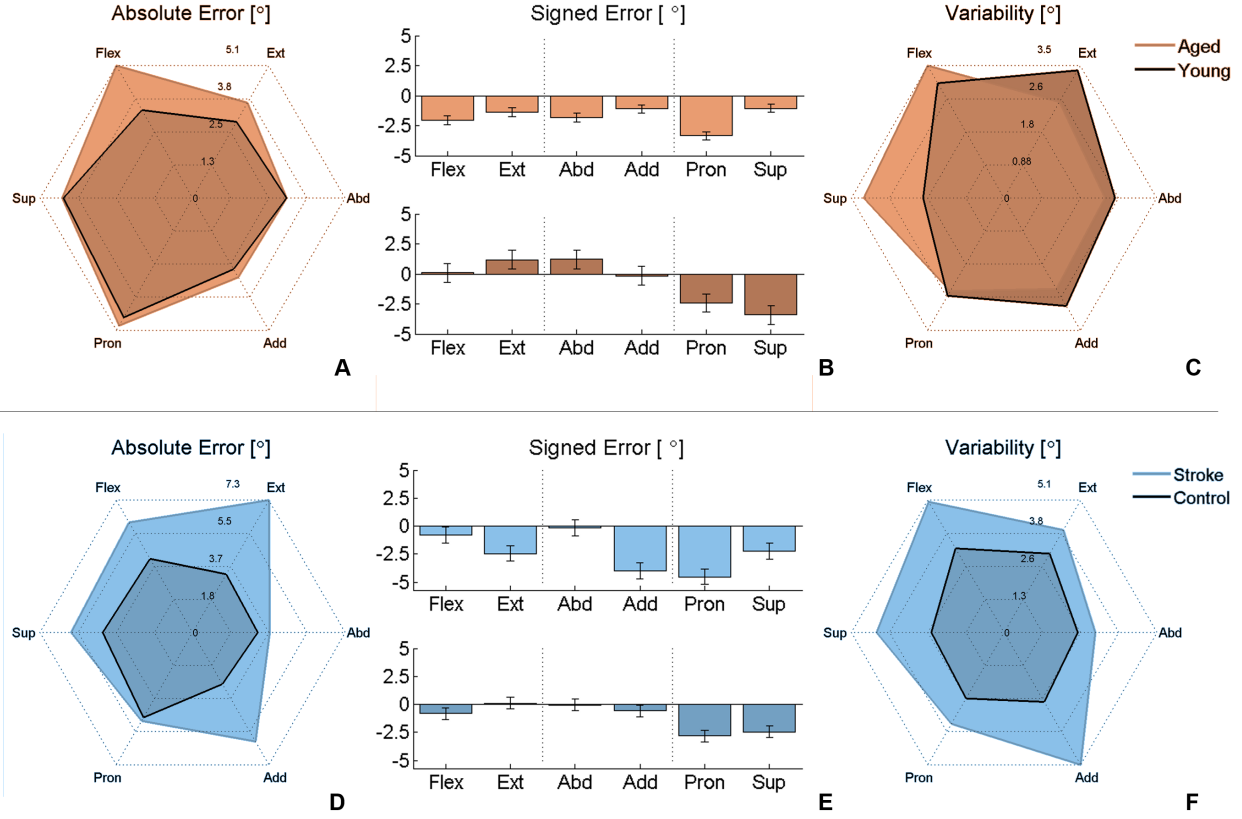


Fig. 3. Top: comparison of healthy Aged and Young groups for different movement directions: (A) Absolute errors, (B) Signed errors and (C) Variability. Bottom: Comparison between Controls and Stroke subjects: (D) Absolute errors, (E) Signed errors and (F) Variability.

For each participant, the median value across trials was used as measures of *Absolute* and *Signed errors* to limit the influence of outlying values. Data from the healthy group undergoing the revised JPM task were analyzed to evaluate the effect of age and target position by mean of a mixed design ANOVA with between-factor Age (Aged, Young) and within-factor Movement (Flexion, Extension, Abduction, Adduction, Pronation, Supination).

Similarly, differences in proprioceptive performance between all healthy participants and stroke patients were analyzed with a mixed ANOVA with between-factor Group (Stroke, Control) and within-factor Movement (Flexion, Extension, Abduction, Adduction, Pronation, Supination). Pairwise comparisons were also performed to evaluate similarities in matching performance in the different DoFs (FE, AA and PS). Results with p -values < 0.05 were considered significant and were submitted to Bonferroni corrected post-hoc analyses.

III. RESULTS

A. Effect of age and movement in healthy matching performance

Data analysis revealed that one subject among the *Young* group could not correctly perform the assessment due to a misunderstanding of the task instructions. Indeed, the

analysis of errors for Subject 5 revealed *Variability* values which exceeded the mean values by 3 standard deviations or more: 16.2° and 12.3° for FE, 9.1° and 8.5° for AA and 8.2° and 5.6° for PS. Data from this participant were therefore excluded from further analysis.

The statistical test detected a significant effect of Movement on *Absolute errors*, $F_{(5,50)} = 3.38$, $p = 0.01$. Pairwise comparisons revealed differences between errors in Flexion and Abduction ($p = 0.04$), and the analysis of DoF revealed that the highest difference between DoFs was found between the AA ($2.99 \pm 1.21^\circ$) and PS ($4.50 \pm 1.70^\circ$), which however did not quite reach significance ($p = 0.07$). Mean *Absolute error* \pm SEM was $3.64 \pm 1.45^\circ$ for FE. *Absolute errors* in the two groups were not significantly affected by Age, $F_{(1,10)} = 0.61$, $p = 0.45$, as shown in Fig. 3A.

A significant effect of Movement was found for the *Signed errors*, $F_{(5,50)} = 5.02$, $p = 0.001$, with a significant difference between movements in Extension and Pronation ($p = 0.01$). The analysis of the separate DoFs showed a significant difference between the PS DoF ($-2.62 \pm 3.37^\circ$) and both FE ($-0.35 \pm 3.64^\circ$) and AA ($-0.31 \pm 2.94^\circ$), both p 's < 0.01 . The analysis of *Signed errors* revealed that the *Aged* group had a preference for target overshooting in all directions, which was not observed in the *Young* group (Fig. 3B). However, the statistical analysis reported that *Signed errors* were not

significantly different between groups, $F_{(1,10)} = 0.41$, $p = 0.54$.

No differences associated to Movement and Age were found for the *Variability* metric, $F_{(5,50)} = 0.96$, $p = 0.45$, $F_{(1,10)} = 0.01$, $p = 0.94$ respectively. Mean values \pm SD are shown in Fig. 3C, and were $3.14 \pm 1.02^\circ$, $2.57 \pm 0.65^\circ$ and $2.49 \pm 1.23^\circ$ respectively for FE, AA and PS.

B. Comparison of healthy and stroke matching performance

Mean *Absolute error* \pm SEM evaluated in the *Stroke* group was $5.6 \pm 0.4^\circ$, which resulted significantly higher compared to that of the *Control* group ($3.7 \pm 0.3^\circ$), $F_{(1,19)} = 14.81$, $p = 0.001$. The analysis revealed also a significant effect of Movement, $F_{(5,95)} = 2.38$, $p = 0.04$, and an interaction effect between Group and Movement, $F_{(5,95)} = 2.88$, $p = 0.02$. Errors magnitude was higher for the *Stroke* group in all movement directions, as shown in Fig. 3D, and the post-hoc analysis detected significant differences between the two groups for movements in Extension (mean difference \pm SEM = $4.08 \pm 1.0^\circ$) and Adduction ($3.17 \pm 0.8^\circ$), both $p = 0.01$.

The analysis of *Signed errors* showed the tendency to overshoot the target positions for both groups in all movement directions (Fig. 3E). Matching performed by stroke patients resulted in an average *Signed error* of $-2.3 \pm 1.2^\circ$ which was similar to the analogous error for the *Control* group ($-1.1 \pm 1.0^\circ$), $F_{(1,19)} = 0.66$, $p = 0.43$. An effect of Movement was found, $F_{(5,95)} = 3.48$, $p = 0.006$, with greater overshooting amplitude in the PS DoF ($< -2.33^\circ$) and no preference in over/undershooting in Abduction ($-0.1 \pm 0.8^\circ$). The post-hoc analysis reported significant differences between Abduction and Adduction (mean difference \pm SEM = $2.2 \pm 0.5^\circ$) and Abduction and Pronation ($3.6 \pm 0.8^\circ$). No interaction between Movement and Group was found, $F_{(5,95)} = 1.24$, $p = 0.30$.

Stroke patients showed a more variable estimation of the target position ($4.2 \pm 0.6^\circ$) compared to the *Control* group ($2.7 \pm 0.5^\circ$). However, the statistical analysis failed to detect a significant difference in matching precision between groups, $F_{(1,19)} = 3.56$, $p = 0.07$. *Variability* was similar independently from movement direction, $F_{(5,95)} = 1.71$, $p = 0.14$, and ranged from $2.8 \pm 0.3^\circ$ for Abduction to $4.1 \pm 0.6^\circ$ for Flexion, as shown in Fig. 3F.

IV. DISCUSSIONS

The first goal of this preliminary study was to establish proprioceptive performances of healthy subjects by mean of a revised JPM task and to verify the efficacy of this approach before its application in clinical environments. The data gathered are the initial components of a database that will be increasingly populated to form the baseline measurements for applications with stroke patients. We evaluated the capability of the passive JPM protocol to discriminate *Matching errors* and *Variability* along the wrist DoFs, which, due to different innervations, have been shown to present different proprioceptive performances. We observed significant difference across directions in terms of *Absolute* and *Signed errors*, with smaller errors found in the AA DoF, which is an expected outcome considering the higher density of receptors

in the ligaments involved in these movements [18], [19]. This result provides evidence in support of the good sensitivity of the protocol for detecting small differences in acuity in the different DoFs. Similarly to the healthy group, we found differences in matching accuracy across movements for the stroke group, which, again, may be related to the mechanoreceptor density and innervation. Moreover, the common trend of target overshooting in PS can be related to the different anatomical districts involved (the proximal radioulnar joint and the distal radioulnar joint) and consequently different sets of muscles, ligaments and hence mechanoreceptors [20].

The second goal of the study was to examine the effect of aging on proprioception by comparing data collected from two groups of healthy participants, i.e. *Young* and *Aged*, where the age of the latter group was chosen to match the stroke patients' one. Similar to the results obtained for the arm proprioception [21], we found no significant changes in matching accuracy as a result of aging in the population analyzed. However, due to the small sample size and the absence of healthy participants older than 60 years, a further study is needed to confirm this finding, as previous studies on the effect of aging on proprioception which tested performance of older participants, reported a reduction of limb position acuity with aging [22], [23]. This future study will also determine if such result is due to the methodologies employed by the groups of Adamo and Stelmach, which consisted in the bilateral active limb matching tasks.

Finally, we compared *Matching errors* and *Variability* of position estimation of acute and subacute stroke patients with control data to verify the robustness of the proposed approach in differentiating between healthy and stroke participants in relation to movement dependence. We limited the effect of non-sensory factors, including motor impairment, inadequate comprehension and visuo-perceptual impairment by passively imposing wrist positions and by using selection criteria that excluded the presence of cognitive issues and neglect.

All participants could complete the assessment thanks to the passive nature of the test, for which wrist movements were imposed by the robot, allowing the screening of highly impaired patients, such as S2, S3 and S4 (Fugl-Meyer Motor function Assessment score of 4, 4 and 12 respectively). The robotic test can be therefore implemented in clinical settings to screen a wide range of stroke patients, at the same time limiting problems of inter-rater variability and can reduce costs by lowering the reliance of a clinician or therapist to obtain proprioceptive diagnostics. The approach can be potentially applied to more proximal/distal joints by mean of robotic devices with similar performances. In particular, they must have high encoder resolution, elevate positioning accuracy, and wide torque range.

The analysis of *Matching errors* of the stroke group revealed that, similarly to healthy participants, patients systematically overshoot the target position, but that the magnitude of the errors was significantly higher than the control group, and that the final position estimate was, in general, more variable, but not statistically different, than the one observed in

the control group. These results support the previous findings reporting the presence of a significant proportion of patients displaying somatosensory impairments after stroke [8], [9], while do not corroborate the results obtained by Niessen et al, who did not find differences in performance for passive reproduction of shoulder positions between 22 patients and 10 control subjects [24]. This finding supports the idea that proprioceptive scores are joint specific and should not be generalized to other body locations due to the high variability in lesion site and severity of stroke. Moreover, in the study by Niessen et al, joint position sense was evaluated 14.7 weeks post-stroke, which was performed later than the studies by the groups of Kattenstroth and Carey (2.3 and 7 weeks respectively). In our study, patients were screened before an average of 2.7 weeks post-stroke, with 5 patients screened within two weeks from the event. Therefore, it is possible that our results succeed in better capturing the transient loss or disturbance in sensation occurring during the first weeks post-stroke [25]. A future study will address this point by evaluating proprioceptive changes over time through multiple assessments by mean of the same device and protocol in order to evaluate its correlation with rehabilitation practice and motor recovery.

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