IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received 7 September 2023, accepted 2 October 2023, date of publication 13 October 2023, date of current version 18 October 2023.
Digital Object Identifier 10.1109/ACCESS.2023.3323398

RESEARCH ARTICLE

Upper Limb Position Matching After Stroke: Evidence for Bilateral Asymmetry in Precision but Not in Accuracy

GIULIA BALLARDINI[1,2], ADELE CHERPIN[3,4], KAREN S. G. CHUA[5], ASIF HUSSAIN[4], SIMONE KAGER[6,7], (Member, IEEE), LIMING XIANG[8], DOMENICO CAMPOLO[3], AND MAURA CASADIO[1,9]

[1]Department of Informatics, Bioengineering, Robotics, and Systems Engineering, University of Genova, 16126 Genoa, Italy
[2]Max Planck Institute for Intelligent Systems, 70569 Stuttgart, Germany
[3]Robotic Research Center, Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore 639798
[4]Articares Pte Ltd., Singapore 139950
[5]Clinic for Advanced Rehabilitation Therapeutics, Tan Tock Seng Hospital Rehabilitation Centre, Singapore 569766
[6]NUS Graduate School for Integrative Sciences and Engineering, National University of Singapore, Singapore 119077
[7]Future Health Technologies Programme, Singapore-ETH Centre, Singapore 138602
[8]School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore 639798
[9]RAISE Ecosystem, 16126 Genoa, Italy

Corresponding author: Giulia Ballardini (giulia.ballardini@edu.unige.it)

This work was supported in part by the Project ''RAISE—Robotics and AI for Socio-economic Empowerment;'' in part by the European Union—NextGenerationEU; in part by the Ministry of Science and Technology, Israel Joint Israel-Italy Laboratory in Biorobotics ''Artificial Somatosensation for Humans and Humanoids;'' in part by the National Medical Research Council (NMRC), Singapore, under Grant NMRCB2b0006c; in part by the Ministry of Health, Singapore, through the H-Man Project, under Grant NMRC/BnB/0006b/2013; in part by the Ageing Research Institute for Society and Education (ARISE), Singapore, under Grant M4082063; and in part by the Interdisciplinary Graduate School, Nanyang Technological University, Singapore, from 2013 to 2018.

This work involved human subjects or animals in its research. Approval of all ethical and experimental procedures and protocols was granted by the National Healthcare Group Domain Specific Review Boards and Nanyang Technological University Domain Specific Review Boards.

ABSTRACT Assessment and rehabilitation of the upper limb after stroke have focused primarily on the contralesional arm. However, increasing evidence highlights functional sensorimotor alterations also in the ipsilesional arm. This study aims to evaluate the position sense of both arms after stroke using a passive position matching task. We hypothesized that the ipsilesional arm would have higher accuracy and precision than the contralesional arm but lower than the dominant arm in unimpaired participants. Additionally, we hypothesized a correlation in performance between the two arms in stroke survivors. The study included 40 stroke survivors who performed the proprioceptive test with both arms and 24 unimpaired participants who performed it with their dominant arm. During each trial, a planar robot moved their hand to a target and back. In the Participants had to indicate when their hand reached the target position in the second phase. We evaluated performance by computing the matching accuracy and precision. We found that the ipsilesional arm had similar matching accuracy but higher precision than the contralesional arm. Furthermore, only the matching accuracy of the two arms was correlated in the left and central regions of the workspace. When comparing stroke survivors to unimpaired participants, the ipsilesional arm exhibited significantly lower accuracy, yet not different precision. These findings support the notion that the ipsilesional arm is not 'unaffected' by stroke but rather 'less-affected', suggesting that stroke does not impact ipsilesional position sense precision. Additionally, the results suggest a dissociation between accuracy and precision in passive multi-joint position matching tasks.

INDEX TERMS Hemispheric asymmetries, matching task, proprioception, robotic assessment, stroke survivors.

The associate editor coordinating the review of this manuscript and approving it for publication was Jingang Jiang.

I. INTRODUCTION

Stroke is the second leading cause of disability worldwide [1]. Six months after stroke, more than 50% of stroke survivors experience reduced upper limb function [2], severely limiting their ability to perform daily activities and live autonomously [3]. Therefore, rehabilitation of upper limb function in stroke survivors is a crucial objective [4]. This requires evaluating and accounting for any atypical movement patterns, alterations in strength, and sensory perception in both arms [5], [6]. In relation to the cerebral lesion, the ipsilesional upper limb (iUL) - often referred to as the 'unaffected' or 'unimpaired' - is used as a reference for assessing the - 'affected' or 'impaired' - contralesional upper limb (cUL) [7], [8]. However, increasing evidence suggests that significant impairment of the ipsilesional arm may persist from the acute to the chronic stage of stroke (see [6] for a review). Although previous studies on ipsilesional impairment have predominantly evaluated motor deficits, limited attention has been paid to somatosensation or proprioception. Early studies of motor deficits in the ipsilesional arm reported muscle weakness [8], [9], [10], while more recent studies have shown that it also exhibits deficits in accuracy, dexterity, and motor coordination [5], [11], [12], [13], [14], [15], [16], [17], [18]. On the other hand, studies on sensory deficits have shown impairments in stereognosis [19], tactile perception [20], and altered thresholds for light touch [21], [22], motion detection [23], point localization [19], [24], two-point discrimination [25], [26], and pressure sensitivity [25], [27]. Some of these deficits can be detected by standard clinical methods such as the Jebsen Hand Function Test [5], [7].

Currently, approximately fifty techniques could be used to assess position sense in both clinical and research settings [28], often with inconsistent results. Many of these methods require participants to perform active movements [29], [30], [31], [32], making it difficult to assess motor and proprioceptive performance separately. More generally, these methods can be categorized into three approaches that investigate the effects of stroke on proprioceptive performance. In the first two approaches, the proprioceptive performance of control subjects is compared with that of either the contralesional - most commonly - or the ipsilesional arm. The third approach directly compares the proprioceptive performance of the two arms, providing information on the lateral asymmetry of proprioceptive performance. For this reason, this approach is also used to investigate hemispheric specialization [33]. The mirror position matching task is the most commonly used assessment method in stroke survivors. In this task, the contralesional arm is moved to specific positions by either a physiotherapist or a robotic device. Participants are then asked to replicate the position of their contralesional arm with the ipsilesional arm using mirror-symmetric movements [29], [31], [34], [35]. However, this paradigm requires active movements by the participants and assesses proprioception of both arms simultaneously [36], [37]. Thus, it does not allow for independent determination of deficits in each arm or their mapping in the workspace, which can only be determined with unimanual position matching tasks.

Furthermore, recent studies suggest that hemispheric specialization influences the sensorimotor deficits observed in both arms after stroke [5], [12], [14], [38], [39], [40]. Nevertheless, current evidence is limited and conflicting regarding the influence of both hemisphere lesion side and arm position in the workspace on upper limb position sense. For example, tactile sensation in stroke survivors with right brain damage (RBD) has been reported to be either better [22], [25], equal [21], or worse [20] than that of survivors with left brain damage (LBD).

In this context, this study aims to fill these gaps by assessing the position sense of the ipsilesional arm after stroke in a passive unimanual position matching task. We compared the proprioceptive performance of the ipsilesional arm with that of the contralesional arm and investigated the influence of the hemisphere lesion side with respect to the target position in the workspace. We further evaluated the proprioceptive performance of the ipsilesional arm by comparing it with that of the dominant arm (D) of a group of unimpaired adult participants.

II. MATERIAL AND METHODS

A. PARTICIPANTS

40 stroke survivors (age range: 31-72 years old, see Table 1) and 24 participants without any known sensorimotor impairment or history of neurological, psychiatric, or neuromuscular disorders (age range: 21-58 years old, mean age $\pm$ std: 37.2 $\pm$ 14.2 years old; 10 females) completed the proprioceptive test.

Stroke survivors underwent an initial screening described in [41]. In fact, the stroke survivors in this study are a subset of the participants recruited in [41]. The inclusion criteria were: (i) first-ever stroke event diagnosed by neurologists or neurosurgeons and brain imaging; (ii) age ranging from 21 to 85 years; (iii) being between 3 and 24 months after the stroke event - post-acute stroke phase; (iv) having a score on the Upper Extremity portion of the Fugl-Meyer Assessment (FMA-UE) > 20, and the absence of motor ataxia; (v) having the ability to understand instructions and give informed consent; (vi) absence of uncontrolled medical conditions and pregnancy; (vii) having a life expectancy greater than 6 months; (viii) having the ability to sit upright with support for more than 90 minutes; (ix) absence of arm-related contraindications to robot-aided therapy such as shoulder pain (Visual Analog Scale for pain $\leq$ 4); (x) absence or low level of spasticity (Modified Ashworth Scale $\geq$ 2); (xi) absence of hemispatial neglect as assessed by the line bisection test; (xii) having a mini-mental state examination score $\geq$ 27.

Inclusion criteria for all participants were to be naïve to the study and right-handed. For stroke survivors, the latter requirement was based on their hand dominance prior to the stroke event. This was motivated by the fact that hand

TABLE 1. Demographic data and clinical test results.

	Lesion Side Left	Lesion Side Right	All
Sex (female/male)	13 / 15	5 / 7	18 / 22
Age (years), mean (SD)	57 (9)	54 (13)	56 (10)
Nature (hemorrhagic/ischaemic)	16 / 12	4 / 8	20 / 20
Days after stroke, mean (SD)	358 (203)	476 (197)	395 (208)
Location			
Basal Ganglia-Thalamus-subcortical	14	1	15
Lacunar Stroke	7	1	8
Posterior Circulation Stroke	2	1	3
Partial Anterior Circulation Stroke	3	4	7
Cortical	0	3	3
Other	2	2	4
FMA-UE [a] scores, mean (SD)	40.4 (10.5)	33.7 (8.0)	38.4 (10.3)
ARAT [b] scores, mean (SD)	24.4 (15.9)	18.4 (14.7)	22.6 (15.8)
FAT [c] scores, mean (SD)	1.5 (1.5)	0.8 (1.3)	1.3 (1.5)

[a]FMA-UE: Upper Extremity portion of the Fugl-Meyer Assessment (0-66); [b]ARAT: Action Research Arm Test (0-57); [c]FAT: Frenchay Arm Test (0-5).

dominance could be a confounding factor in this study, which takes into account the hemispheric location of the lesion.

A total of 41 stroke survivors who met the inclusion criteria were included in the study. However, one participant's data was excluded from the analysis because he/she did not complete the proprioceptive test and performed it with only one arm. Based on clinical history, it was determined that 28 stroke survivors had left hemisphere damage, while 12 had right hemisphere damage (Table 1).

As a preliminary analysis, we performed a Wilcoxon rank sum test to verify that there were no statistically significant differences in age or clinical scores (FMA-UE, Action Research Arm Test: ARAT, Frenchay Arm Test: FAT, reported in Table 1) between the stroke survivors with left and right hemisphere damage. The results showed no significant difference in either age ($p = 0.701$) or clinical scores (FMA-UE $p = 0.111$; ARAT $p = 0.360$; FAT $p = 0.169$) between the two groups. However, the differences between the two groups in the ARAT and FMA-UE scores of 6 and 6.7 points, respectively, are above the minimally clinically important difference (MCID) obtained as change over time in the same population of chronic stroke survivors (5.7 for ARAT [42], [43] and 5.25 for FMA-UE [44]). It is worth noting that stroke survivors and unimpaired participants had a significant difference in age ($p<0.001$); therefore, they cannot be considered age-matched groups. We acknowledge this limitation and have taken it into account in the analysis and discussion. Further analysis of the effect of age on unimpaired participants is presented in Appendix A.

The stroke participants' assessments were conducted by locally licensed senior occupational therapists at the Center for Advanced Rehabilitation Therapeutics (CART), Tan Tock Seng Hospital (TTSH), Singapore. Stroke participants were recruited consecutively from discharged inpatients and outpatients from the TTSH Rehabilitation Centre and CART. Prior to recruitment, ethical approval for all procedures was obtained from the National Healthcare Group Domain Specific Review Boards (NHG-DSRB 2014/00122) for stroke survivors and from Nanyang Technological University (NTU), Domain Specific Review Boards for unimpaired participants. All participants provided written informed consent to participate in the study. The study was conducted in accordance with the revised Declaration of Helsinki (2013). Proprioceptive tests on unimpaired participants were conducted at the NTU robotic research center.

B. EXPERIMENTAL SET-UP

The proprioceptive assessment was performed using H-Man, a portable and planar endpoint robot designed to assess and train upper limb sensorimotor function. This robot has been used in studies with unimpaired participants and stroke survivors [41], [45], [46], [47].

Briefly, participants were seated in a height-adjustable chair in front of the H-Man robot. The participants' sternum was aligned with the midline of the robot's workspace. Their hand either grasped or was secured to the handle of the robot, which in the starting position was on their midline, approximately 25 cm from their sternum. This positioning required an elbow angle of approximately 90° (Fig. 1). To prevent trunk movement, shoulder straps were fastened to the chair, restricting movement to shoulder rotation and elbow flexion/extension only.

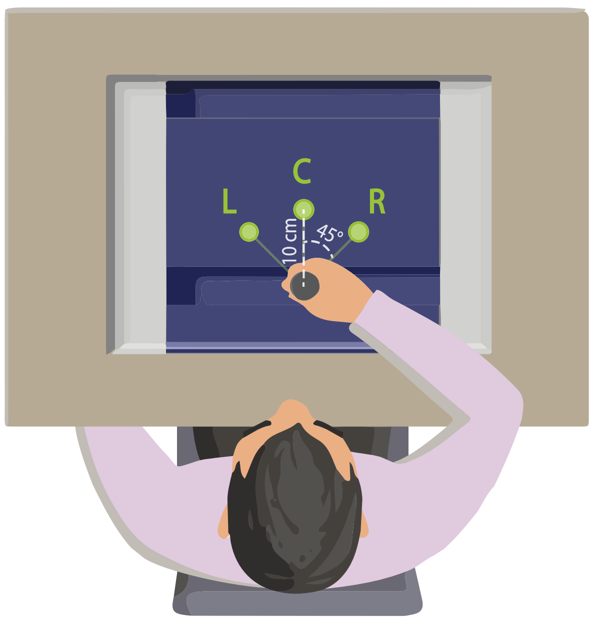

FIGURE 1. Experimental set-up. Participants were seated in front of H-Man, with the center of their sternum aligned with the center of the robot's workspace, where the starting position was located (gray). They had to grasp the robot's handle, which was moved by the robot to one of three possible target locations (green), located 10 cm from the starting position at 0° (central: C) and ± 45° (right: R, left: L) with respect to the participant's midline.

C. PROTOCOL

Throughout the experiment, participants were asked to keep their eyes closed (or blindfolded, if requested by the participant), and their arm muscles relaxed.

Each trial consisted of two phases: the 'reference' phase and the 'matching' phase. In the reference phase, the handle of the robot moved at a constant speed of 7 cm/s from the starting position to a target position, where it remained for 2 s before returning to the starting position at the same speed. After a 1-second interval, the matching phase started. In this phase, the robot's handle moved at a constant speed of 2 cm/s toward the same target. Participants were instructed to verbally report when they felt that their hand had reached the target position (perceived target position). The experimenter immediately ended the trial by stopping the movement of the handle, after which the handle returned to the starting position. Since proprioception is affected by speed [48], the same speed of the robot's handle was used in all trials to make performance comparable. However, participants could not rely on movement time to identify the target position because the speed varied between the two trial phases. In addition, participants did not receive any feedback on their performance in each trial. Targets were positioned at a distance of 10 cm from the starting position in three different directions: 0° (central target) and ± 45° (left and right targets) relative to the participants' midline. Each target was presented 6 times in random order for a total of 18 trials. Unimpaired participants performed the test with their dominant arm (see Appendix B for the analysis of the differences between the two arms in unimpaired participants). Stroke survivors performed the same test with both their contralesional and ipsilesional arms. The order in which arms were tested was counterbalanced across participants. All participants completed at least 3 and up to 10 trials to become familiar with the task prior to the proprioceptive assessment.

D. DATA ANALYSIS

First, we computed the matching error as the signed difference between the perceived and the true target position, as in [49]. Then, to assess proprioceptive performance, we computed the following indicators:

- Constant error, as the mean of the matching error across trials to the same target. Before averaging across participants, we considered the unsigned value of the matching error, since we were interested in evaluating overall accuracy, not the tendency of participants to overshoot or undershoot the target distance;
- Variable error, as the standard deviation of the matching error across trials to the same target. This represents precision, i.e., the repeatability (consistency) of performance across trials.

This study did not evaluate the difference between the contralesional arm and the dominant arm of unimpaired participants, as this has already been investigated in previous studies using the same experimental design and protocol [47], [50].

1) STATISTICAL ANALYSIS

The aim of this study was to evaluate whether there were differences between the proprioceptive performance of the two arms in stroke survivors during a passive unimanual position matching task. To achieve this, we compared the proprioceptive performance of the ipsilesional and contralesional arms using repeated measures ANOVA (rm-ANOVA) with two within-subjects factors: 'arm' (2 levels: 'iUL' and 'cUL'), and 'target' (3 levels: 'left', 'central' and 'right'). Furthermore, we also compared the performance of the ipsilesional arm and the dominant arm of the unimpaired participants using a mixed-design ANOVA with 'population' as a between-subjects factor (2 levels: 'unimpaired' and 'stroke'), and 'target' as a within-subjects factor (3 levels). Before running the ANOVAs, we tested the normality of the data with the Anderson-Darling test. Since the null hypothesis was rejected, we used a two-step transformation based on fractional ranks reported in [51] to correct the data. For both ANOVAs, we tested for sphericity using Mauchly's test, and for the mixed ANOVA, we also tested for equality of variances using Levene's test. None of the metrics violated these assumptions. Statistical significance was set at a family-wise error rate of $\alpha = 0.05$. To account for multiple comparisons, we applied the Bonferroni correction and set the threshold required for the significance at $\alpha = 0.05/2 = 0.025$. No further pairwise comparisons or post hoc analyses were performed.

Finally, we investigated whether there was a correlation between the proprioceptive performance of the two arms in stroke survivors and whether this correlation was influenced by the hemisphere of the lesion or the target position in the workspace. To this end, we computed Spearman's correlation coefficient between the performance of the two arms. Two separate factors were considered: (i) the side of the brain lesion (LBD and RBD stroke survivors), and (ii) the target position (left, central, right). According to [52], Spearman's correlation coefficient (ρ) ranging from 0.20 to 0.39 indicates a moderate correlation, while a range of 0.40 to 0.59 is considered relatively strong, and 0.60 to 0.79 is a strong correlation. A correlation coefficient equal to or over 0.80 indicates a very strong correlation. When we found at least a moderate correlation ($\rho \geq 0.20$), curve fitting was performed using monotonic least-squares splines, and the R-squared was used to examine the proportion of variance that was predictable.

III. RESULTS

To investigate whether the position sense of the ipsilesional arm in stroke survivors was impaired, we compared its performance indicators, namely constant error (Fig. 2a) and variable error (Fig. 2c), with (i) the contralesional arm and (ii) the dominant arm of unimpaired participants.

Comparing the two arms of stroke survivors, we found no significant difference in the matching accuracy ($F_{1,39} = 0.05$, $p = 0.823$, $\eta^2 = 0.001$), while there was a significant difference in the matching precision ($F_{1,39} = 6.94$, $p = 0.012$, $\eta^2 = 0.151$). Specifically, the ipsilesional arm had higher precision than the contralesional arm, i.e., less variability in identifying the same position in space.

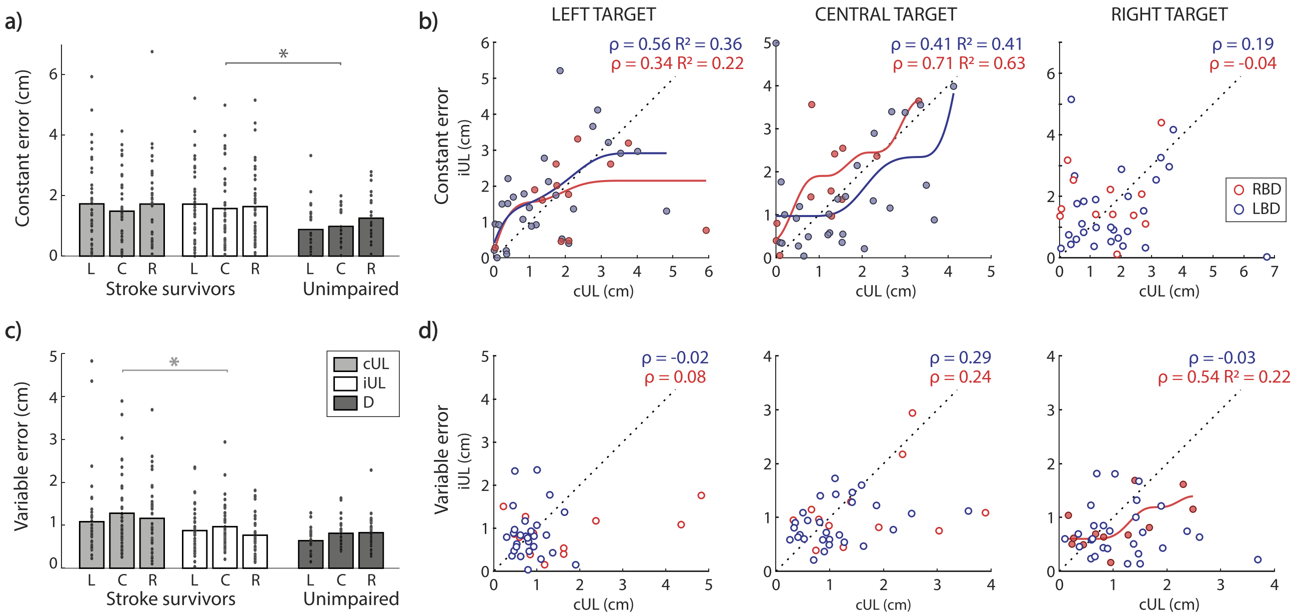

FIGURE 2. **a,b) Constant error - the unsigned value of the constant component of the matching error - c,d) Variable error. a,c) Performance parameters of the ipsilesional (white), contralesional (gray) arm of stroke survivors, and the dominant arm of unimpaired participants (dark gray) for left, central, and right targets with respect to the participant's midline. * indicates statistical significance, p<0.025; dots indicate single-subject data. b,d) Correlation between the two arms of stroke survivors for the three targets. Red and blue circles indicate the errors of RBD and LBD stroke survivors, respectively. Circles are filled when there is at least moderate correlation (Spearman's coefficient $\rho \geq 0.20$). In these cases, we also report the R^2 value and the monotonic fit curve. The dashed line represents the equal performance of the two arms.**

Furthermore, the ipsilesional arm showed significantly lower accuracy ($F_{1,62} = 5.57$, $p = 0.021$, $\eta^2 = 0.132$) than the dominant arm of unimpaired participants, although there was no significant difference in precision ($F_{1,62} = 0.78$, $p = 0.379$, $\eta^2 = 0.015$). Taken together, those results suggest that stroke affected the accuracy of the ipsilesional arm in our population, while precision remained largely unaffected.

Regarding the influence of target location on the ipsilesional proprioceptive performance, we found that it was not significantly altered after stroke (constant error: $F_{2,78} = 1.19$, $p = 0.147$, $\eta^2 = 0.024$; variable error: $F_{2,78} = 3.47$, $p = 0.034$, $\eta^2 = 0.041$). When comparing two arms in stroke survivors, we observed a significant dependence of precision ($F_{2,78} = 3.94$, $p = 0.024$, $\eta^2 = 0.092$) but not accuracy ($F_{2,78} = 1.23$, $p = 0.297$, $\eta^2 = 0.031$), on the target position. Specifically, both arms of stroke survivors showed slightly higher variability for the central target, with no significant arm*target interaction ($F_{2,78} = 0.61$, $p = 0.548$, $\eta^2 = 0.015$). Unimpaired participants did not show the same trend of higher variability in the central target. However, a direct comparison of precision between stroke survivors and unimpaired participants did not yield significant effects after applying Bonferroni corrections (population*target interaction: $F_{2,78} = 2.98$, $p = 0.055$, $\eta^2 = 0.035$). Interestingly, a significant population*target interaction was found in the matching accuracy ($F_{2,124} = 4.21$, $p = 0.017$, $\eta^2 = 0.054$). In unimpaired participants, it increased from the left to the right region of the workspace, while stroke survivors had the lowest accuracy in the central target.

To investigate the correlation between the proprioceptive performance of the two arms in stroke survivors and its relationship to the hemisphere of brain lesion, we computed Spearman's coefficients separately for survivors with right and left brain damage in the three targets.

For the central target, we observed a correlation in accuracy between the two arms of all stroke survivors (LBD: $\rho = 0.41$, RBD: $\rho = 0.71$, Fig. 2b) but not in precision (both $\rho < 0.30$, Fig. 2d). Similar results were also obtained for the left target (Fig. 2b and Fig. 2d), where accuracy had a relatively strong correlation for the LBD group ($\rho = 0.56$) and a moderate correlation for the RBD group ($\rho = 0.34$), while precision showed no correlation in either group of stroke survivors ($\rho < 0.10$). In the right target, the only correlation observed was precision in the RBD group ($\rho = 0.54$, others $\rho < 0.20$).

IV. DISCUSSION

We investigated the position sense of the ipsilesional arm in stroke survivors in a unimanual position matching task that requires passive movement of the shoulder and elbow. Our results suggest that, in terms of matching precision, stroke does not affect the two arms differently. Specifically, we observed that the ipsilesional arm had less variability than the contralesional arm and was comparable to that of unimpaired participants. The precision of the two arms showed only a weak relationship in the right workspace for the RBD stroke survivors.

Conversely, the two arms had comparable matching accuracy, that correlated along the midline and in the left region of the workspace for all stroke survivors, regardless of the hemispheric localization of the brain lesion. The matching accuracy of the ipsilesional arm in stroke survivors was lower than that of the group of unimpaired participants, highlighting a significant decrease in this performance metric.

These findings are discussed in detail below.

A. IN UNILATERAL PASSIVE MATCHING TASK, ONLY THE PRECISION OF THE IPSILESIONAL ARM IS AFFECTED AFTER STROKE

Our findings reveal proprioceptive differences between the two arms of stroke survivors in terms of precision but not in terms of accuracy. This suggests that stroke affects the proprioception of the ipsilesional arm differently than the contralesional arm. These results support the notion that the ipsilesional arm is not 'unaffected' but rather 'less-affected' after stroke.

Our results also suggest a degree of dissociation between accuracy and precision in passive multi-joint matching tasks, which is in line with previous observations in single-joint matching tasks involving active movements [31]. This dissociation seems to be influenced by stroke and/or age. We acknowledge that the group of unimpaired participants included in our study was slightly younger than the group of stroke survivors. It is well known that proprioception deteriorates with age [36], [53], [54], so in this study, we cannot attribute this difference in accuracy solely to stroke. It is more likely that a combination of both age and stroke contributed to this observed effect, although we did not find significant age-related differences in performance within our group of unimpaired participants (see Appendix B).

B. THE CORRELATION BETWEEN THE POSITION SENSE OF THE TWO ARMS DEPENDS ON THE WORKSPACE REGION

We observed a correlation between the proprioceptive performance of the two arms in all of our stroke survivors, specifically in the left and central regions of the workspace relative to the body midline. This finding supports previous studies that have demonstrated the inhomogeneity of perceptual acuity across the 2D workspace in both unimpaired participants [55], [56], [57], [58] and stroke survivors [15], [29], [31], [34], [35] even with the same experimental design in a smaller population of stroke survivors [49]. Furthermore, Contu et al. [49] found that both the contralesional arm of stroke survivors and the dominant (right) arm of age-matched unimpaired participants showed lower matching precision and accuracy for the contralesional target (i.e., the right/left target for the left/right arm). Previous studies have suggested that position sense is impaired after stroke, leading to spatial contraction [29], [34], greater variability, and higher systematic shift [29] compared to controls. However, these studies mainly used wearable robotic devices and did not separately consider the contribution of the two arms [29], [31], [34], [35] or used single-joint paradigms [15].

These spatial differences arise from the interaction of many factors, including limb geometry [56], [59], limb anisotropy [60], spatial biases in muscle spindle firing rates [61], joint movement amplitude (e.g., there is a tendency to overestimate large joint angles [57]) and joint coupling (e.g., elbow extension is overestimated only when the shoulder is abducted [57]). Therefore, further investigation of position sense in multi-joint tasks is needed, as it is not just an extension of findings from unimanual single-joint tasks.

C. MAPPING OF PROPRIOCEPTIVE ACCURACY IN A 2D WORKSPACE IS INDEPENDENT OF THE HEMISPHERE OF THE STROKE LESION

The accuracy of the two arms showed a correlation in the central and left workspace regions relative to the body midline, regardless of the hemisphere affected by the brain lesion. However, the matching precision was only a correlation between the performance of the two arms in the RBD group and was limited to the right workspace.

On one hand, this result supports the hypothesis of a dissociation between accuracy and precision in passive multi-joint matching tasks. On the other hand, the lack of effects of the side of brain lesion on matching performance was unexpected, since its effects on the spatial and temporal aspects of arm movement are well known [11], [12], [13], [16], [38], [39], [40]. Specifically, regarding the ipsilesional arm, Schaefer et al. [39] reported that RBD survivors exhibited lower final position accuracy during reaching movements in the ipsilateral workspace, suggesting deficits in hand position control, while LBD survivors exhibited deficits in trajectory control, suggesting impairment in multi-joint coordination. Conversely, sensory deficits and their dependence on the side of the brain lesion have received less attention compared to motor alterations [62], [63], [64]. However, these studies often provide task-dependent and/or inconsistent results. For instance, some studies have found reduced tactile sensitivity in RBD compared to LBD survivors [22], [25], while others have found the opposite result [20] or no difference [21], [65]. These discrepancies may be due to the different experimental methods used and/or the characteristics of the participants, e.g., age and level of impairment.

To the best of our knowledge, only a few studies have examined the relationship between deficits in upper limb position sense and the side of the brain lesion. Leibowitz et al. [66] found no difference between RBD and LBD groups in the mirror position matching test. Rinderknecht et al. [67] evaluated hand proprioception in a single-joint task and found more severe proprioceptive deficits in RBD than LBD survivors but only for the contralesional hand. They also reported that all stroke survivors had lower proprioceptive performance in the left hand compared to control participants. Thus, although these previous findings may not be directly comparable to our results, they do support our main findings. In particular, the correlation in matching accuracy we found is consistent with the study by Leibowitz et al. [66]. On the other hand, the slight difference in matching precision between the two groups, which we observed only in the right workspace, has not been reported previously. It could be due to the interaction of several factors, such as handedness (with only the LBD group having the contralesional as the dominant arm), differences in position sense between the two arms (as found in single-joint tasks [67]), and differences in tactile ability between the two sides [20]. Further investigation with larger RBD and LBD groups is needed to better understand this latter point.

D. LIMITATIONS

We acknowledge that our proprioceptive assessment requires participants to rely on memory to complete the task [53], as the same arm is used both as a reference in the first phase and to match in the second phase. To mitigate this issue, one of our inclusion criteria for participant enrollment was a score above 27 on the mini-mental state examination.

Another limitation of this study is the absence of clinical evaluation of bilateral proprioception and sensorimotor abilities before the test with the robot. Furthermore, the difference between the motor scores (ARAT and FMA-UE) of the contralesional arm of the two groups of stroke participants, although not statistically significant, is above the minimally clinically important difference. We can not exclude the possibility that this may have contributed to the differences found between the two groups, even though the participants have to rely solely on their proprioception to successfully complete the task. Additionally, the influence of performance based on the region of the workspace may underline a mechanism related to the handedness of the participants, which remains predominant despite the stroke. This is consistent with the findings of Rinderknecht et al. [67]. They reported lower proprioceptive performance for the left (non-dominant) hand of stroke survivors, regardless of the side of their brain lesion. Further studies with left-handed participants in both groups could clarify this point.

V. CONCLUSION

The results of this study add to the actual knowledge of upper limb position sense asymmetries in stroke survivors with respect to passive unilateral matching tasks, their mapping in the 2D workspace, and their relationship with the hemisphere of the brain lesion. It also provides evidence for the need to quantitatively assess both ipsilesional and contralesional proprioceptive deficits for a more complete assessment, which is essential for designing and tailoring effective rehabilitation treatments.

APPENDIX A
EFFECT OF AGE ON POSITION SENSE PERFORMANCE IN UNIMPAIRED PARTICIPANTS

To evaluate the effect of age on the position sense performance of unimpaired participants in this task, we compared the constant and variable components of the matching error (as described in the Data Analysis section). Furthermore, the unimpaired participants were divided into 'younger' (15 participants; age range: 20-34 years, mean age ± std: 26.7 ± 4.0 years; 4 females) and 'older' (9 participants; age range: 46-58 years, mean age ± std: 54.8 ± 3.7 years; 6 females). We performed a mixed-design ANOVA with 'age' as a between-subjects factor (2 levels. 'younger' and 'older') and 'target' as a within-subjects factor (3 levels: 'left', 'central', and 'right'). Before running the ANOVAs, we tested the normality of the data with the Anderson-Darling test. Since the null hypothesis was rejected, we used a two-step transformation based on fractional ranks reported in [51] to correct the data. We also tested for sphericity using Mauchly's test and for equality of variances using Levene's test. None of the metrics violated these assumptions. We found no difference between them in either accuracy ($F_{1,22} = 0.362$ $p = 0.554$) or in precision ($F_{1,22} = 0.231$ $p = 0.636$). This is consistent with previous findings using the same experimental set-up and protocol on a smaller population by Contu et al. [46].

APPENDIX B
DIFFERENCES BETWEEN THE POSITION SENSE OF THE TWO ARMS IN UNIMPAIRED PARTICIPANTS

9 right-handed unimpaired participants (age range: 21-34 years, mean age ± std: 26.2 ± 4.8 years; 2 females) performed the assessment with both the dominant and non-dominant arm. As a preliminary analysis, we evaluated whether there was a difference in performance between the two upper limbs in terms of matching accuracy and precision, computed as described in the Data Analysis section. Therefore, we performed an rm-ANOVA with two within-subjects factors: 'arm' (2 levels: 'dominant' and 'non-dominant') and 'target' (3 levels: 'left', 'central', and 'right'). Before running the rm-ANOVA, we tested the normality of the data using the Anderson-Darling test. Since the null hypothesis was rejected, we used a two-step transformation based on fractional ranks reported in [51] to correct the data. We also tested sphericity using Mauchly's test. None of the metrics violated this assumption. We found that there was no significant difference between the performance of the two arms, neither in terms of accuracy ($F_{1,8} = 0.061$ $p = 0.812$) nor in precision ($F_{1,8} = 0.248$ $p = 0.632$). This result allows us to compare the performance of stroke survivors with only the dominant arm of unimpaired participants. This is consistent with the results found using other proprioceptive evaluations, such as the mirror-matching task [34], [66] and the single-joint 2-alternative choice paradigm [67].

ACKNOWLEDGMENT

The authors would like to acknowledge Sara Contu for her contribution to the clinical trials.

CONFLICT OF INTEREST

Asif Hussain and Domenico Campolo hold equity positions in ARTICARES Pte. Ltd., the company that manufactures and commercializes the robotic technology used in the present study under license from Nanyang Technological University, Singapore. The other authors (Giulia Ballardini, Adele Cherpin, Karen S. G. Chua, Simone Kager, Liming Xiang, and Maura Casadio) have no competing interests to declare and ensure that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

REFERENCES

[1] V. L. Feigin, "Anthology of stroke epidemiology in the 20th and 21st centuries: Assessing the past, the present, and envisioning the future," *Int. J. Stroke*, vol. 14, no. 3, pp. 223–237, Apr. 2019.

[2] D. Buvarp, L. Rafsten, and K. S. Sunnerhagen, "Predicting longitudinal progression in functional mobility after stroke: A prospective cohort study," *Stroke*, vol. 51, no. 7, pp. 2179–2187, Jul. 2020.

[3] G. Birke, S. Wolf, T. Ingwersen, C. Bartling, G. Bender, A. Meyer, A. Nolte, K. Ottes, O. Pade, M. Peller, J. Steinmetz, C. Gerloff, and G. Thomalla, "Protocol for a multicenter observational prospective study of functional recovery from stroke beyond inpatient rehabilitation—The interdisciplinary platform for rehabilitation research and innovative care of stroke patients (IMPROVE)," *Neurological Res. Pract.*, vol. 2, no. 1, pp. 1–8, Dec. 2020.

[4] E. C. V. Lieshout, I. G. van de Port, R. M. Dijkhuizen, and J. M. A. Visser-Meily, "Does upper limb strength play a prominent role in health-related quality of life in stroke patients discharged from inpatient rehabilitation?" *Topics Stroke Rehabil.*, vol. 27, no. 7, pp. 525–533, Oct. 2020.

[5] S. Wetter, J. L. Poole, and K. Y. Haaland, "Functional implications of ipsilesional motor deficits after unilateral stroke," *Arch. Phys. Med. Rehabil.*, vol. 86, no. 4, pp. 776–781, Apr. 2005.

[6] G. H. Kitsos, I. J. Hubbard, A. R. Kitsos, and M. W. Parsons, "The ipsilesional upper limb can be affected following stroke," *Sci. World J.*, vol. 2013, pp. 1–7, Oct. 2013.

[7] A. Sunderland, M. P. Bowers, S.-M. Sluman, D. J. Wilcock, and M. E. Ardron, "Impaired dexterity of the ipsilateral hand after stroke and the relationship to cognitive deficit," *Stroke*, vol. 30, no. 5, pp. 949–955, May 1999.

[8] H. Y. Jung, J. S. Yoon, and B. S. Park, "Recovery of proximal and distal arm weakness in the ipsilateral upper limb after stroke," *NeuroRehabilitation*, vol. 17, no. 2, pp. 153–159, Jun. 2002.

[9] A. Brodal, "Self-observations and neuro-anatomical considerations after a stroke," *Brain*, vol. 96, no. 4, pp. 675–694, 1973.

[10] F. Chollet, V. Di Piero, R. J. S. Wise, D. J. Brooks, R. J. Dolan, and R. S. J. Frackowiak, "The functional anatomy of motor recovery after stroke in humans: A study with positron emission tomography," *Ann. Neurol.*, vol. 29, no. 1, pp. 63–71, Jan. 1991.

[11] Y.-H. Kwon, C. S. Kim, and S. H. Jang, "Ipsi-lesional motor deficits in hemiparetic patients with stroke," *NeuroRehabilitation*, vol. 22, no. 4, pp. 279–286, Oct. 2007.

[12] S. Y. Schaefer, K. Y. Haaland, and R. L. Sainburg, "Ipsilesional motor deficits following stroke reflect hemispheric specializations for movement control," *Brain*, vol. 130, no. 8, pp. 2146–2158, Aug. 2007.

[13] S. Y. Schaefer, P. K. Mutha, K. Y. Haaland, and R. L. Sainburg, "Hemispheric specialization for movement control produces dissociable differences in online corrections after stroke," *Cerebral Cortex*, vol. 22, no. 6, pp. 1407–1419, Jun. 2012.

[14] S. Mani, P. K. Mutha, A. Przybyla, K. Y. Haaland, D. C. Good, and R. L. Sainburg, "Contralesional motor deficits after unilateral stroke reflect hemisphere-specific control mechanisms," *Brain*, vol. 136, no. 4, pp. 1288–1303, Apr. 2013.

[15] S. M. Son, Y. H. Kwon, N. K. Lee, S. H. Nam, and K. Kim, "Deficits of movement accuracy and proprioceptive sense in the ipsi-lesional upper limb of patients with hemiparetic stroke," *J. Phys. Therapy Sci.*, vol. 25, no. 5, pp. 567–569, 2013.

[16] D. B. Carvalho, S. M. S. F. Freitas, F. A. D. Alencar, M. L. Silva, and S. R. Alouche, "Performance of discrete, reciprocal, and cyclic movements of the ipsilesional upper limb in individuals after stroke," *Exp. Brain Res.*, vol. 238, no. 10, pp. 2323–2331, Oct. 2020.

[17] L. Pellegrino, M. Coscia, C. Pierella, P. Giannoni, A. Cherif, M. Mugnosso, L. Marinelli, and M. Casadio, "Effects of hemispheric stroke localization on the reorganization of arm movements within different mechanical environments," *Life*, vol. 11, no. 5, p. 383, Apr. 2021.

[18] G. Marchesi, G. Ballardini, L. Barone, P. Giannoni, C. Lentino, A. De Luca, and M. Casadio, "Modified functional reach test: Upper-body kinematics and muscular activity in chronic stroke survivors," *Sensors*, vol. 22, no. 1, p. 230, Dec. 2021.

[19] J. S. Kim and S. Choi-Kwon, "Discriminative sensory dysfunction after unilateral stroke," *Stroke*, vol. 27, no. 4, pp. 677–682, Apr. 1996.

[20] T. Boll, "Right and left cerebral hemisphere damage and tactile perception: Performance of the ipsilateral and contralateral sides of the body," *Neuropsychologia*, vol. 12, no. 2, pp. 235–238, Mar. 1974.

[21] J. P. Essing, J. W. Gersten, and P. Yarnell, "Light touch thresholds in normal persons and cerebral vascular disease patient: Bilateral deficit after unilateral lesion," *Stroke*, vol. 11, no. 5, pp. 528–533, Sep. 1980.

[22] N. M. Lima, K. C. Menegatti, É. Yu, N. Y. Sacomoto, T. D. Oberg, and D. C. Honorato, "Motor and sensory effects of ipsilesional upper extremity hypothermia and contralesional sensory training for chronic stroke patients," *Topics Stroke Rehabil.*, vol. 22, no. 1, pp. 44–55, Feb. 2015.

[23] M. H. Niessen, D. H. Veeger, P. A. Koppe, M. H. Konijnenbelt, J. van Dieen, and T. W. Janssen, "Proprioception of the shoulder after stroke," *Arch. Phys. Med. Rehabil.*, vol. 89, no. 2, pp. 333–338, Feb. 2008.

[24] S. Corkin, B. Milner, and T. Rasmussen, "Effects of different cortical excisions on sensory thresholds in man," *Trans. Amer. Neurological Assoc.*, vol. 89, pp. 112–116, Jan. 1964.

[25] H. G. Vaughan and L. D. Costa, "Performance of patients with lateralized cerebral lesions. II: Sensory and motor tests," *J. Nervous Mental Disease*, vol. 134, no. 3, pp. 237–243, Mar. 1962.

[26] G. Gainotti and C. Tiacci, "Homolateral and controlateral disturbances in the tactile discrimination of the hemispheric lesions," *Rivista di Neurologia*, vol. 45, no. 3, pp. 339–352, 1975.

[27] A. Carmon, "Disturbances of tactile sensitivity in patients with unilateral cerebral lesions," *Cortex*, vol. 7, no. 1, pp. 83–97, Mar. 1971.

[28] L. Santisteban, M. Térémetz, J.-P. Bleton, J.-C. Baron, M. A. Maier, and P. G. Lindberg, "Upper limb outcome measures used in stroke rehabilitation studies: A systematic literature review," *PLoS ONE*, vol. 11, no. 5, May 2016, Art. no. e0154792.

[29] S. P. Dukelow, T. M. Herter, K. D. Moore, M. J. Demers, J. I. Glasgow, S. D. Bagg, K. E. Norman, and S. H. Scott, "Quantitative assessment of limb position sense following stroke," *Neurorehabilitation Neural Repair*, vol. 24, no. 2, pp. 178–187, Feb. 2010.

[30] E. Otaka, Y. Otaka, S. Kasuga, A. Nishimoto, K. Yamazaki, M. Kawakami, J. Ushiba, and M. Liu, "Clinical usefulness and validity of robotic measures of reaching movement in hemiparetic stroke patients," *J. NeuroEng. Rehabil.*, vol. 12, no. 1, pp. 1–10, Dec. 2015.

[31] N. Gurari, J. M. Drogos, and J. P. A. Dewald, "Individuals with chronic hemiparetic stroke can correctly match forearm positions within a single arm," *Clin. Neurophysiol.*, vol. 128, no. 1, pp. 18–30, Jan. 2017.

[32] G. Mochizuki, A. Centen, M. Resnick, C. Lowrey, S. P. Dukelow, and S. H. Scott, "Movement kinematics and proprioception in post-stroke spasticity: Assessment using the kinarm robotic exoskeleton," *J. NeuroEng. Rehabil.*, vol. 16, no. 1, pp. 1–13, Dec. 2019.

[33] C. B. Walter and S. P. Swinnen, "Asymmetric interlimb interference during the performance of a dynamic bimanual task," *Brain Cognition*, vol. 14, no. 2, pp. 185–200, Nov. 1990.

[34] I. Cusmano, I. Sterpi, A. Mazzone, S. Ramat, C. Delconte, F. Pisano, and R. Colombo, "Evaluation of upper limb sense of position in healthy individuals and patients after stroke," *J. Healthcare Eng.*, vol. 5, no. 2, pp. 145–162, Jun. 2014.

[35] N. Gurari, J. M. Drogos, and J. P. A. Dewald, "Investigation of how accurately individuals with hemiparetic stroke can mirror their forearm positions," *PLoS ONE*, vol. 16, no. 4, Apr. 2021, Art. no. e0250868.

[36] D. J. Goble, B. C. Noble, and S. H. Brown, "Proprioceptive target matching asymmetries in left-handed individuals," *Exp. Brain Res.*, vol. 197, no. 4, pp. 403–408, Aug. 2009.

[37] J. Bernard-Espina, M. Beraneck, M. A. Maier, and M. Tagliabue, "Multisensory integration in stroke patients: A theoretical approach to reinterpret upper-limb proprioceptive deficits and visual compensation," *Frontiers Neurosci.*, vol. 15, Apr. 2021, Art. no. 646698.

[38] B. P. Cunha, S. M. S. F. de Freitas, and P. B. de Freitas, "Assessment of the ipsilesional hand function in stroke survivors: The effect of lesion side," *J. Stroke Cerebrovascular Diseases*, vol. 26, no. 7, pp. 1615–1621, Jul. 2017.

[39] S. Y. Schaefer, K. Y. Haaland, and R. L. Sainburg, "Hemispheric specialization and functional impact of ipsilesional deficits in movement coordination and accuracy," *Neuropsychologia*, vol. 47, no. 13, pp. 2953–2966, Nov. 2009.

[40] J. E. Schaffer, C. Maenza, D. C. Good, A. Przybyla, and R. L. Sainburg, "Left hemisphere damage produces deficits in predictive control of bilateral coordination," *Exp. Brain Res.*, vol. 238, no. 12, pp. 2733–2744, Dec. 2020.

[41] A. Budhota, K. S. G. Chua, A. Hussain, S. Kager, A. Cherpin, S. Contu, D. Vishwanath, C. W. K. Kuah, C. Y. Ng, L. H. L. Yam, Y. J. Loh, D. K. Rajeswaran, L. Xiang, E. Burdet, and D. Campolo, "Robotic assisted upper limb training post stroke: A randomized control trial using combinatory approach toward reducing workforce demands," *Frontiers Neurol.*, vol. 12, Jun. 2021, Art. no. 622014.

[42] J. H. van der Lee, V. de Groot, H. Beckerman, R. C. Wagenaar, G. J. Lankhorst, and L. M. Bouter, "The intra- and interrater reliability of the action research arm test: A practical test of upper extremity function in patients with stroke," *Arch. Phys. Med. Rehabil.*, vol. 82, no. 1, pp. 14–19, Jan. 2001.

[43] J. H. van der Lee, L. D. Roorda, H. Beckerman, G. J. Lankhorst, and L. M. Bouter, "Improving the action research arm test: A unidimensional hierarchical scale," *Clin. Rehabil.*, vol. 16, no. 6, pp. 646–653, Sep. 2002.

[44] S. J. Page, G. D. Fulk, and P. Boyne, "Clinically important differences for the upper-extremity Fugl-Meyer scale in people with minimal to moderate impairment due to chronic stroke," *Phys. Therapy*, vol. 92, no. 6, pp. 791–798, Jun. 2012.

[45] D. Campolo, P. Tommasino, K. Gamage, J. Klein, C. M. L. Hughes, and L. Masia, "H-man: A planar, H-shape cabled differential robotic manipulandum for experiments on human motor control," *J. Neurosci. Methods*, vol. 235, pp. 285–297, Sep. 2014.

[46] S. Contu, A. Hussain, L. Masia, and D. Campolo, "A preliminary study for quantitative assessment of upper limb proprioception," in *Proc. 38th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. (EMBC)*, Aug. 2016, pp. 4614–4617.

[47] A. Cherpin, S. Kager, A. Budhota, S. Contu, D. Vishwanath, C. W. K. Kuah, C. Y. Ng, L. H. L. Yam, L. Xiang, A. Hussain, K. S. G. Chua, and D. Campolo, "A preliminary study on the relationship between proprioceptive deficits and motor functions in chronic stroke patients," in *Proc. IEEE 16th Int. Conf. Rehabil. Robot. (ICORR)*, Jun. 2019, pp. 465–470.

[48] D. J. Goble and S. H. Brown, "The biological and behavioral basis of upper limb asymmetries in sensorimotor performance," *Neurosci. Biobehavioral Rev.*, vol. 32, no. 3, pp. 598–610, Jan. 2008.

[49] S. Contu, A. Hussain, S. Kager, A. Budhota, V. A. Deshmukh, C. W. K. Kuah, L. H. L. Yam, L. Xiang, K. S. G. Chua, L. Masia, and D. Campolo, "Proprioceptive assessment in clinical settings: Evaluation of joint position sense in upper limb post-stroke using a robotic manipulator," *PLoS ONE*, vol. 12, no. 11, Nov. 2017, Art. no. e0183257.

[50] A. Hussain, A. Budhota, C. M. L. Hughes, W. D. Dailey, D. A. Vishwanath, C. W. K. Kuah, L. H. L. Yam, Y. J. Loh, L. Xiang, K. S. G. Chua, E. Burdet, and D. Campolo, "Self-paced reaching after stroke: A quantitative assessment of longitudinal and directional sensitivity using the H-Man planar robot for upper limb neurorehabilitation," *Frontiers Neurosci.*, vol. 10, p. 477, Oct. 2016.

[51] G. F. Templeton, "A two-step approach for transforming continuous variables to normal: Implications and recommendations for IS research," *Commun. Assoc. Inf. Syst.*, vol. 28, p. 4, 2011.

[52] L. M. Rea and R. A. Parker, *Designing and Conducting Survey Research: A Comprehensive Guide*. Hoboken, NJ, USA: Wiley, 2014.

[53] D. J. Goble, "Proprioceptive acuity assessment via joint position matching: From basic science to general practice," *Phys. Therapy*, vol. 90, no. 8, pp. 1176–1184, 2016.

[54] A. Ferlinc, E. Fabiani, T. Velnar, and L. Gradisnik, "The importance and role of proprioception in the elderly: A short review," *Materia Socio Medica*, vol. 31, no. 3, p. 219, 2019.

[55] G. Wilson, M. Halvey, S. A. Brewster, and S. A. Hughes, "Some like it hot: Thermal feedback for mobile devices," in *Proc. SIGCHI Conf. Human Factors Comput. Syst.*, May 2011, pp. 2555–2564.

[56] R. J. van Beers, A. C. Sittig, and J. J. Denier van der Gon, "The precision of proprioceptive position sense," *Exp. Brain Res.*, vol. 122, no. 4, pp. 367–377, Oct. 1998.

[57] C. T. Fuentes and A. J. Bastian, "Where is your arm? Variations in proprioception across space and tasks," *J. Neurophysiol.*, vol. 103, no. 1, pp. 164–171, Jan. 2010.

[58] R. Iandolo, V. Squeri, D. De Santis, P. Giannoni, P. Morasso, and M. Casadio, "Testing proprioception in intrinsic and extrinsic coordinate systems: Is there a difference?" in *Proc. 36th Annu. Int. Conf. IEEE Eng. Med. Biol. Soc.*, 2014, pp. 6961–6964.

[59] S. Scott and G. Loeb, "The computation of position sense from spindles in mono- and multiarticular muscles," *J. Neurosci.*, vol. 14, no. 12, pp. 7529–7540, Dec. 1994.

[60] C. Ghez, J. Gordon, and M. F. Ghilardi, "Impairments of reaching movements in patients without proprioception. II. Effects of visual information on accuracy," *J. Neurophysiol.*, vol. 73, no. 1, pp. 361–372, Jan. 1995.

[61] K. E. Jones, J. Wessberg, and Å. B. Vallbo, "Directional tuning of human forearm muscle afferents during voluntary wrist movements," *J. Physiol.*, vol. 536, no. 2, pp. 635–647, Oct. 2001.

[62] U. Proske and S. C. Gandevia, "The proprioceptive senses: Their roles in signaling body shape, body position and movement, and muscle force," *Physiological Rev.*, vol. 92, no. 4, pp. 1651–1697, Oct. 2012.

[63] V. Gritsenko, N. I. Krouchev, and J. F. Kalaska, "Afferent input, efference copy, signal noise, and biases in perception of joint angle during active versus passive elbow movements," *J. Neurophysiol.*, vol. 98, no. 3, pp. 1140–1154, Sep. 2007.

[64] C. Grefkes and G. R. Fink, "Reorganization of cerebral networks after stroke: New insights from neuroimaging with connectivity approaches," *Brain*, vol. 134, no. 5, pp. 1264–1276, 2011.

[65] J. P. Brasil-Neto and A. C. De Lima, "Sensory deficits in the unaffected hand of hemiparetic stroke patients," *Cognit. Behav. Neurol.*, vol. 21, no. 4, pp. 202–205, 2008.

[66] N. Leibowitz, N. Levy, S. Weingarten, Y. Grinberg, A. Karniel, Y. Sacher, C. Serfaty, and N. Soroker, "Automated measurement of proprioception following stroke," *Disability Rehabil.*, vol. 30, no. 24, pp. 1829–1836, Jan. 2008.

[67] M. D. Rinderknecht, O. Lambercy, V. Raible, I. Busching, A. Sehle, J. Liepert, and R. Gassert, "Reliability, validity, and clinical feasibility of a rapid and objective assessment of post-stroke deficits in hand proprioception," *J. NeuroEng. Rehabil.*, vol. 15, no. 1, pp. 1–15, Dec. 2018.

GIULIA BALLARDINI received the M.Sc. degree (cum laude) in bioengineering (neuroengineering and bio-ICT) and the Ph.D. degree in bioengineering and robotics from the University of Genova, Italy, in 2017 and 2022, respectively. She is currently a Postdoctoral Researcher with the Haptic Intelligence Department, Max Planck Institute for Intelligent Systems, Stuttgart, Germany.

ADELE CHERPIN received the M.Sc. degree in biomedical engineering (biomechanics) from Imperial College London, in 2017. She was a Research Associate with the Rehabilitation Research Institute of Singapore, Nanyang Technological University, Singapore. She was the Software Project Manager of Articares Pte Ltd.

KAREN S. G. CHUA received the Medical degree from the National University of Singapore, in 1988, and the Ph.D. degree in physical medicine and rehabilitation (neurorehabilitation and brain injury rehabilitation) from the Baylor College of Medicine, Houston, USA, in 1997. She has been a Visiting Rehabilitation Consultant with St. Luke's Hospital, since 2006, and the Ng Teng Fong Hospital, since 2015. She is currently a Senior Consultant Rehabilitation Physician with the Tan Tock Seng Hospital's Rehabilitation Centre and the Ambulatory Facility, Centre for Advanced Rehabilitation Therapeutics, Singapore. She is also an Adjunct Associate Professor with the Lee Kong Chian School of Medicine and a Senior Clinical Tutor with the Yong Loo Lin School of Medicine, National University of Singapore.

ASIF HUSSAIN received the Ph.D. degree from Imperial College London, in 2014. He is currently the Co-Founder and the CEO of Articares Pte Ltd., an international company specializing in rehabilitation and assistive robotics.

SIMONE KAGER (Member, IEEE) received the B.Sc. and M.Sc. degrees in mechanical engineering from the Technical University of Munich, and the Ph.D. degree from the National University of Singapore in collaboration with Nanyang Technological University, Singapore. She is currently a Postdoctoral Researcher with the Future Health Technologies Program, Singapore-ETH Centre.

LIMING XIANG received the Ph.D. degree in statistics from the City University of Hong Kong, China, in 2002. She is currently an Associate Professor with the School of Physical and Mathematical Sciences, Nanyang Technological University, Singapore.

DOMENICO CAMPOLO received the Ph.D. degree in microengineering from Scuola Superiore Sant'Anna, Pisa, Italy, in 2002. He is currently an Associate Professor and the Director of the Robotics Research Centre, School of Mechanical and Aerospace Engineering, Nanyang Technological University, Singapore. He is also the Co-Founder of ArtiCares Pte Ltd., an international company specializing in rehabilitation and assistive robotics.

MAURA CASADIO received the M.Sc. degree in electronic engineering from the University of Pisa, Italy, in 2002, and the Ph.D. degree in bioengineering and the M.Sc. degree in biomedical engineering from the University of Genova, Italy, in 2006 and 2007, respectively. She was with the Don C. Gnocchi Foundation, La Spezia, Italy, and the Italian Institute of Technology. From 2008 to 2011, she was a Postdoctoral Fellow with Northwestern University (Rehabilitation Institute of Chicago, IL, USA). She is currently an Associate Professor with the Department of Informatics, Bioengineering, Robotics, and System Engineering, University of Genova.

Open Access funding provided by 'Università degli Studi di Genova' within the CRUI CARE Agreement