Testing proprioception in intrinsic and extrinsic coordinate systems: is there a difference?

Riccardo Iandolo[1], Valentina Squeri[2], Dalia De Santis[2] *IEEE Graduate Student Member*, Psiche Giannoni[3] , Pietro Morasso[1, 2] and Maura Casadio[1], *IEEE Member* *

Abstract—**An intact position sense is considered important for neuromotor recovery, but the available methods and protocols for its assessment are still limited. In the clinical practice it is generally tested trough a bimanual position matching test, that consists of replicating with one arm the angular positions of the other arm in space (intrinsic coordinates matching). However, the same test could be carried out by matching the hand location in space (extrinsic coordinates matching). Is there any difference between the procedures that may be relevant to the evaluation of position sense deficits? In this study we compared the performance of eight right handed subjects and two stroke survivors with left hemiparesis performing the test in the two conditions. A robotic manipulandum passively moved the left arm of the participants in twenty-four positions in the workspace. Subjects had to match the left arm position with their right arm either in intrinsic or extrinsic coordinates. The results show that all the subjects (impaired and controls) performed better when using the extrinsic paradigm.**

INTRODUCTION

In order to plan and control limb posture and movement, we need proprioceptive information from muscle, skin and joint receptors. In individuals with compromised proprioceptive ability, impairments in the control of muscle interaction torques [1], motor output monitoring [2] and in acquiring internal models of skilled movement [3, 4] have been observed. Moreover, preserved motor learning after stroke is related to the degree of proprioceptive deficits [5, 6]. Thus, a proprioceptive impairment is likely to affect in a significant manner the capacity of stroke survivors to recover functionality of the upper limb [7]. For these reasons, it is crucial to quantify the proprioceptive deficit of each stroke subject to plan the proper rehabilitation training. Robotics provides the opportunity to increase precision and accuracy of the measurement, as well as better reliability compared to standardized observer-based ordinal scales. Other groups developed robotic routines to objectively identify and assess position sense deficits. They were quantified by computing the matching error between the two hands positions measured with tests in intrinsic [4, 8-10] or in extrinsic coordinates [11] in both healthy and neurological subjects.

Here we investigated if there may be differences in the position matching depending on the task requirement i.e. if we ask blinded subjects to position both hands in the same location in the operational space (extrinsic coordinate system) or in mirror symmetric locations with respect to the body midline (intrinsic coordinate system). Our hypothesis is that there may be a difference in the results obtained under the two testing modalities depending on the coordinate system subjects use for estimating the position of hands in space and for planning movements.

I. METHODS

A. Subjects

Eight individuals with no history of neurological or musculoskeletal disorder participated in this study (age 33.5mean±3.5std years, 2 males). Their handedness was assessed by the Edinburgh test [12]. We tested the set-up and protocol also with 2 stroke survivors, recruited among the outpatient population of the ART Education and Rehabilitation Center in Genoa according to the following inclusion criteria: 1) diagnosis of a single, unilateral stroke verified by brain imaging; 2) sufficient cognitive and language abilities to understand and follow instructions; 3) chronic condition (at least 1 year after stroke); 4) stable clinical conditions for at least one month before being enrolled in this study. Their demographic and clinical data are reported in Table I.

The study conforms to the standard of the declaration of Helsinki and was approved by the institutional ethical committee. All subjects provided written informed consent prior to participation in the study. The experiments were carried out at the NeuroLab of the University of Genoa

TABLE I - DEMOGRAPHIC AND CLINICAL DATA OF THE PATIENTS

SUBJECT	AGE	PARETIC HAND	FMA (0-66)	ASH (0-4)
S1	37	L	15	2
S2	63	L	55	1

Age years; FMA: arm portion of Fugl-Meyer score (0-66) at the time of the study; ASH: modified Ashworth scale of muscle spasticity (0-4).

* The research leading to these results was supported by Marie Curie Integration Grant FP7-PEOPLE-2012-CIG-334201 (REMAKE) and by the kind contribution of the Ministry of Foreign Affairs, Unit for S/T cooperation. and by the ACIRAS project, supported by Regione Liguria.

R. Iandolo is student at University of Genoa, Genoa, Italy (www.riccardo.iandolo@gmail.com).

V. Squeri is senior post-doctoral researcher with the Italian Institute of Technology, Dept. of Robotics, Brain and Cognitive Sciences, 16163, Genoa, Italy (email: valentina.squeri@iit.it).

D. De Santis is Ph.D. student with the Italian Institute of Technology, Dept. of Robotics, Brain and Cognitive Sciences, 16163, Genoa, Italy (email: dalia.desantis@iit.it).

P. Giannoni is physical therapist at ART Education and Rehabilitation Center, Genoa, Italy.

P. Morasso is senior scientist with the Italian Institute of Technology, Dept. of Robotics, Brain and Cognitive Sciences, 16163 Genoa, Italy (email: pietro.morasso@iit.it).

M. Casadio is assistant professor at the University of Genoa, Dept. Informatics, Bioengineering, Robotics and Systems Engineering, University of Genoa, Genoa, Italy (corresponding author: phone: +3901071781464; fax: +390107170817 email: maura.casadio@unige.it).

978-1-4244-7929-0/14/$26.00 ©2014 IEEE

(Genoa, Italy), under the supervision of experienced clinical personnel and engineers.

B. *Experimental setup*

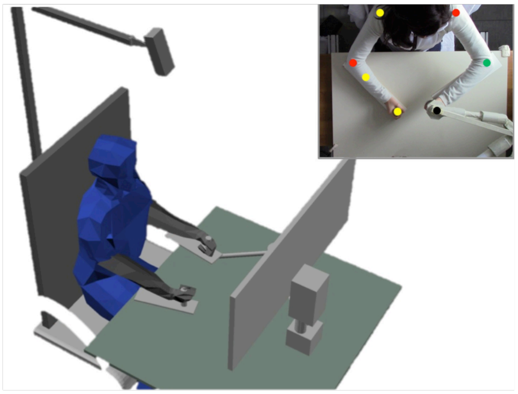

Fig.1 Experimental set-up (left bottom panel) and marker position (right top panel).

The experimental set-up consisted of a planar manipulandum [13] and a calibrated camera. Subjects, blindfolded, sat on a chair with back support, and held the end effector of the robot with their left hand – non-dominant arm for controls and impaired arm for stroke survivors. The other hand held an equally shaped, but not actuated end-effector. The two arms operate on two parallel planes positioned at slightly different heights (Fig.1). The robot passively moved the left arm in different locations of the space. The camera recorded the position of 7 markers that allowed for the reconstruction of shoulders, elbow, and hand positions (Fig.2). After calibration, the error in the reconstruction of the markers' positions was less than 2 mm in the overall workspace.

C. *Experimental protocol*

The assessment protocol was articulated in four movement sets, of 40 trials each. A trial consisted of the following steps:

- Starting from target position $\bar{\mathbf{x}}_i$, the robot passively moved the left arm to other target $\bar{\mathbf{x}}_{i+1}$ according to minimum-jerk profile, with a movement duration T=1s:
$$\bar{\mathbf{x}}_{i+1}(t) = \bar{\mathbf{x}}_i + (\bar{\mathbf{x}}_T - \bar{\mathbf{x}}_i)[6\xi^5 - 15\xi^4 + 10\xi^3]$$
with $\xi = t/T$
- As the left hand reached the test position, an acoustic prompt alerted the subject to move the right hand (non-paretic hand for the stroke subjects and dominant arm for the controls) in order to match the position of the other hand. The arm connected to the robot was kept fixed in the test position until the end of the matching operation.
- The subject verbally confirmed the end of his movement and the operator enabled the beginning of the next trial.

In each movement set subjects reached 24 targets lying on three concentric squares with their centers aligned with the midline of the subject's body. For control subjects the square sides were 10, 20 and 30 cm, for controls, and 5, 10 and 20 cm for stroke survivors (they had difficulty with the complete extension of the arm, even in presence of the assistive force mediated by the robot).

The targets were presented in two different modalities: (1) completely random order (Fig.2 bottom-right panel); (2) sequence of 4 targets lying on the same square (Fig.2 top-right panel), in this case only the order of the sequences was randomized.

Each subject completed the proprioceptive tests in two different experimental conditions: (1) hands in the same location in the workspace, i.e. match in extrinsic coordinates, (2) hands in mirror symmetric position in the workspace i.e. match in intrinsic-joint coordinates.

Each subject performed four movement sets in a single session: 2 of matching in intrinsic and 2 of matching in extrinsic coordinates. For a given condition, one of the two matching sets had targets presented in random order, while the other in sequences of squares.

The evaluation session lasted about 45 minutes, each movement set lasted about 8 minutes. Subjects remained constantly blindfolded during the assessment procedure.

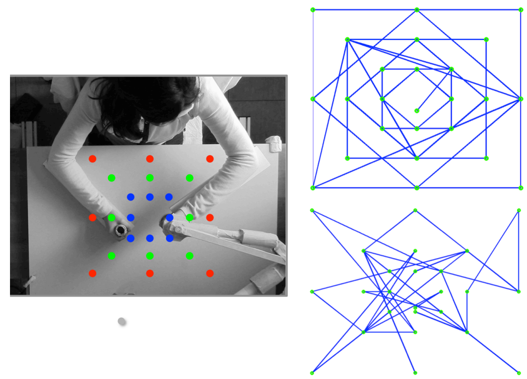

Fig. 2 Left panel: Targets' position in the workspace. Right panels: squared (top panel) and randomized (bottom panel) order of target' presentation.

D. *Data Analysis*

To evaluate the accuracy of the hand matching we computed the following indicators, similar to the ones proposed by [8]:

- Shift. It accounts for the displacement between the actual and desired position of the hand:

$$shift = \sqrt{shift_x^2 + shift_y^2}$$

where, $shift_x$ and $shift_y$ are the dispacements obtained for the x and y coordinate, respectively.

- Variability. Measure of variability of the position of the matching hand for a given desired target position:

$$variability = \sqrt{\mathrm{var}_x^2 + \mathrm{var}_y^2}$$

where var_x and var_y are the standard deviation - in the mediolateral x and distal y direction, respectively - of the matching hand positions for each target location, averaged for all the targets in the workspace. This indicator was

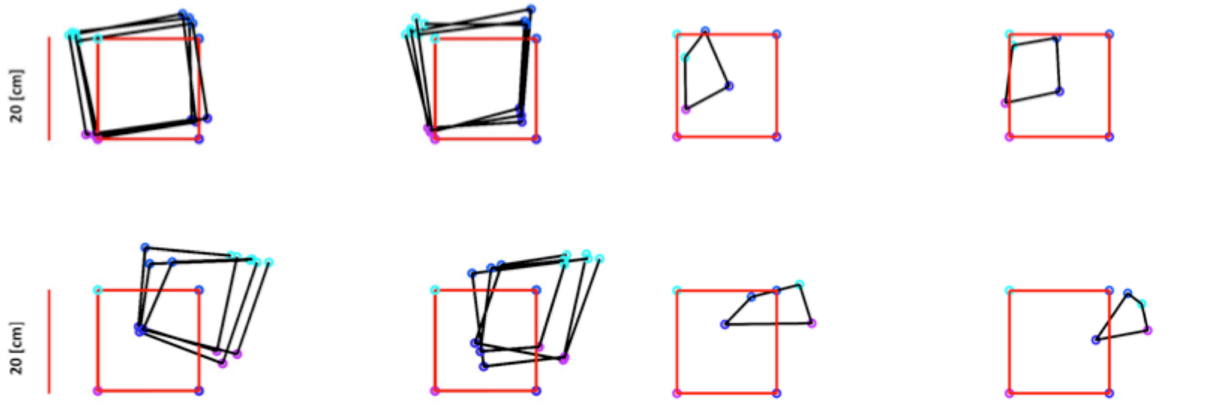

Fig.3 Data for a control subject (C2 – 2 left columns) and stroke survivor (S1 – 2 right columns). The top row represents a matching example in the extrinsic system while the bottom row shows the error for the intrinsic modality. The columns refer to the same targets position proposed to the subjects with different presentation orders: sequence of 4 targets laying on the same square (first and third columns) and completely random order (second and forth columns).

computed only for the target positions presented at least six times in the session.

- Scaling. It accounts for the expansion and contraction in the representation of the space of the hand motion:

$$scaling_x = \left| \Delta x_M / \Delta x_D \right|$$

where Δ is the difference between the mean *x/y* position for the 3 right/top and 3 left/bottom targets laying on each square (M=measured, D=desired). We computed this indicator separately for the distal (*y*) and medio-lateral (*x*) directions.

Statistical analysis was based on repeated measures ANOVA with two factors: the matching modality (matching test in intrinsic vs extrinsic coordinates) and the order of the target (sequence vs completely random).

II. Results

Each subject had his own strategy to solve the task, and some of them –i.e. subject 2 Fig. 3- exhibited a greater error than others. However, the majority of the control subjects had better performance when executing the task in extrinsic with respect to intrinsic coordinates: the shift between the desired and the actual hand position was lower, the distortion in the representations of the space was reduced and there was less variability in the matching hand position in correspondence of a same target reached several times.

The analysis of the indicators confirmed these findings. The shift indicator and the variability (Fig.4-top panels) on reaching the same target position were significantly lower ($F=6.924$ $p=0.034$ and $F=22.14$ $p=0.002$) for the isospatial matching (mean±std: 2.87±1.69 cm and 1.61±0.31 cm, respectively) with respect to the mirror symmetric matching (mean±std: 6.04±2.87 cm and 3.27±1.25 cm, respectively). Also the scaling indicator was different in the two matching tasks. When the matching was performed in extrinsic coordinates, it was slightly bigger than 1 for some subjects (mean±std: x-axis, 1.08±0.08; y-axis: 1.00±0.05), indicating a small stretch of the space. When the matching was performed in intrinsic coordinates, for most subjects was less than 1, i.e the space was shrunk (mean±std: x-axis, 0.85±0.18; y-axis, 0.90±0.06). The difference in the distortions of the space between the two tasks was present in both the mediolateral (Fig.4 – left bottom panel. $F=9.294$ $p=0.019$) and the distal (Fig.4 – right bottom panel. $F=8.884$ $p=0.020$) directions, but was significantly greater in the mediolateral one. Instead, we found no significant differences with respect to the order of targets' presentation.

We tested our set-up and protocol also with 2 chronic stroke survivors (Fig.3 right panel and Fig. 4 red dots). They had larger errors in most parameters with respect to the control group. However, their results confirmed an increased difficulty when the matching was performed in intrinsic coordinates. We noticed (Fig.3) that, while in extrinsic coordinates the hand positions are still on the vertex of square forms as required by the task (i.e. target positions), in the intrinsic coordinates they often are not.

III. Discussion

We found errors in the position matching tasks that are comparable with those reported in other studies [8, 11]. The novelty of this study is the comparison of the matching errors with different task requirements: the subjects were requested to perform the position-matching test both in intrinsic and in extrinsic coordinates.

We found significant differences between the two testing modalities: when subjects had to put both hands in the same location, they executed the task with smaller errors, in a more precise and less variable way than when they had to position the hands in mirror symmetric locations with respect to the body midline. The two left-impaired stroke survivors showed, as expected, poorer performance with respect to the control subjects. However, they too exhibited more difficulty to perform the task in intrinsic than in extrinsic coordinates.

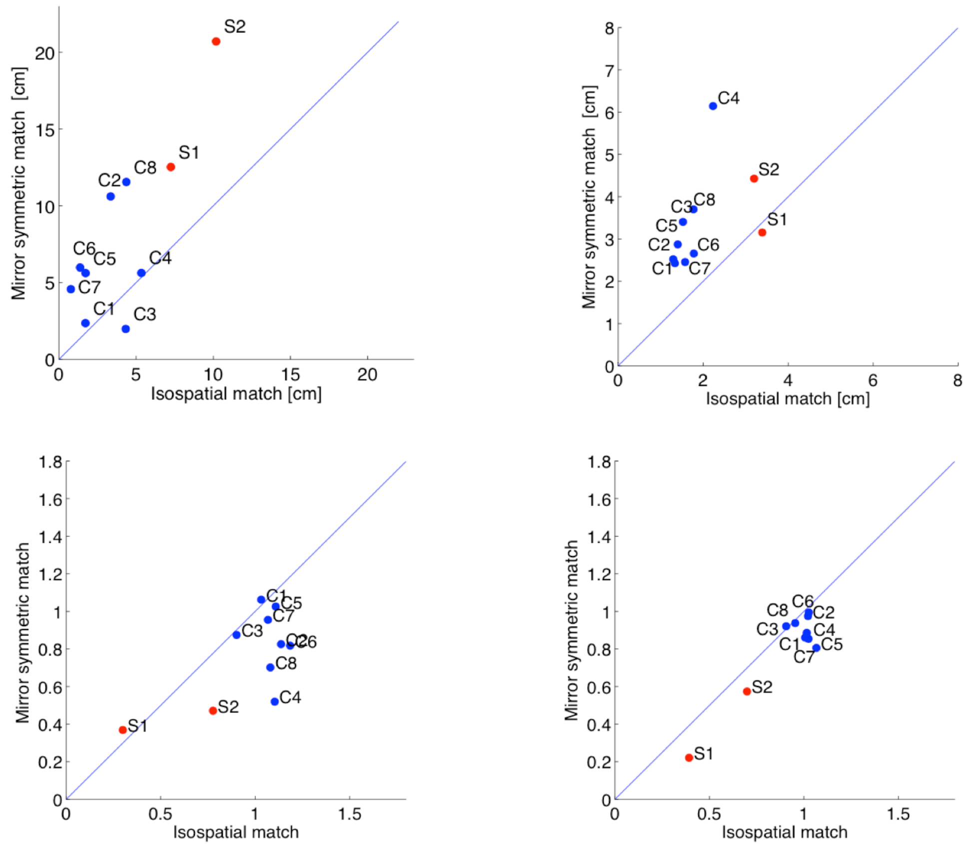

Fig. 4. Performance indicators. Top panels: shift indicator (left panel) and variability index (right panel). Bottom panels: scaling indicator along the mediolateral (left panel) and distal (right panel) movement direction. Blue dots: control subjects, red dots: stroke survivors.

These results may depend on the space representation subjects used for estimating the position of hands and for planning movements: if they used an extrinsic coordinate system, the task that requires the mirror symmetric matching would have been more challenging because they should have computed the position of the hand in the other symmetric hemi-space.

A possible limitation of the study derives from the use of different planes for the two hands. We are currently improving the set-up in order to reduce this distance to a minimum. We are planning to further perform this test on a larger sample of controls and stroke survivors. We will investigate the correlation of the performance difference under the two conditions with the location and size of the brain damage.

ACKNOWLEDGMENTS

The authors thank I. Tamagnone and S. Summa for the help with the control software of the manipulandum.

REFERENCES

[1] R. L. Sainburg, M. F. Ghilardi, H. Poizner, and C. Ghez, "Control of limb dynamics in normal subjects and patients without proprioception," *J Neurophysiol,* vol. 73, pp. 820-35, 1995.

[2] J. C. Rothwell, M. M. Traub, B. L. Day, J. A. Obeso, P. K. Thomas, and C. D. Marsden, "Manual motor performance in a deafferented man," *Brain,* vol. 105, pp. 515-42, 1982.

[3] J. Messier, S. Adamovich, M. Berkinblit, E. Tunik, and H. Poizner, "Influence of movement speed on accuracy and coordination of reaching movements to memorized targets in three-dimensional space in a deafferented subject," *Exp Brain Res,* vol. 150, pp. 399-416, 2003.

[4] H. A. Ingram, P. van Donkelaar, J. Cole, J. L. Vercher, G. M. Gauthier, and R. C. Miall, "The role of proprioception and attention in a visuomotor adaptation task," *Exp Brain Res,* vol. 132, pp. 114-26, 2000.

[5] W. de Weerdt, N. B. Lincoln, and M. A. Harrison, "Prediction of arm and hand function recovery in stroke patients," *International Journal of Rehabilitation Research,* vol. 10, pp. 110-112, 1987.

[6] W. J. La Joie, N. M. Reddy, and J. L. Melvin, "Somatosensory evoked potentials: their predictive value in right hemiplegia," *Arch Phys Med Rehabil.,* vol. 63, pp. 223-6, 1982.

[7] L. M. Carey, T. A. Matyas, and L. E. Oke, "Sensory loss in stroke patients: effective training of tactile and proprioceptive discrimination," *Arch Phys Med Rehabil,* vol. 74, pp. 602-11, 1993.

[8] 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," *Neurorehabil Neural Repair,* vol. 24, pp. 178-87, Feb 2010.

[9] D. J. Goble and S. H. Brown, "Task-dependent asymmetries in the utilization of proprioceptive feedback for goal-directed movement," *Exp Brain Res,* vol. 180, pp. 693-704, Jul 2007.

[10] J. A. Semrau, T. M. Herter, S. H. Scott, and S. P. Dukelow, "Robotic Identification of Kinesthetic Deficits After Stroke," *Stroke,* Nov 5 2013.

[11] N. Leibowitz, N. Levy, S. Weingarten, Y. Grinberg, A. Karniel, Y. Sacher, C. Serfaty, and N. Soroker, "Automated measurement of proprioception following stroke," *Disabil Rehabil,* vol. 30, pp. 1829-36, 2008.

[12] R. C. Oldfield, "The assessment and analysis of handedness: the Edinburgh inventory," *Neuropsychologia,* vol. 9, pp. 97-113, 1971.

[13] M. Casadio, V. Sanguineti, P. G. Morasso, and V. Arrichiello, "Braccio di Ferro: a new haptic workstation for neuromotor rehabilitation," *Technol Health Care,* vol. 14, pp. 123-42, 2006.