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A new method for evaluating kinesthetic acuity during haptic interaction

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SUMMARY
Although proprioceptive impairment is likely to affect in a significant manner the capacity of stroke patients to recover functionality of upper limb, clinical assessment methods currently in use are rather crude, with a low level of reliability and a limited capacity to discriminate the relevant features of this severe deficit. In the present paper, we describe a new technique based on robot technology, with the goal of providing a reliable, accurate, and quantitative evaluation of kinesthetic acuity, which can be integrated in robot therapy. The proposed technique, based on a pulsed assistance paradigm, has been evaluated on a group of healthy subjects.

KEYWORDS: Haptic interaction; Proprioception; Force perception; Robot assistance; Kinesthetic acuity.

1. Introduction

In recent years, neuromotor rehabilitation particularly related to recovery from sensorimotor deficits play a crucial role in the design of effective training protocols, with particular reference to the use of robot and virtual reality training techniques[1–10] aiming to recover proprioceptive acuity.

A large number of subjects with stroke present a significant and severe impairment in kinesthesia.[8] Furthermore, in the presence of kinesthetic deficits it is not clear yet whether position sense, a component of proprioception, physiologically correlates with the chance of motor recovery: previous studies support the hypothesis of a correlation between motor recovery and proprioception,[11,12] while others provide evidence that the two phenomena are not strictly related.[13,14]

One of the open challenges is to implement effective and reliable tests for proprioceptive perception that go beyond the mere subject's position sense evaluation; with particular reference to kinesthetic acuity that comprises both sense of position and sense of movement,[15] these new assessments should overcome the difficulties related to the discrimination of proprioceptive and motor performance, mainly due to their tight integration into the well-known "perception–action loop".[16,17] Sensors and actuators of living organisms are constantly engaged in complicated interactions that allow the emergence of purposive skills, a key concept that was clear in Gibson's early work.[18] This study evaluates proprioceptive perception in the context of a goal-oriented movement also taking into account that proprioception is not a general body attribute, but has a side-general nature and it is site-specific. Indeed, proprioception at different joints is experience-dependent[19,20] and is affected by training.[21,22]

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In our previous work[1] we proposed a new paradigm for robot training of stroke patients, which was based on pulsed assistance, namely a target-oriented force field applied to the hand that is pulsed in time (pulse duration 200 ms, repetition rate two pulses/second) on top of a continuous bias force. The preliminary outcomes showed that if pulsed assistance is compared with pure continuous assistance, the former is at least as effective as the latter in promoting functional recovery, but with an average assistive force level half of the one required for continuous assistance. In both cases the subjects were trained with or without vision, and in the absence of visual feedback only relying on haptic feedback. We clearly forced them to focus solely on the proprioceptive channel in order to understand the direction of the assistive force field and thus completing the task. In spite of the demonstrated effectiveness of the proposed robot training paradigm, a question remained unanswered: was the recorded motor improvement, induced by robot training, associated with a perceptual improvement of proprioceptive channel?

To answer the question, we devised the following study, in which 13 healthy control subjects performed a similar reaching task in absence of visual feedback. No continuous bias field was present in this case because healthy subjects do not require "assistance" for completing the task but only "haptic cues" for delivering appropriate motor commands. In particular, we were interested in the sensorimotor threshold, namely the minimum level of force impulses that was functionally effective for evoking voluntary control. Indeed, the challenge of robot assistance is to facilitate the emergence of active responses by promoting intentionality through haptic feedback of the desired motion direction rather than imposing passive motions.[3,23]

For this purpose, we designed an experimental paradigm that combines a generic procedure for the psychometric estimation of kinesthetic perceptual threshold with a specific procedure for the evaluation of Active Contribution (AC) index,[1] based on pulsed haptic interaction, to compare the two methods in a quantitative manner. The analysis of the results shows that, in spite of a rather large inter-subject variability of proprioceptive thresholds, the AC index is rather stable, provided that the pulsed force feedback amplitude accounts for these differences. If we consider that the classic procedure for psychometric estimation is extremely time-consuming and quite impractical for the training of stroke patients whereas the computation of AC index is quick and intrinsic to the training paradigm, we may conclude that the results of this study yield an important preliminary step toward integrating in an efficient manner motor and proprioceptive training within the overall rehabilitation process.

2. Methods

The study aims at quantifying the participation of the kinesthetic sense in an interactive task mediated by a haptic interface. We conducted two separate experiments. The first (Experiment 1) involved an evaluation of a novel proprioceptive performance indicator (AC index) over 13 subjects during a single-session protocol. In order to better evaluate the reliability of the proposed perceptual score as a correlate of perceptual acuity, we conducted the second experiment (Experiment 2), in which three subjects out of 13 (S11, S12, and S13) repeated the same protocol in three consecutive days. Our objective was twofold: (i) to assess the extent to which the proposed paradigm based on pulsed haptic guidance is able to promote a plastic modulation of kinesthetic acuity, and (ii) to evaluate the degree of correlation between the AC index and the kinesthetic performance.

2.1. Protocol

The protocol has been designed to have three separate blocks: the first evaluation block, the training block made of six movement sets, and the final evaluation block. The duration of the session is overall less than 2 h, approximately 30 min per block, separated by 5–10-min breaks.

Subjects sat in front of a manipulandum[24] that allows for shoulder and elbow movements along the transversal plane, their torso strapped to a chair by means of seat belts to avoid trunk compensation. The manipulandum is driven by two direct drive motors and its kinematics consists in highly back-drivable planar parallelogram linkages, allowing to estimate accurately the force transmitted to the subjects from current inputs to motors. The subjects interacted with robot by holding a handle attached to its end-effector, which also provided forearm support. They were blindfolded during the evaluation and training blocks, except for the first training movement set: during this initial training phase, visual

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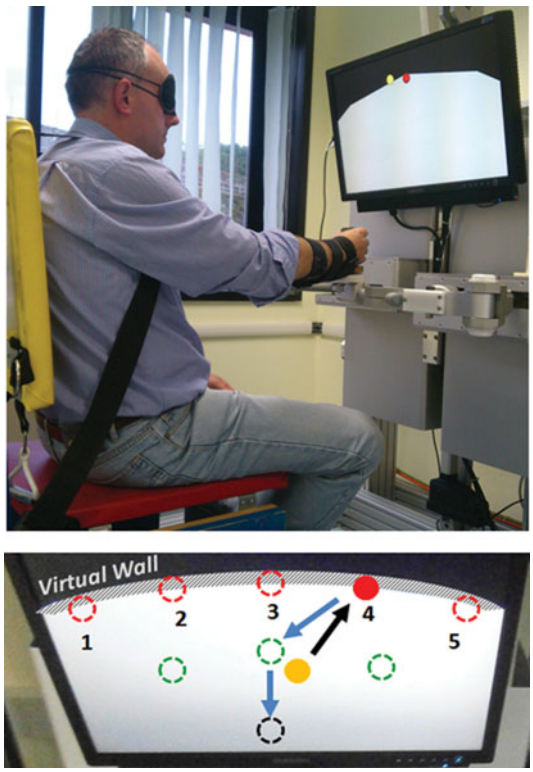


Fig. 1. Top panel: Experimental setup. Bottom panel: Visual feedback. The workspace is limited by a virtual wall (black background) that subjects cannot overstep. The red circles represent the "far" [F] targets (the filled red circle is the current, visible target). The green circles are the intermediate I targets. The black circle is the starting S target. The yellow-filled circle is the current hand position, aimed at the current target (black arrow). The two blue arrows correspond to the two following inward movements. The circles have a 2-cm diameter. Example of visual feedback is provided to the subject.

feedback was provided by using a screen (Fig. 1) to help the subjects to correctly understand and promptly familiarize with the task.

The evaluation block comprised a psychometric estimate of the subject's kinesthetic perception on both right (dominant) and left arms. The robot applied a sudden and quick force stimulus that displaced the arm randomly in two different directions (45° on the right or left with respect to the shoulder–elbow line during a full forward reach). The intensity profile of the stimulus was bell-shaped, with duration of 200 ms and a peak value chosen pseudo-randomly in the range 0.25–4 N with a minimum step of 0.2 N. The peak amplitude was chosen according to a supervised constant stimuli approach to estimate the psychometric curve of each arm during two forced-choice tests. The first set of 22–38 stimuli around a tentative threshold of 2 N was used to obtain the first estimate of the curve. After evaluating the stimulus intensity that yielded 90% probability of positive response, smaller intensities were sampled in steps of 0.5 N and greater intensities in steps of 1 N. This preliminary estimate was subsequently used to adjust stimuli distribution and sampling resolution to increase efficiency. The whole procedure was repeated until a goodness-of-fit criterion was met.

The exercise occurring in the training blocks was based on a reaching task. Subjects had to reach a set of target points as shown in the bottom panel of Fig. 1, and presented one by one to the subject. The target distance from the starting position (S) is 26 cm in the case of far targets (F), located 22.5° apart, and 13 cm for the intermediate ones (I). A target was reached when the end-effector arrived to a minimum distance of 2 cm from its center. Subjects completed a total of six target sets comprising 90 reaching movements in the following sequence: S->F->I->S. In the first reaching set, we provided the subjects with both visual and haptic feedback of the hand position with respect to the target. Moreover, an auditory feedback was generated each time a target point was hit. Throughout the remaining five target sets, we suppressed visual feedback, asking the volunteers to keep the eyes closed or to wear a mask. Whenever necessary, we allowed them to take a short break after the

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Table I. Volunteers' demographic and handedness data.

Subject	Age	Sex	*E*-score	$F_{85\%}$ (N) Right hand		$F_{85\%}$ (N) Left hand	
				Pre	Post	Pre	Post
S1	23	F	95	1.20	1.62	0.78	1.18
S2	21	F	75	1.58	1.25	1.30	0.53
S3	26	M	80	1.75	1.64	1.07	0.90
S4	20	F	80	2.20	2.32	1.10	1.19
S5	43	M	100	0.70	0.52	0.65	0.54
S6	29	F	95	1.70	1.80	0.93	0.79
S7	31	F	85	1.05	1.25	1.18	1.04
S8	21	F	80	1.39	1.10	0.82	0.85
S9	33	M	100	1.65	1.08	0.99	0.80
S10	38	M	90	0.65	1.52	0.87	0.68
S11	26	F	90	2.41	2.65	0.99	1.07
S12	25	F	85	1.78	1.82	0.84	0.78
S13	32	F	75	1.39	1.09	0.95	0.89

Notes: Mean age is 28.3 ± 6.7 years, and mean Edinburgh score (*E*-score) is 88 ± 8.7.
$F_{85\%}$ represents the force needed to elicit a perception equivalent to 85% probability of giving a correct answer.

completion of each target set. Haptic feedback comprised a series of force impulses directed as the line joining the hand position and the target. Single impulse duration was fixed to 200 ms, while the frequency of the train of impulses was set to 0.5 Hz. A viscous field mitigated the elastic back-bounce due to impulse application. A virtual wall acted as a haptic elastic barrier to prevent the hand from going beyond the distance of F layer. The net force field acting on the hand takes the form of Eq. (1), where $P(t)$ is the pulsed haptic guidance force field, always directed toward the target point, B is the coefficient of viscous field (12 Ns/m), K_w is the elastic coefficient of virtual wall (1000 N/m), x_H is hand's position vector, and x_w is its projection on the wall surface:

$$F(t) = P(t) - B\dot{x}_H - K_W(x_W - x_H), \tag{1}$$

$$P(t) = [F_{\text{PEAK}} \cdot I_{\Delta t}(t)] \frac{(x_T - x_H)}{\|x_T - x_H\|}, \tag{2}$$

$$\xi = t/\Delta t$$

$$I_{\Delta t}(t) = \begin{cases} \dfrac{1}{1.875}[30\xi^4 - 60\xi^3 + 30\xi^2] & \text{for} \quad 0 \le \xi \le 1 \\ 0 & \text{for} \quad 1 \le \xi \le T/\Delta t \end{cases}. \tag{3}$$

Equations (2) and (3) describe the impulse shape, F_{PEAK} being the maximum impulse amplitude, and x_T being the target position.

2.2. Subjects

Thirteen right-handed subjects (four males, nine females, age = 28.3 ± 6.7 years), with no known neuromuscular disorders and naïve to the task, participated in the experiment. Hand preference was evaluated according to the Edinburgh Handedness Questionnaire[25] (*E*-score; Table I). Their laterality index was greater than 70 on a (−100, 100) scale (−100: completely left handed; 100: completely right handed). All participants gave their informed consent prior to testing. The local ethics committee approved the study.

2.3. Outcome measures

2.3.1. Evaluation phase. For each stimulus intensity, we computed the percentage of correctly perceived force stimuli and then fitted a cumulative Gaussian function to the data set, yielding two psychometric sensitivity functions for each subject before and after the training block (PRE

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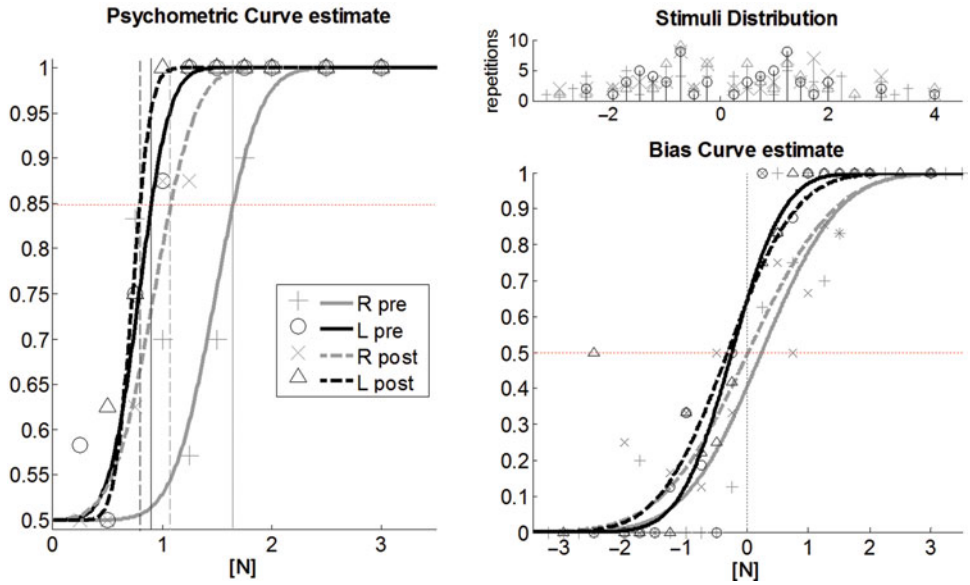


Fig. 2. (Colour online) Left panel: Example of psychometric curves for force threshold estimate for subject S3. The ordinate values indicate the probability of perceiving the direction of force stimulus, and the abscissa represents the magnitude of force stimulus. Different colors represent psychometric function evaluated for two hands (R – right hand, in gray; L – left hand, in black) and before (continuous line) and after (dotted line) the training (pre and post respectively). Markers (black circles = L pre, black triangles = L post, gray plus = R pre, gray cross = R post) denote the probability with which S3 subject reported to perceive force stimulus in the exact direction. Subject's responses were fit to a logistic function. The threshold was defined as the force magnitude yielding 85% of correct responses. Top right panel: Distribution of the force intensity stimuli used to fit logistic function to the response probability data. Negative values represent stimuli pointing to the leftward directions, while positive values stand for stimuli toward the right. On the vertical axis is reported the frequency of presentation of each stimulus intensity. Bottom right panel: Example of psychometric function for bias estimate for subject S3. The bias was defined as the force intensity yielding 50% of correct response, i.e., the bias level is the force intensity corresponding to zero probability of giving a correct answer when the stimuli direction is rightward.

and POST). The psychometric curves obtained before and after the training phase were compared considering the force intensity corresponding to a probability of giving a correct answer equal to 85%. We called this parameter $F_{85\%}$ and successively used it as the maximum assistive force impulse amplitude in the training phase, F_{PEAK}. We chose a threshold of 85% of the cumulative probability function instead of 75% threshold, which is typically used in forced two-choice discrimination tasks, because it is dependent on the slope of logistic regression. The steeper the curve, the more accurate is the discrimination around the threshold.

In order to estimate whether a preference for one of the two directions exists, we computed the probability of perceiving a rightward perturbation, given a stimulus directed 45° leftward or directed 45° rightward. Subsequently, we obtained the *bias curve* by fitting a logistic function between −4 N and +4 N, where negative force intensities were used to identify stimuli directed to the left. Therefore, we obtained the *bias level* as the stimulus intensity corresponding to a 50% probability of perceiving the stimulus as directed toward the right. For instance, if stimuli displacing the hand to the left were easier to identify than stimuli toward the right, the mean value of the curve would be shifted in the direction of positive stimuli. This is because forces directed to the right would require higher stimulus intensity to be identified correctly. This is the case represented in Fig. 2 for right hand curves (red lines).

2.3.2. Training phase. In order to evaluate subjects' both kinesthetic and motor performances during the training phase, we adopted a set of three indicators: *mean speed* of movement and *straightness* of path (path length score) evaluate the motor performance of the reaching movement, and the AC index measures the appropriateness of kinesthetic response to the pulsed force field.

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2.4. Perceptual score: AC index

The AC index is designed to evaluate the degree of coordination between the movements executed during the guidance active phase with respect to the one immediately following the force impulse.

The rationale of this indicator exploits the pulsed nature of assistive force field. Indeed, our hypothesis is that if the subject is able to interpret correctly the kinesthetic sensation given by the impulse, the movement that follows the haptic stimulus will be aligned to the direction of the force. This means that accuracy in perception increases as the angle between the force vector and the movement vector decreases. Moreover, the indicator should be independent of movement speed: a higher motor response to haptic cue does not imply a greater accuracy and it might depend upon the strategy that the subject adopts to accomplish the task. Therefore, in our previous work[1] we proposed to compare the integral of velocity vector with the integral of speed. In the case of a perfectly straight trajectory, all velocity vectors are aligned to the line joining the start position to target one and the ratio between the two quantities is equal to 1. This value decreases if the path curvature increases, as the integral of velocities would necessarily be inferior to the integral of speed. In particular, the score tends to zero if the subject does not provide any active focal motor command, i.e., aimed at the target, as we may expect that the force impulse would determine a small displacement in the direction of the target that would be followed by an almost equivalent backward displacement during the off phase.

This evaluation can be computed over every single impulse period i, and we call AC_i the corresponding ratio as formulated in Eq. (4), where N_T is the number of samples in an impulse period and $\overrightarrow{v_j}$ is the jth velocity vector. Since the off phase of the impulse (300 ms) is greater than its active phase (200 ms), the contribution to the ith score of the active movement executed in the absence of force is weighted more than the movement executed during the impulse active phase. In order to obtain a global score for the trajectory, we computed the AC index in Eq. (5) as the sum of the partial scores over the N_p impulses weighted for the ideal trajectory length S_i and the cosine of the angle between the force direction and the integral vector over the corresponding impulse period, α_i,

$$AC_i = \left\| \sum_{j=1}^{N_T} \vec{v}_j \right\| \Bigg/ \sum_{j=1}^{N_T} \left\| \vec{v}_j \right\|, \quad S_i = \sum_{j=1}^{N_T} \left\| \vec{v}_j \right\|, \tag{4}$$

$$AC = \left(\sum_{i=1}^{N_P} \alpha_i S_i \cdot AC_i \right) \Bigg/ \sum_{i=1}^{N_P} S_i. \tag{5}$$

2.5. Motor scores

Mean speed (m/s): It is computed as the mean speed of movement from the onset of movement until the target point is reached (distance between cursor and target ≤ 2 cm). The onset of movement is the first instant after the new target presentation in which the speed exceeds a threshold of 0.01 m/s.

Path length (PL) *score*: It is an error measure that accounts for deviations from straightness in the execution of trajectory. It is obtained as a normalized difference between the hand trajectory length (L) and the length of the shortest line joining the initial and final points of the trajectory, and it is computed as follows:

$$PL = \frac{L - \|\vec{x}_N - \vec{x}_1\|}{\|\vec{x}_N - \vec{x}_1\|}, \tag{6}$$

where $\overrightarrow{x_1}$, $\overrightarrow{x_N}$ are respectively the initial and final hand position vectors and $L = \sum_{i=1}^{N} \|\vec{v}_i\| \cdot \Delta t$, with $\overrightarrow{v_i}$ indicating the movement velocity and Δt the sample time. A straight trajectory corresponds to PL $= 0$.

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Table II. Independent samples *t*-test for $F_{85\%}$ over subjects before and after the training phase.

		Pre	Post
Mean	Right	1.4962	1.5123
[N]	Left	0.9592	0.8646
SD	Right	0.5170	0.5634
[N]	Left	0.1754	0.2138
DoF		24	24
t		3.5463	3.8750
p		0.0016	0.0007

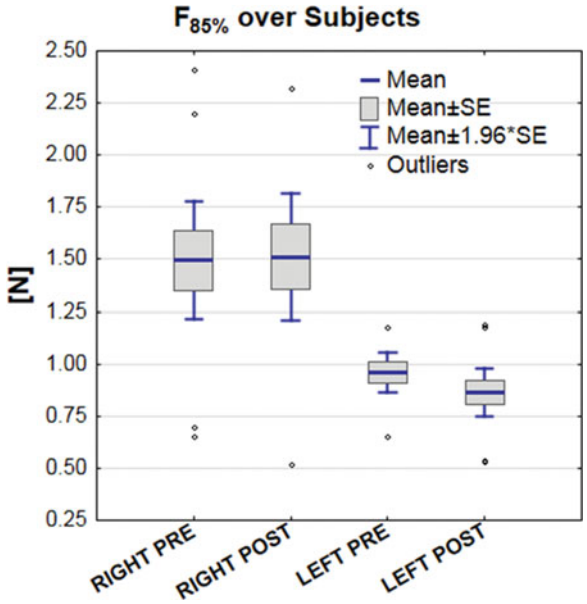


Fig. 3. (Colour online) Distribution of force threshold corresponding to 85% probability of giving a correct response to a force stimulus ($F_{85\%}$) for the two hands (right–left) before (pre) and after (post) the training block. Gray boxes represent the standard error (SE) around the mean value (horizontal blue line). Whiskers length is equal to 1.96 × SE. Outlier values are marked by black cirlces.

3. Results

3.1. Experiment 1

3.1.1. Psychometric curves. Table II shows the force threshold at 85% ($F_{85\%}$) of the estimated psychometric function for both right and left arms before and after the training phase. According to a *t*-test for independent samples, the force required to correctly distinguish a 45° displacement to the right from a 45° displacement to the left is significantly higher for the right arm when compared with the left arm both before ($t(24) = 3.556$, $p = 0.0016$) and after ($t(24) = 3.875$, $p = 0.0007$) the training. This means that all the subjects that took part in this study exhibited a higher kinesthetic sensitivity for the left, non-dominant arm, as shown in Fig. 3. On the contrary, when comparing paired data obtained before and after the training phase, no difference is found (right arm: $t(12) = -0.154$, $p = 0.880$, left arm: $t(12) = 1.312$, $p = 0.214$). Interestingly, the non-dominant arm shows an overall tendency to increase its sensitivity to the applied force after the training with the dominant arm. Indeed, the mean value of $F_{85\%}$ for the left – not trained – hand decreases in spite of the difference being not statistically significant (see Table II).

To investigate whether a difference in perception thresholds for the two directions is present, we analyzed perception bias curves. Table III reports the mean value and the slope (standard deviation) of psychometric curves (Fig. 2) before and after the exercise phase.

From data reported in Table III, it is apparent that a bias in perception exists, as the mean value is different from zero for every subject. In particular, Fig. 4 shows that bias values for the right arm are

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Table III. Point of subjective equality (PSE) (mean ± 75–25%).

	Right hand		Left hand	
	Pre	Post	Pre	Post
S1	0.368 ± 0.676	0.618 ± 0.789	−0.136 ± 0.492	0.154 ± 0.760
S2	0.120 ± 1.112	0.112 ± 0.776	0.047 ± 1.185	−0.168 ± 0.432
S3	0.238 ± 0.986	0.016 ± 1.100	−0.248 ± 0.664	−0.319 ± 0.875
S4	−0.176 ± 1.584	−0.440 ± 1.648	0.066 ± 0.728	0.100 ± 1.009
S5	0.163 ± 1.106	−0.115 ± 1.455	−0.291 ± 0.525	−0.288 ± 0.816
S6	0.115 ± 0.508	0.011 ± 0.322	0.088 ± 0.388	0.003 ± 0.347
S7	0.056 ± 0.688	0.025 ± 0.840	0.152 ± 0.788	0.024 ± 0.672
S8	−0.072 ± 1.300	−0.108 ± 0.739	−0.168 ± 0.580	−0.168 ± 0.580
S9	0.320 ± 1.024	0.040 ± 0.704	−0.040 ± 0.580	−0.088 ± 0.516
S10	−0.136 ± 0.392	0.020 ± 0.982	0.104 ± 0.912	0.168 ± 0.420
S11	−0.208 ± 1.480	−0.010 ± 1.660	0.312 ± 0.700	0.088 ± 0.700
S12	0.298 ± 1.080	0.070 ± 1.184	−0.080 ± 0.544	−0.008 ± 0.516
S13	−0.088 ± 0.904	0.270 ± 0.735	−0.128 ± 0.584	−0.036 ± 0.608

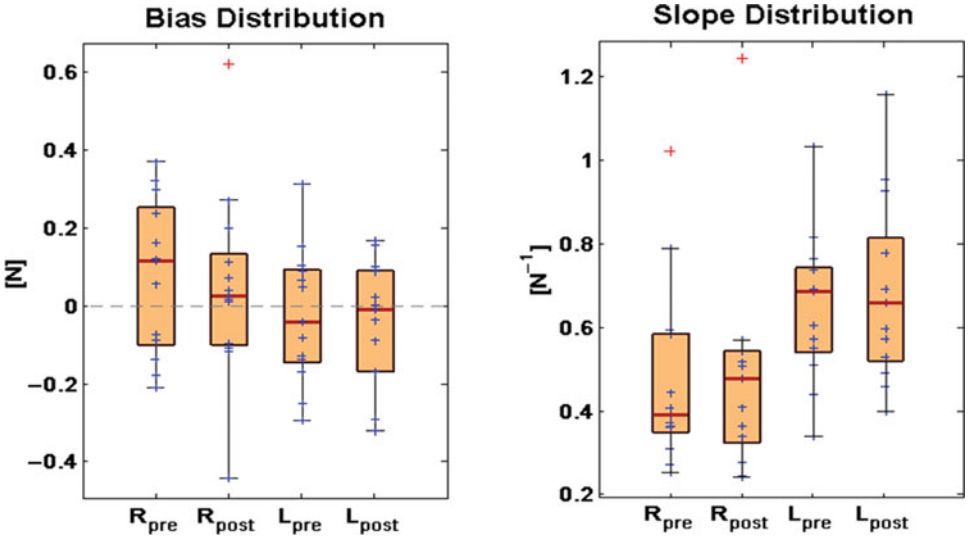


Fig. 4. (Colour online) Distribution of force perception bias (left panel) and bias curve slope (right panel) among testing conditions (before – pre, and after – post the training block) over subjects. R stands for right arm, L for left arm. Orange boxes represent the IQR, and the horizontal red lines is the median value. Whiskers length is equal to $\pm 2.7\sigma$. Outlier values are marked by red crosses.

mainly positive, indicating that forces directed to the left have a lower detection threshold with respect to forces directed rightwards. Conversely, the left arm perceives more sharply the stimuli directed to the right than those to the left. Bias distribution has high variability, but generally this asymmetry is more pronounced for the right arm. Instead, the left arm exhibits a greater accuracy (higher slope). The difference in accuracy is significant both before and after the training phase (Wilcoxon ranking test – pre: $p = 0.039$, post: $p = 0.002$). It is worth noting that although the mean $F_{85\%}$ level for the right hand is unaltered after the training, the mean bias is closer to zero and the slope of the curve increases.

3.1.2. Performance indices. All the participants could successfully complete the training blocks, yielding to 15 reaching repetitions for each F-target location. In the familiarization trial, in spite of the fact that the subjects were instructed to move as straight as possible and without giving any explicit time constraint, the duration of each movement subset S->F->I->S was consistent among participants and movement sets, and it was not dependent on the target location and on average was equal to 3.0 ± 0.6 s. On the contrary, when vision was obscured, the movement subset duration was highly variable among the subjects and seemed to differ depending on the outward movement

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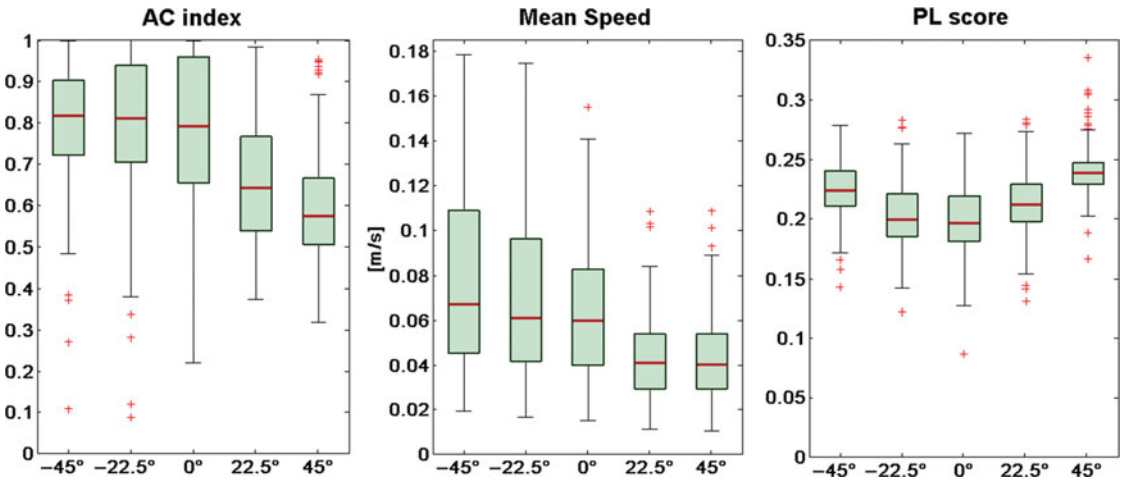


Fig. 5. (Colour online) Boxplots of three indicators used to asses subject's performance during the training block: AC index (left panel), mean speed (m/s) (middle panel), and path length (PL) score (m) (right panel). Each box summarizes the distribution of indicator values over all the trials (15) for each target direction separately.

direction (median ± Interquartile Range (IQR): –45° : 13.5 ± 11.7 s; −22.5° : 12.3 ± 9.9 s; 0° : 12.0 ± 10.7 s; 22.5° : 17.3 ± 12.0 s; 45° : 23.1 ± 17.3 s). The number of impulses conveyed to the subjects changed accordingly (median ± IQR: −45° : 26 ± 24; −22.5° : 24 ± 20.5; 0° : 23 ± 21; 22.5° : 33 ± 24; 45° : 44.5 ± 34.5).

Figure 5 summarizes the distribution of three indicators across the five possible force directions (−45° , −22.5° , 0° , 22.5° , and 45°) throughout the training phase. The AC index shows that the force direction has a relevant influence on the kinesthetic performance, which degrades moving from the left to the right hemiplane. Indeed, the median score is the highest for forces acting along −45° (AC = 0.8156), while it is minimal for forces acting along 45° (AC = 0.5728). The increased difficulty in perceiving the haptic cue might explain the lower mean speed rightward directions (−45° : 0.067 m/s, 45° : 0.040 m/s). On the contrary, the PL score is almost symmetric with respect to the middle position.

In support of these observations, a repeated measure analysis of variance over the score values obtained throughout the training highlighted a strong significant effect of force direction ($p \ll 0.001$). In particular, the two rightmost directions statistically differ from the others in both mean speed and AC index (Sheffè's *post hoc* test). In contrast, PL score values were comparable among the three middle targets (−22.5° , 0° , 22.5°) but significantly greater when considering two extreme directions. The statistical test revealed also that repetition of movements caused the indicators to change with time ($p \ll 0.001$).

To test for training effects on our performance indicators, we compared the second target set with the last one. The first target set served for familiarization. For each indicator we tested for differences among force direction and subjects (the significance level was fixed at 0.05):

1. AC index: The analysis among subjects and across force directions reveals that the score is quite stable throughout the training as no significant variation can be found. Nonetheless, there is a noticeable difference in performance among force directions ($p \ll 0.0001$), as shown in Fig. 6, left panel. In particular, the *post hoc* test identified the two rightmost directions (22.5° and 45°) as significantly different from the other three. According to the AC index (Fig. 7, top panel), none of the subjects varied significantly his score at the end of the exercise if compared with others (p-value = 0.048, but no significant comparison found).
2. Mean speed: Globally all the subjects exhibit a significant variation between the first and the last target set on all the target directions ($p = 0.009$). Even though the training affects significantly the indicator values ($p \ll 0.001$), the performance over the force direction still differs significantly at the end of the exercise (there is no interaction effect), as can be seen from Fig. 6, right panel. The three leftward directions, i.e., −45° , −22.5° , and 0° , exhibit the most striking differences (Duncan's *post hoc* test), as shown in Fig. 6, right panel. When testing for differences among

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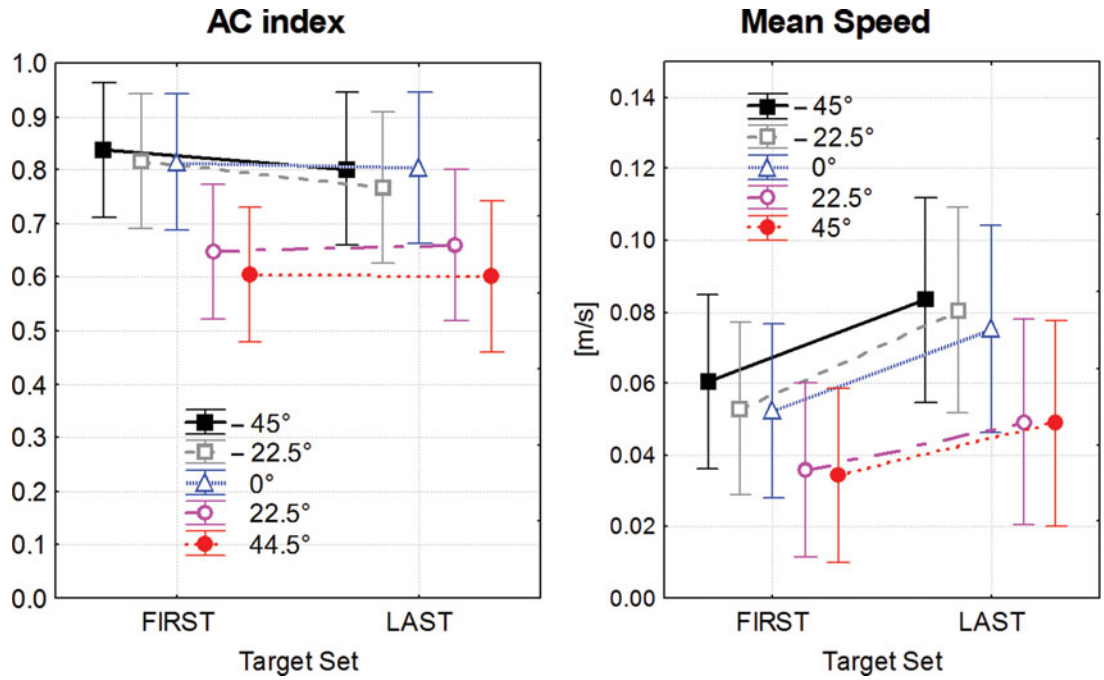


Fig. 6. (Colour online) Mean value and 95% confidence intervals for AC index (left panel) and mean speed (m/s) (right panel) values during the first target set (FIRST) compared with the last one (LAST) for each force impulse direction.

subjects (Fig. 7, middle panel), we found a significant effect of training ($p \ll 0.001$), especially for 4/13 subjects (S1, S4, S7, and S8) that exhibit a considerable improvement on the mean speed of movement in the last target set compared with the first one.

3. PL index: Globally there is no effect of the exercise on the score over different target directions. However, the index value is strongly affected by the force direction: it is minimal for the middle target (0°) and progressively increases moving to the lateral ones. The difference between the middle target and the extreme ones is indeed significant according to the Sheffè's *post hoc* test ($[0^\circ , -44.5^\circ] = 0.006$, $[0^\circ , 44.5^\circ] \ll 0.001$). As expected, observing data in Fig. 7 (bottom panel), not all the volunteers reported a similar trend and only subject S6 ($p = 0.0446$) significantly improved his performance during training according to this indicator.

3.2. Experiment 2

3.2.1. Psychometric curves. Figure 8 shows bias and slope parameters estimated from the bias curve in the beginning (dark gray columns) and in the end (light gray columns) of each testing session for both right and left arms. The bias level for the right arm (Fig. 8 left panel) tends to increase as an effect of the training block and it is variable among the three sessions. Interestingly, the left-hand bias seems to vary among training days, displaying a consistent shifting toward the left direction, especially after the exercise. On the contrary, a remarkable effect of the training is present on the slope parameter of both right and left sides (Fig. 8 right panel). In spite of the absence of significant variation in the slope parameter of the bias curve within the same session, both hands showed a noticeable positive trend in perceptual accuracy from one session to the following, indicating an improvement in perceptual accuracy.

3.2.2. AC index. The mean AC index throughout sessions for the three subjects is shown in Fig. 9. The boxplots are obtained considering the AC index over the five target directions, and the median value is shown as a red line. Over each box, we reported the value of $F_{85\%}$, which was computed after the initial psychometric testing block. All three subjects succeeded in improving their average AC index and reducing its variability after three sessions of training. Most important, they also remarkably reduced the intensity of haptic guidance, i.e., $F_{85\%}$ (mean $\pm$ standard error $= -0.627 \pm 0.196$ N).

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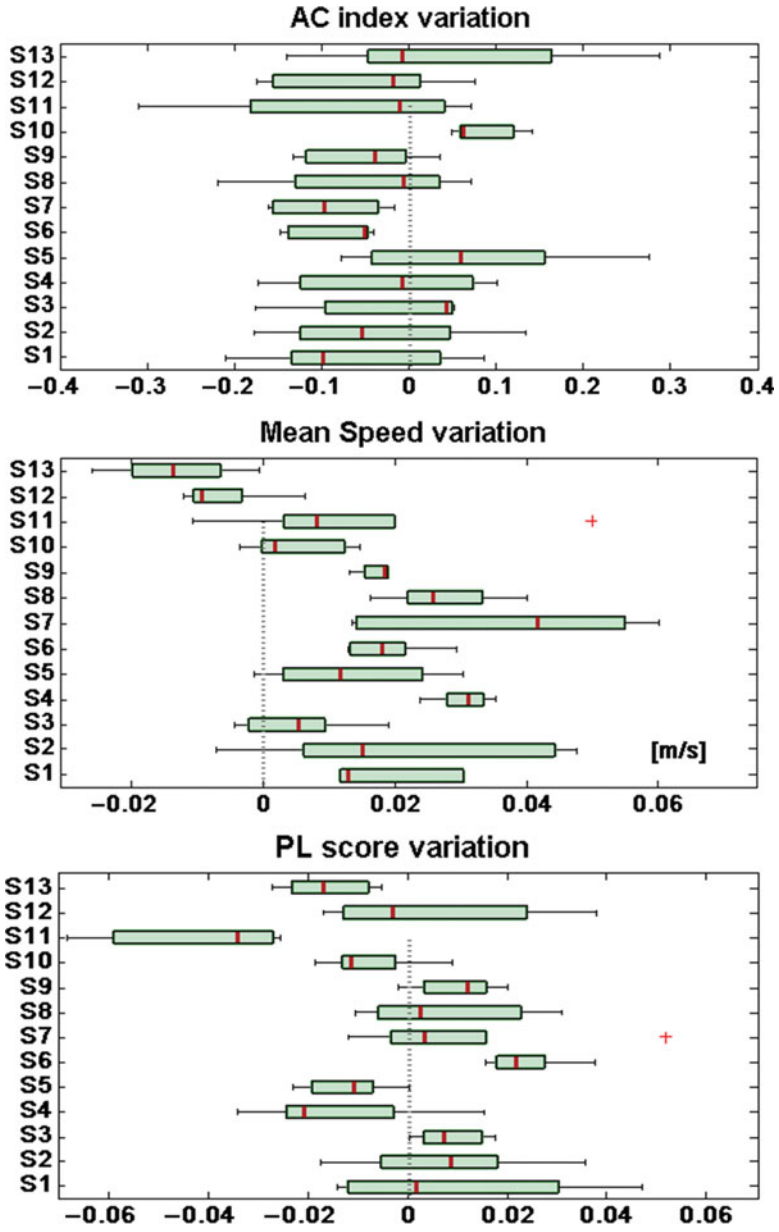


Fig. 7. (Colour online) Mean variation between the first and the last target set along all force directions for each subject. Top panel: AC index. Middle panel: Mean speed (m/s). Bottom panel: PL score (m). Green boxes represent the IQR, and the vertical red lines represent the median value. Whiskers length is equal to $\pm$ 2.7σ. Outlier values are marked by red crosses.

Since certain variability in the mean score among target directions exists, we analyzed the profile of the AC indicator in time separately for each direction. Figure 10 shows the mean value (column height) and the standard deviation (whiskers) of the AC index on the five possible force directions for day 1 (gray), day 2 (green), and day 3 (orange). In spite of reduction in haptic guidance throughout the training sessions, all subjects exhibited an improvement on the mean value of the AC index, especially in the rightward directions, where the kinesthetic acuity was the lowest at the beginning of the training.

4. Discussion

In accordance with the hypothesis that perceptual training is able to support motor learning through the modulation of sensory systems,[26] we designed a novel paradigm that integrates kinesthetic acuity

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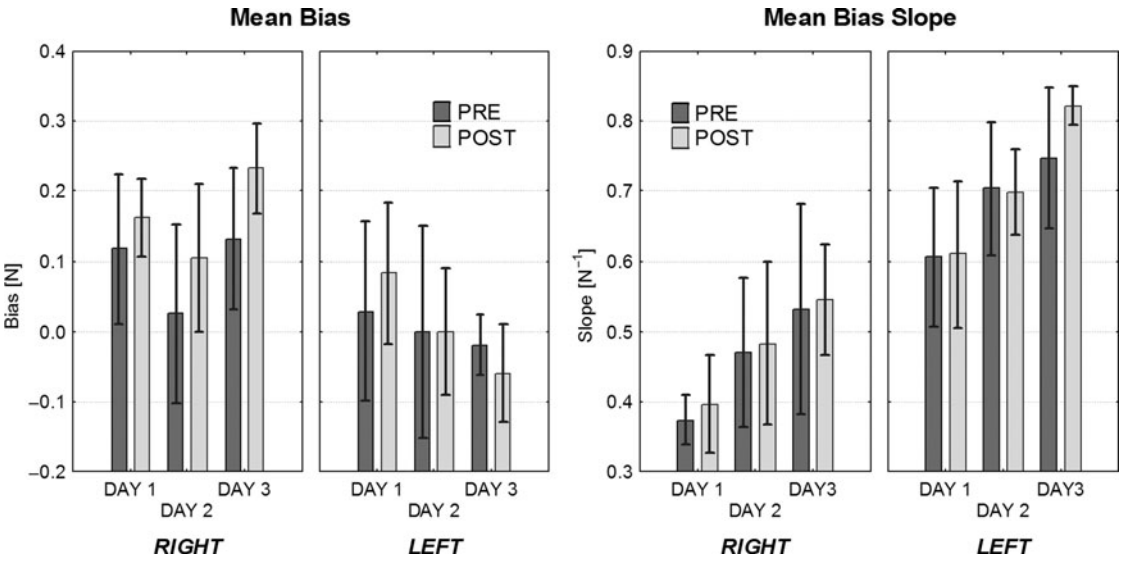


Fig. 8. Left panel: Mean value of bias over three subjects across the training sessions. Right panel: Mean value of bias curve slope over three subjects across the training sessions. Column height is equal to the mean value; data obtained before (PRE) the training session are filled in dark gray wheres data relative to after (POST) training are in light gray; whiskers length is equal to 1.96 × SE.

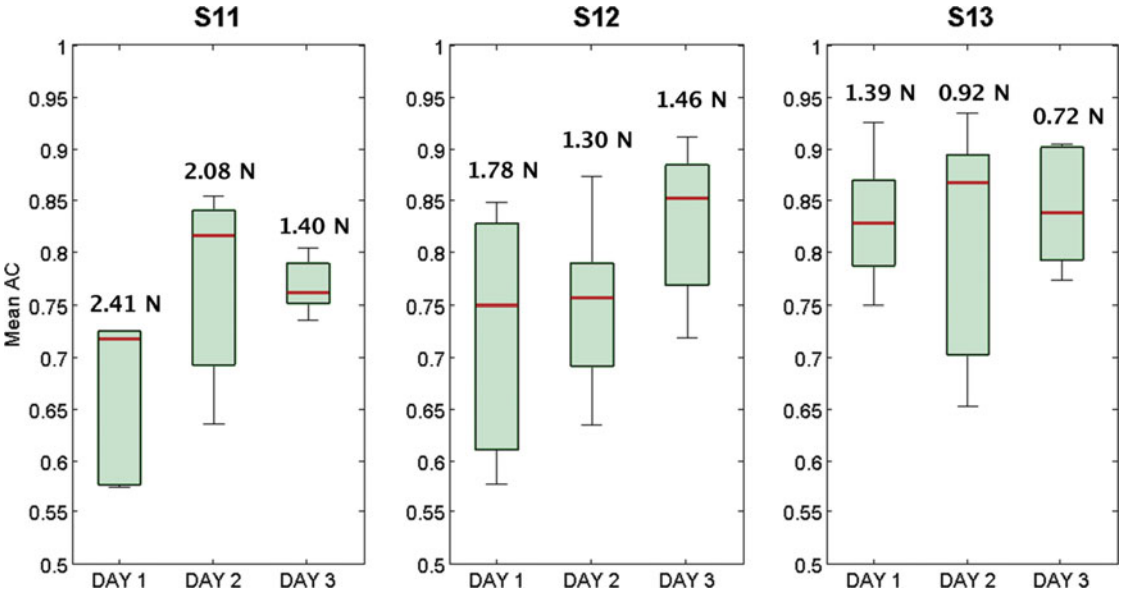


Fig. 9. (Colour online) Mean AC index over target directions for three subjects across the training sessions (day 1, day 2, and day 3). Green boxes represent the IQR, and the horizontal red lines represent the median value; whiskers length is equal to $\pm$ 2.7σ. The numbers over each box are the values of $F_{85\%}$ esteemed by the psychometric curve and used as F_{PEAK} throughout the execrcise.

estimation into a training paradigm for reaching movements to combine perception with the motor aspects of the movement. In particular, right-handed subjects were required to move their dominant arm in the direction of haptic cue until they reached a target position on the horizontal plane, exploiting the haptic feedback information to generate a consistent motor plan. The experimental design was conceived to induce an active sensory experience that is attention-demanding, since volitional effort and active engagement were found to be necessary to recruit plasticity at cortical level.[27,28]

In order to evaluate kinesthetic performance during the exercise, we measured the AC index in presence of a pulsed haptic guidance paradigm. The level of force provided during the exercise was selected by taking into account inter-subject variability of perceptual acuity. The AC evaluation was

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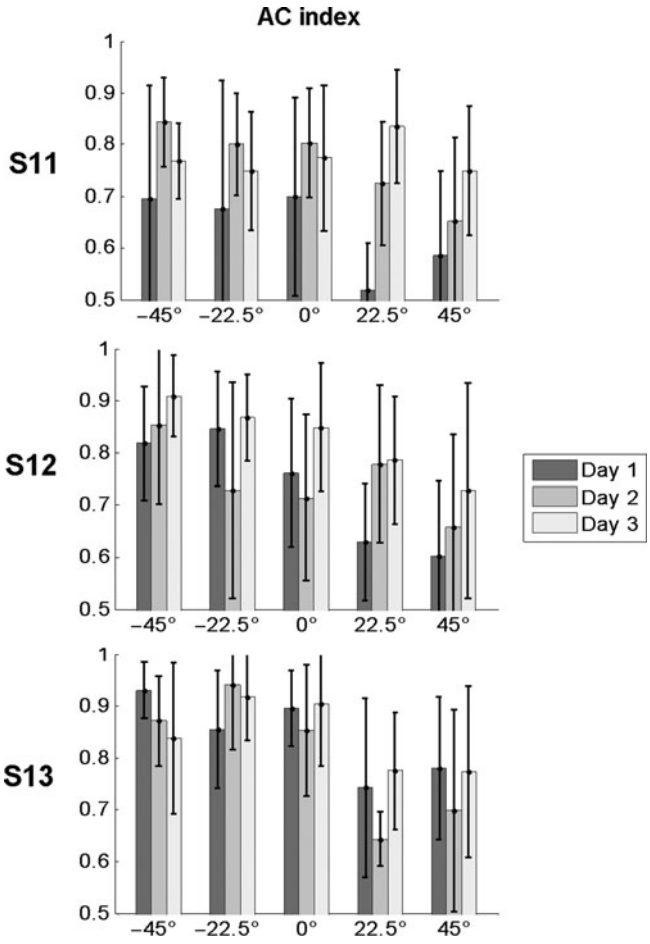


Fig. 10. Mean AC index of three subjects over the training sessions for each target direction. Day 1, day 2, and day 3 are coded from darker to lighter color. Column height is the mean value of AC index over all the trials of five target sets (15 values); whiskers represent standard deviation.

preceded and followed by a psychometric estimate of the kinesthetic perception threshold to test for short-time proprioceptive modulations because of the exercise. In addition, we computed two indicators of motor performance during the task, namely mean speed and PL score.

These motor scores identify improvement in motor performance during the exercise. However, it is possible for this effect to be due to practice with the robotic device and not necessarily due to an increased acuity on the perception of force direction.

Our results show that when the level of haptic guidance accounted for inter-subjective differences in kinesthetic acuity, all the subjects consistently exhibited similar AC index values throughout the training session and a similar anisotropic distribution of score values among force directions. In particular, their performance during training was on average 30% higher for leftward perturbations compared with rightward hand displacements. This result was less evident from the measurements of the bias in the initial and final psychometric evaluations that were obtained during passive static conditions and were characterized by a higher degree of variability. Therefore, our results support the observation by van Beers *et al.*[29] that the accuracy and precision of proprioceptive-guided reaching depend on the location of the target in the workspace. These authors advance two hypotheses: (i) movement planning takes into account the sensitivity of arm to external perturbations and the uncertainty in the information about the joint angles or proprioception, and (ii) the pattern of proprioceptive localization errors depends on arm's geometry. Similar patterns of directional bias were also observed during an obstacle avoidance reaching exercise.[30] In fact, it is possible that arm configuration influences the discrimination of force direction so that either the left or the right perturbation might be easier to perceive. For instance, inertial anisotropies and limb stiffness properties

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might play a role in mediating kinesthetic perception, as the force of equal intensity may be more effective in displacing the arm along the direction in which inertia is minimal.

Gordon *et al.*[31] have shown that when generating a targeted movement in the absence of visual feedback, the peak acceleration markedly varied with the movement direction and doubled when moving along the axis perpendicular to the forearm (60° , 30° in our convention), where the inertial load is lower with respect to the forearm axis (150° , -50° according to our convention).

If we consider a constant force applied to the hand, the initial accelerations induced by this force are determined by the mobility tensor, the inverse of the inertia matrix, which are distributed according to the mobility ellipse, rotated 90° with respect to the inertial one.[32] Therefore, a force acting along the major axis of the mobility ellipse (minor axis of the inertia ellipse) would result in a greater peak acceleration if compared with forces aligned in the orthogonal direction (aligned with the forearm). However, our results have shown that forces acting along the 30° directions are prone to greater perceptual errors. The fact of having an anisotropic inertial tensor implies that any force not aligned with the principal axes of inertia would result in hand accelerations that are rotated with respect to the applied force in the direction of the eigenvector associated with the highest eigenvalue of the matrix. Let us consider the case of a force that acts in the direction close to the minor axis of the arm inertia, but is not aligned with it. This force, when projected in the inertial tensor subspace, will have a non-null component along the major eigenvector of the tensor. Thus, it will result into an acceleration rotated toward the major inertial axis. The greater the force magnitude, the greater the angle between the force and the acceleration directions. In the hypothesis of a very accurate sensation, this effect could explain perceptual biases through direction closer to the main axes of inertia. This implication is also consistent with the bias levels estimated for right and left arms: the two arms showed mirrored bias values in the endpoint space because the perception thresholds are lower for the directions aligned with the forearm.

By generating a pulsed force field in the training phase of our experiment, we provided subjects with repeated intermitted feedback with the aim of boosting the integration of afferent signals into the ongoing trajectory formation process. Given the absence of visual information about the target position, the planning of movement has to take place incrementally with the availability of feedback information. Therefore, we might expect that anisotropies in arm properties play a major role in determining movement characteristics. Indeed, not only the kinesthetic performance (AC index) but also the associated kinematic scores were markedly superior along directions in which uncertainty in the estimation of displacement was lower: the mean movement speed was significantly higher and the path covered by the hand was straighter (lower PL score). This means that essentially anisotropy is a source of systematic, although predictable, uncertainty of the measured quantity. In principle, this measurement error could be eliminated by compensating the overall anisotropy of the robot+arm system with an appropriate acceleration-dependent feedback, but in the current configuration of robot controller, an accurate online estimate of acceleration would introduce unacceptable delays.

Ghez *et al.*[33] proposed that proprioception might also have an important role in forming and updating internal representations of limb properties. Darainy *et al.*[26] have recently shown that perceptual training acts to reduce uncertainty in somatosensory domain and to aid the development of a desired trajectory that guides subsequent movements, leading to greater improvement on kinematic characteristics after motor training. They also found that the effects on the motor system are dependent on perceptual judgment and reinforced decision-making. Since the AC index proved to be a reliable measure of kinesthetic acuity, we conducted a second experiment to test for any effect of repeated exercise on perceptual scores. Three subjects repeated the protocol over three consecutive days and we compared the AC index values and psychometric parameters (bias and the slope of bias curve) throughout the training.

Results lead us toward a twofold consideration. On one side, they highlight the correlation between the AC index and psychometric measures of kinesthetic perception: indeed, the improvement of kinesthetic acuity detected by the AC index on the right arm is reflected by an increase in the slope of bias curves in all the three subjects considered (+44.61%). On the other side, the results strongly support the hypothesis that the pulsed guidance-based protocol that we adopted to evaluate and train proprioceptive acuity was effective in promoting some kind of kinesthetic plasticity, as we observed a retention phenomenon in both AC index and $F_{85\%}$ value.

It is also worth observing that adaptive modulation of performance is not confined to the trained arm but appears to spread beyond. In fact, the perceptive accuracy, as reflected by the slope parameter

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of the bias curve, was also consistently increased in the non-trained left arm (+35.78%). Moreover, the values of psychometric parameters that we obtained in both experiments highlight the existence of a significant perceptual asymmetry between right and left sides. In particular, the left side appears on average less biased and more sensitive to perturbations induced by a pulsed force (−0.50 N on average with respect to the right side). This finding might reflect the role of non-dominant hand in inter-limb coordination for bimanual tasks.[34] Wang and Sainburg[35] suggested that there may be dominant arm system advantages in controlling aspects of movement planning (e.g., direction of movement) and non-dominant arm system advantages in controlling aspects of movement execution (e.g., correction and control of the limb during movement). Sainburg[36] observed that in right-handed individuals the dominant right limb/left hemisphere system is specialized for controlling limb dynamics, and the non-dominant left limb/right hemisphere system is specialized for controlling static limb position. Indeed, Han *et al*.[20] found that in strongly right-handed subjects, left limb/right hemisphere is integrating all normally available proprioceptive information from different joints and different joint receptors in active proprioceptive tasks, thus being more efficient in making use of site-specific proprioceptive feedback during the movement.

5. Conclusions

The results highlighted that the AC score is very sensitive to perceptual anisotropies due to haptic feedback directionality. Thus, this indicator may be used in motor training exercises as a parameter for an adaptive and site-specific regulation of haptic guidance level. In addition, the AC value can serve as an evaluation metric for the modulation of kinesthetic sensation following a training exercise. On the other hand, we have shown that the AC index level is correlated to the emergence of a durable modulation in the kinesthetic perceptual channel as evaluated by the $F_{85\%}$ parameter. Recently, Darainy *et al*.[26] found that perceptual training helps to define the sensorimotor goals of movement and facilitates motor learning. To what extent this type of exercise can be effective in training kinesthetic acuity has to be further investigated, since a more intensive and prolonged training is required. In our case, the AC index improvement may still be partially dependent on the haptic guidance level that is also diminishing throughout sessions. For instance, a more prolonged training may first minimize the intensity of haptic feedback, and second bring the AC index closer to its maximum level. Therefore, it would be interesting to test whether the AC index improvement is reflected by an increase in motor performance, and to analyze whether the integration of such a proprioceptive training paradigm can be of any benefit in a motor retraining program.

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