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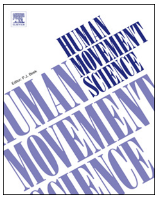

Proprioceptive identification of joint position versus kinaesthetic movement reproduction

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ABSTRACT

Regarding our voluntary control of movement, if identification of joint position, that is independent of the starting condition, is stronger than kinaesthetic movement reproduction, that implies knowledge of the starting position and movement's length for accuracy, is still a matter of debate in motor control theories and neuroscience.

In the present study, we examined the mechanisms that individuals seem to prefer/adopt when they locate spatial positions and code the amplitude of movements.

We implemented a joint position matching task on a wrist robotic device: this task consists in replicating (i.e. matching) a reference joint angle in the absence of vision and the proprioceptive acuity is given by the goodness of such matching.

Two experiments were carried out by implementing two different versions of the task and performed by two groups of 15 healthy participants. In the first experiment, blindfolded subjects were asked to perform matching movements towards a fixed target position, experienced with passive movements that started from different positions and had different lengths. In the second experiment, blindfolded subjects were requested to accurately match target positions that had a different location in space but were passively shown through movements of the same length.

We found a clear evidence for higher performances in terms of accuracy (0.42 ± 0.01 1/°) and precision (0.43 ± 0.01 1/°) in the first experiment, therefore in case of matching positions, rather than in the second where accuracy and precision were lower (0.36 ± 0.011/° and 0.35 ± 0.01 1/° respectively). These results suggested a preference for proprioceptive identification of joint position rather than kinaesthetic movement reproduction.

1. Introduction

How humans plan their movements toward a target is a fascinating research topic in biomechanics, movement science and neuroscience. Despite there are many possible ways to move one's hand towards an object, due to the redundancy of our musculoskeletal system, it is now certain that humans tend to move in a specific way (Morasso, 1981). Nonetheless, the theory of the mechanism behind this voluntary motor planning is still under debate. Specifically, two main sensorimotor strategies have been identified (Miall & Wolpert, 1996).

A first perspective claims that the movement is generated after a prior estimation of the relative distance between the limb and the target (Miall & Wolpert, 1996; Morasso, 1981; Wolpert, Ghahramani, & Jordan, 1995), thus entailing a vectorial coding of space

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representation, based on the amplitude of the movement to plan (Bock & Eckmiller, 1986; Ghez, Gordon, & Ghilardi, 1995; Meyer, Abrams, Kornblum, Wright, & Smith, 1988). Conversely, it is also thought that the motor system controls limb movements by setting muscle length-tension parameters (Feldman, 1980), so that the final equilibrium point corresponds to the position of the target, whatever the initial position of the limb in space (Bizzi, Polit, & Morass, 1976; Feldman, 1980; Latash & Gottlieb, 1991).

From a simplistic viewpoint we can say that, while the first idea is fully dependent from the knowledge of the initial position of the movement, and therefore its amplitude, the second one unbinds the motor planning to the initial position, claiming that our motor system only needs the final location for a good motor planning. Accordingly, considering point-to-point movement around a single joint, one can then describe the two processes respectively as *amplitude* control and *position* control (Miall, Haggard, & Cole, 2017).

This dichotomy has been mesmerising researchers for more than forty years (Jones, 1972; Marteniuk & Roy, 1972), but only few studies have tried to systematically investigate the problem from different perspectives. Specifically, all the above mentioned studies have considered the movement as an entity generated by the motor system with the contribution of both visual and proprioceptive information.

Our insight is that restraining the visual feedback and forcing the subject relying only on proprioceptive information could fill the existing knowledge gaps, tipping the balance between the two theories.

The sensory stream responsible for the unconscious perception of body movements and spatial awareness is called proprioception (McCloskey et al., 1978), and it originates from mechanoreceptors within muscles, tendons, and skin, giving rise to kinaesthesia and the sense of joint position (Gandevia, Refshauge, & Collins, 2002). While the sense of joint position is the proprioceptive process which underlies the interpretation of body segments' location in space, kinaesthesia is the ability to sense the motion of a joint. Although there is clear evidence for both joint position sense and kinaesthesia to play a crucial role in all the processes related to motor control and learning (Smyth & Mason, 1998), yet, literature about the mechanisms underlying these processes is still sparse (Ostry, Darainy, Mattar, Wong, & Gribble, 2010), such as no clear understanding of principles giving rise to proprioceptive perception have been achieved. Specifically, what it is worth to investigate is the balance between amplitude and position control during proprioceptive matching, which could be revealed by a predominant preference for either proprioceptive *identification of joint position* or *kinaesthetic movement reproduction*.

Only recently, motor control principles, in proprioceptive matching have been investigated with the purpose of ascertain the predominant strategy between the *amplitude* control strategy and the *position* control strategy, and explore the balance between the two, in both heathy participants (Chieffi, Conson, & Carlomagno, 2004; van der Graaff, Brenner, & Smeets, 2017) and a deafferented subject (Miall et al., 2017).

Yet, up to date, no common understanding has been reached and the balance between these two extremes of control remains uncertain. Therefore, in light of these recent papers, with the aim to fill this knowledge gap, we have lately started to investigate human wrist proprioception through a robotic interface, able to provide quantitative, objective and reliable measurements (Marini, Squeri, Morasso, Konczak, & Masia, 2016). The use of a robotic device, with high resolution sensors and high precision actuators, allowed to reach a high level of repeatability and accuracy in measuring subjects' performance. In a preliminary work (Marini, Squeri, Morasso, & Masia, 2016) we found evidences supporting preference for amplitude coding of target positions in proprioceptive tasks, but the random shift in positions from trial to trial in this study, hindered a comprehensive analysis.

We now aim to extend this corpus of work, examining which mechanisms individuals seem to prefer/adopt when they locate spatial positions and code the amplitude of movements, with attention at controlling the different variables contributing to the proprioceptive information (i.e the execution speed Chieffi et al., 2004), possibly affecting the results. Specifically, the main goal of the present study was to investigate whether the proprioceptive acuity in perceiving final positions and in perceiving movement's length is similar, or if conversely, in one of the two cases the proprioceptive system provides a better perception.

Two different versions of a robot-based joint position matching task were implemented on a haptic device and performed by two groups of 15 healthy participants. In the proposed task, individuals were requested to replicate a reference joint angle in the absence of vision; the proprioceptive acuity was given by the goodness of the matching.

The first experiment aimed to test proprioceptive *joint position identification* (*JPI*) (position control strategy), and consisted in matching movements in the absence of vision, towards a fixed target position, experienced with passive movements that started from different positions and had different lengths. In the second experiment, blindfolded subjects were requested to accurately match target positions that had different locations in space but were passively shown trough movements of same length, to test ability in *kinaesthetic movement reproduction* (KMR) (*amplitude control strategy*). Different spatial conditions were presented, to correlate the phenomenon to the amount of the shift or displacement involved.

2. Methods

2.1. Participants

Thirty right-handed subjects (mean age 28.3 ± 4.1 years, 13 females, 17 males), with no history of neuromuscular disorders and naïve to the task, were randomly divided in two groups (each of 15 subjects) and participated to the study. Handedness of all participants was assessed using the Edinburgh Handedness Inventory (Oldfield, 1971) and the study was approved by ethics committee of the regional health authority, Azienda Sanitaria Locale Genovese (ASL) N.3 (Protocol number 311REG2014 approved on 09/12/2015). Experiments were carried out at the Motor Learning, Assistive and Rehabilitation Robotics Lab of the Istituto Italiano di Tecnologia (Genoa, Italy). Each subject signed a consent form that conforms to these guidelines, according to ethics committee

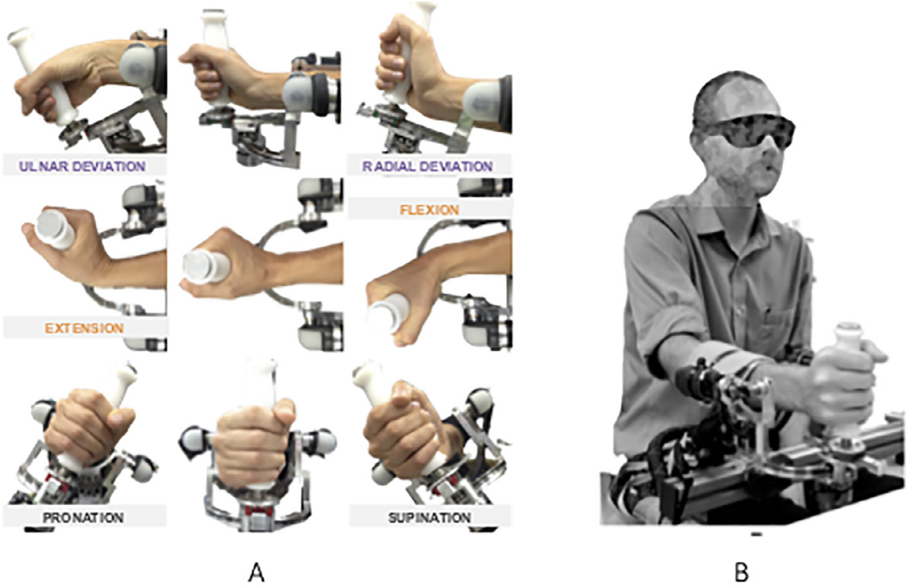

Fig. 1. Wrists DoFs and movements involved in the task (flexion/extension, radial/ulnar deviation, and pronation/supination) and relative kinematics of the robotic device. (B) A sample blindfolded subject grasping the handle of the wrist robot.

requirements.

2.2. Apparatus

The experimental apparatus consisted of a three-degrees of freedom (DoF) wrist manipulandum (Fig. 1) (Marini et al., 2017; Masia, Casadio, Sandini, & Morasso, 2009). The robotic device allowed movements along the three wrist DoFs: Flexion/Extension (FE), Radial/Ulnar deviation (RUD), and Pronation/Supination (PS) for the entire range of motion of the human joint.

Powered by four brushless motors, the robot can provide an accurate haptic rendering. Angular rotations on the three axes are acquired by means of high revolution incremental encoders with 0.17° of overall accuracy. The maximum continuous torque levels provided by the motors at the different joints are as follow: 1.57 Nm for FE, 3.81 Nm for RUD, and 2.87 Nm for PS. The mechanical transparency of the device was enhanced by a control algorithm, for inertia and gravity compensation, intended to reduce force and effort during the task and to avoid involvement of other muscles except those crucial for the task. Furthermore, the handle of the device was carefully designed in order to allow anatomical grasp and minimise fingers stretch that may lead to exaggerated activation of flexor/extensor muscles during the active phase of the matching task.

2.3. Procedure

Participants sat beside the robotic device, facing forward, and placed their forearm on the rigid cast of the robot, with the elbow bent to about 120° and grasped the handle of the robot (Fig. 1 B). After ensuring the correct alignment between the axes of the robotic system and the wrist's anatomical ones, the subjects' forearm was firmly strapped to the mechanical support. This ensured repeatability of wrist positioning and limited inter-trial variability. It also avoided joints misalignment and unwanted relative movements during the entire duration of the task.

Participants were blindfolded to limit the sensory feedback during the task only to proprioception (Fig. 1 B).

To test differences between the ability in *kinaesthetic movement reproduction* versus the ability in proprioceptive *joint position identification*, we implemented, on the robotic device, an ipsilateral joint position matching task (JPM) (Goble, 2010), in which a target wrist configuration was passively presented to a blindfolded participant, who was then asked to replicate it, as accurate as possible (Marini et al., 2016). Proprioceptive acuity was then measured from the comparison between the target ideal position and the position matched by the subject, differences in performance in the two different experiments were then compared.

Fig. 2 shows the breakdown of a typical experimental trial consisting of four phases: (1) the robot passively moved the wrist from the home position to a determined angular configuration, corresponding to the target position (*reaching movement, RM*) and maintained it there for 3 s (Fuentes & Bastian, 2010), (2) the robot passively removed the wrist from that position (*removal movement, R1*), (3) the subject was required to actively reproduce the previously experienced wrist configuration, as accurately as possible (*matching movement, MM*) while the robot was not actuated and provided no assistance. (4) With another *removal movement, R2*, the robot removed the wrist from the matched position and repositioned the wrist in the home position, to start another trial.

Subject's wrist was passively moved to the target position (*reaching movement, RM*), and moved back (*removal movement, R1* and *R2*) at a constant speed of 25 °/s. The speed profile followed a minimum jerk trajectory (Morasso, 1981).

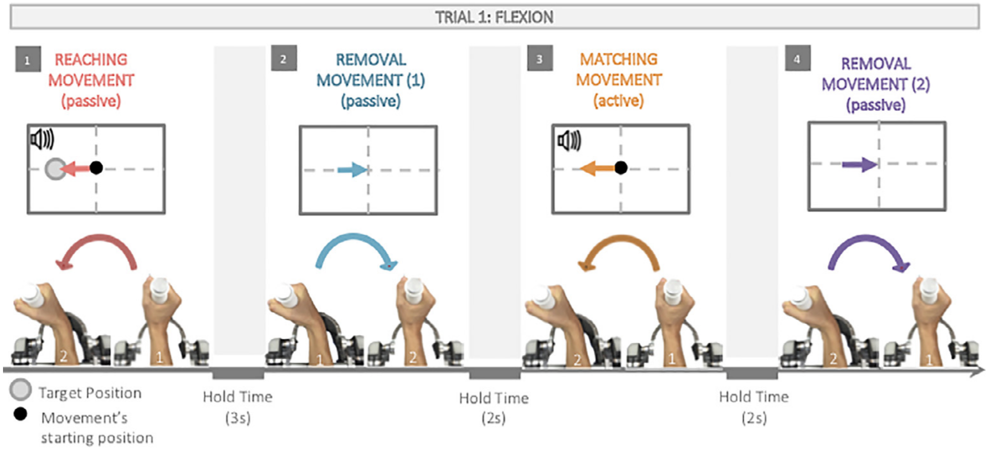

Fig. 2. The schema of a sample trial of the robot-based Joint Position Matching task. The trial is broken down into four parts: (1) *reaching movement* towards the target position, (2) *removal movement* from the target position, (3) *matching movement*, (4) and *removal movement* from the matched position. *Reaching* and *removal* movements were passively imposed by the robot while, the *matching movement* was actively performed by the subject.

The proprioceptive test involved both the directions of the three DoFs separately and one at a time: the robot allowed movements only in the DoF involved in the current trial while keeping the other two in the neutral configuration (i.e. when FE is passively moved the PS and RUD are blocked).

Three auditory cues guided the subject throughout the task. A first cue (high-frequency beep) sounded to mark the beginning of the *reaching movement* and a second auditory cue (low-frequency beep) sounded when the target position was reached. The third auditory cue (high-frequency beep) indicated to the subject that the *matching movement* could start and he/she could attempt matching the previously presented target position. The *matching movement* was considered completed when wrists speed was lower than a $2^{\circ}/s$ threshold for more than 2 s.

During the *reaching* and *removal movements*, the robot control was active and provided forces to move the wrist toward the target position and then back along a minimum jerk trajectory, in passive way. On the contrary, the *matching movement* had to be performed actively by the subject and neither forces nor torques were provided by the haptic device, apart from those necessary for compensation of weight and inertia.

The purpose of the experiment was to ascertain any potential differences between *joint position identification* versus *kinaesthetic movements reproduction*. To this end, we designed two different experiments.

Experiment 1 had the primary goal to elicit *joint position identification*(*JPI*), conversely, Experiment 2 emphasised *kinaesthetic movement reproduction* (*KMR*).

In Experiment 1 instructions to participants were to focus the attention on the final position of the *reaching movement* and try to replicate it as accurate as possible. Vice versa, subjects performing Experiment 2 were instructed to replicate the length of *reaching movement*.

Experiment 1. During Experiment 1, shown in Fig. 3 left panel, after the *reaching movement*, the *removal movement* (*R1*) positioned subject's wrist in a random position of the workspace (along the tested DoF). Therefore, this position became the starting position of the following active *matching movement*. Once the *matching movement* was completed, and the target position matched, another *removal movement* (R2) repositioned the wrist in the neutral configuration (0° FE, 0° RUD and 0° PS). Thus, the next trial always started from the neutral configuration. In this experiment, while the target position never changed (see Table 1), the starting position of the *reaching movement* (SP_{RM}) always differed from the starting position of the *matching movement* (SP_{MM}). Consequently, *reaching* and *matching movement* had different lengths (thus not representing a relevant cue to the subject) while, the focus was centred in replicating the final position (target position, TP) of the *reaching movement* that was constant throughout the whole experiment. The final location (target position) was different for the three DoFs, according to the difference in their functional Range of Motion (fRoM) (Marini et al., 2016) and it is indicated in Table 2.

Experiment 2. During Experiment 2 the *reaching* and the *matching movements* started from the same position (see Table 1 and Fig. 3). This starting position changed from trial to trial in order to shift backward or forward the workspace of the current trial. Specifically, at the end of each trial the *removal movement* after the active matching positioned subject's wrist in a different location that would then become the starting position of both the *reaching* and *matching movements* in the following trial.

Since *reaching* and *matching movements* had the same starting position, in this experiment the amplitude of the movement to match and replicate remained constant (see Table 1), while the target position, TP (final position of the *reaching movement*) was always shifted in order to keep constant the movement's length (see Table 1). A random small shift of an amount ranging between 0° and ± 2° was introduced to avoid learning and the amplitude of the *reaching movement* to replicated was different to the DoF performing the test, according to its fRoM, as indicated in Table 2.

In this experiment instruction to participants were to replicate the entire *reaching movement*. Fig. 3 and Table 1 provide summary of the differences between the two experiments.

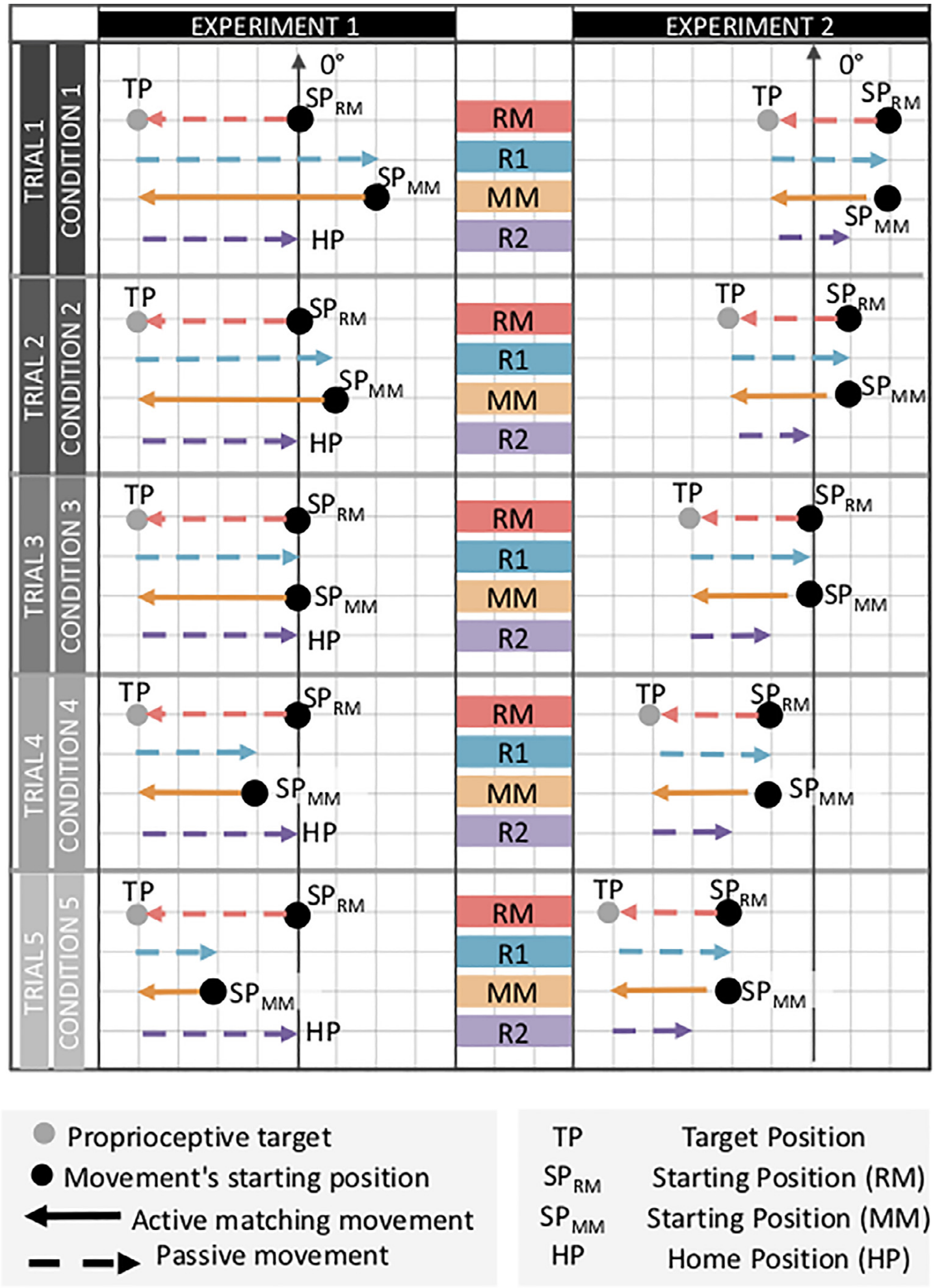

Fig. 3. This figure reports the five experimental conditions in experiment 1 (*JPI*) and experiment 2 (*KMR*). Different colours indicate the four phases which constitute each trial.

In order to test the reliability and consistency of an eventual preference for *identification of joint position* (*JPI*) rather than *kinaesthetic movement reproduction* (*KMR*) or vice versa, for each of the two experiments, five different conditions were presented. This five conditions consisted in five different starting positions of the *reaching movement* (see Table 3). The overall experiment lasted about 90 min and it consisted in 6 target sets of 60 trials. After the completion of every target set, subjects were allowed to rest to avoid fatigue. Specifically, in the 60 trials of each target set, we tested the five conditions in one of the two experiments for the two directions of one DoF (i.e. Flexion and Extension for FE) and each of these target positions was repeated six times.

Trials were randomised across conditions and each DoF was tested separately, with an order that was randomly chosen among subjects. Consistently, also the two directions of each DoF (i.e. Flexion and Extension for FE) were presented in a random fashion.

Table 1

Differences between the two experiments.

	Experiment 1 (JPI)	Experiment 2 (KMR)
Start Position (SP)	$SP_{RM} \neq SP_{MM}$	$SP_{RM} = SP_{MM}$
Target Position (TP)	Constant	Variable
Movement's Length (ML)	Variable	Constant
Home Position (HP)	Constant	Variable

Table 2

Target position (final location of the *reaching movement*) in Experiment 1 and amplitude of the *reaching movement* in Experiment 2. These locations are referred to the neutral position (0° of FE, 0° of RUD and 0° of PS). Each of the three wrist's DoFs was tested separately. In the first experiment participants had to match target positions located along each of them, at 32° for FE; 16° for RUD; 24° for PS. In the second experiment, subjects had to match target positions that had location not fixed in space but that were passively shown trough movements of the same length. Consistently to the first experiment, such length was 32°, 16° and 24° for movement along FE, RUD and PS.

	Experiment 1 – RM final position (target position TP)	Experiment 2 – RM amplitude
FE	32° ± 2°	
RUD	16° ± 1°	
PS	24° ± 1.5°	

Table 3

Five different starting positions of the *reaching movement* (SP_{RM}), expressed as a fraction of the functional range of motion *fRoM*, that represented the five conditions tested for each of the two experiments.

SP_{RM}	Condition 1	Condition 2	Condition 3	Condition 4	Condition 5
	$-\frac{2}{3}fRoM$	$-\frac{1}{3}fRoM$	0°	$+\frac{1}{3}fRoM$	$+\frac{2}{3}fRoM$

These choices allowed us to ensure that the presentation order did not affect the results obtained.

2.4. Data analysis

Wrist joint rotations were recorded from the robot's incremental encoders; acquired signals were post-processed by a third-order Savitzky-Golay low-pass filter (cut-off frequency of 10 Hz) and converted into angular displacements. To estimate the proprioceptive acuity of the wrist position sense and characterise the overall performance, actual (active) and desired (passive) wrist positions were compared.

Specifically, the comparison regarded the final position of the *reaching movement* and the position reached by the subject at the end of the *matching movement* (Dukelow et al., 2010).

From a careful inspection of the data, we calculated 4 outcome measures that reflected distinctive patterns of errors commonly observed in literature (Dukelow, Herter, Bagg, & Scott, 2012; Schmidt & Lee, 1988): the *Matching Accuracy* (*MA*) that provides the angular deviation from the target position and quantifies the performance exactness during the active movement; the *Matching Precision* (*MP*) that highlights if the measurements under unchanged conditions show the same results; the *Matching Bias* (*MB*) that provides the average error in responding considering its direction; and the *Matching Variability* (*MV*) that quantifies matching consistency/inconsistency across the trials.

The *Matching Accuracy* (1/°) is computed by averaging over the N(= 6) trials repeated under identical circumstances (same DoF, direction, condition), the absolute value of the angular deviation from the target position (*matching error ME*):

$$ME_i = |\theta_i - \theta_T| \tag{1}$$

$$MA = \left(\frac{\sum_{i=1}^{N} |\theta_i - \theta_T|}{N}\right)^{-1} = \left(\frac{\sum_{i=1}^{N} |ME_i|}{N}\right)^{-1} \tag{2}$$

where, ME_i is the *Matching Error* for the i-trial, θ_i is wrist's position of the i-trial at the end of the *matching movement*; θ_T is the target position (final position of the *reaching movement*) and N is the number of trials in the tested DoF, direction and condition. Such indicator, that measures the difference between the position matched by the subject and the ideal target position, represents the quality of the matching and how good the subject is in repeating the target position. The averaging by N = 6 (the six repetitions under the same condition, experiment and DoF) allowed to have a representative information of what emerged in each condition, experiment and DoF and allow comparisons among them.

The *Matching Precision* (1/°) is evaluated (for each DoF, direction and condition) from the standard deviation across the 6 trials of wrist's position at the end of the *matching movement* ($\theta_{i=1:N}$) and it provides information about performance consistency (precision) across the whole experiment:

$$MP = (std(\theta_{i=1:N}))^{-1} \tag{3}$$

Precisely, it is related to the variance that exists among the matched positions under identical circumstances: a high *Matching Precision* would suggest a low variance and, therefore, a high confidence for the matched position. It has to be considered that this indicator does not depend on how close is the subject to the target but it rather evaluates how similarly participants match similar targets. For the sake of clarity, if one subject matches a target always in the same position his/her *Matching Precision* will be large, even if such position is highly incorrect. On the contrary, if the matched position is close to the ideal one but it changes from one trial to the other, the *Matching Accuracy* will be low, despite an increased variability (decreased *Matching Precision*). As indicated by the negative power −1 of Eqs. (2) and (3), both the *MA* and the *MP* are reciprocal quantities. MA is the reciprocal of the averaged *Matching Error*, while *MP* is the reciprocal of the deviation. Therefore, higher values of such indicators are due to smaller errors and have to be interpreted as more accurate or precise respectively.

The *Matching Bias* (°), indicating bias in subjects' performance, is determined as the algebraic distance between the ideal target position (final position of *reaching movement*) and the final wrist position at the end of the *matching movement*. It indicates the subjects' tendency of undershooting (negative *Matching Bias*) and overshooting (positive *Matching Bias*) the target. It is evaluated as follows:

$$MB = \sum_{i=1}^{N} (\theta_i - \theta_T) \tag{4}$$

The *Matching Bias* provides information on subject's inclination to underestimate or overestimate target position and perceive movements as shorter or longer.

Finally, the *Matching Variability* (*MV*) (°), quantifies the repeatability of subject's *Matching Error* (see Eq. (1)), during target sets performed under the same circumstances (same DoF, direction, condition):

$$MV = std(ME_{i=1:N}) \tag{5}$$

The *Matching Variability* highlights the condition in which the performance has an higher variance and, vice versa, the one in which it is more consistent.

2.5. Statistical analysis

Due to the small sample size and the inversion operation on MA and MB, that might affect the distribution, the Shapiro–Wilks test was used to ensure if all variables fit the Gaussian distribution. This test revealed that data did not meet the assumption of normality. Therefore, non-parametric analyses were chosen accordingly.

To statistically investigate the difference between Experiment 1 (*JPI*) and Experiment 2 (*KMR*), we could assume that the two groups were homogenous as they have the same number of participants, with the same distribution of gender and age. This assumption allowed us to conduct a test for pairwise comparison between the *JPI* and the *KMR* group. Given that the data did not to meet the assumption of normality, the Wilcoxon signed-rank test was used to investigate differences between the two experiments, with a level of significance set at $p = 0.05$.

To investigate if the effect of the two experiments was consistent for the three DoFs (FE, RUD, PS), a Wilcoxon signed-rank test was conducted for pairwise comparison, with a Bonferroni correction for multiple comparisons resulting in a significance level set at $p < 0.015$.

A Friedman's test for repeated measure was performed on group data for the four variables *MA*, *MP*, *MB* and *MV* (level of significance was set at $p = 0.05$) to investigate the effect of the five conditions and the three DoFs.

3. Results

3.1. Differences between the JPI and KMR group

The main goal of the study was to investigate whether the proprioceptive acuity in perceiving final positions and movements' length is similar, or whether in one of the two cases the proprioceptive system provides a better perception.

We found a clear evidence for higher performances in terms of *Matching Accuracy* and *Matching Precision* in the JPM experiment, suggesting a preference for identification of joint positions (Fig. 4 panel A and B). Specifically, *Matching Accuracy* in the *JPI* and *KMR* experiments resulted to be (mean ± SEM) $MA = 0.42 \pm 0.01$ (1/°) and $MA = 0.36 \pm 0.01$ (1/°) respectively (Fig. 4 panel A), similarly, subjects' average *Matching precision* was found to be higher in the *JPI* experiment ($MP = 0.43 \pm 0.01$ (1/°)) than in the *KMR* ($MP = 0.35 \pm 0.01$ (1/°)), as shown in Fig. 4 panel B. Both differences resulted to be statistically significant for Wilcoxon signed-rank test ($Z = 4.6479$, $p < 0.001$ for *Matching Accuracy* and $Z = 5.4438$, $p < 0.001$ for *Matching Precision*).

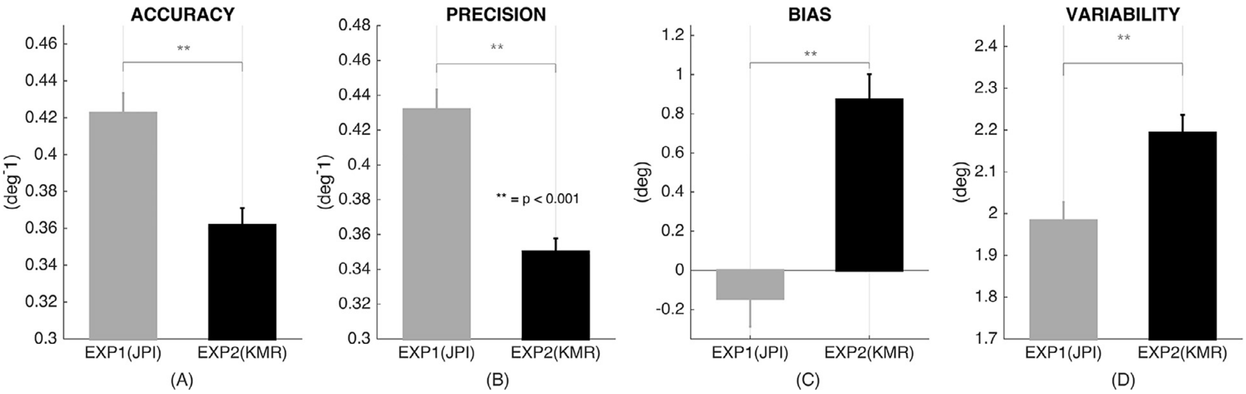

Fig. 4. *Matching Accuracy.*, *Matching Precision*, *Matching Bias* and *Matching Variability* in the Experiment 1 (*JPI*, grey) and Experiment 2 (*KMR*, black). Averaged values over the three DoFs and the five conditions.

As shown by Fig. 4 panel C, the analysis of *Matching Bias* revealed a higher preference for target overshooting in the *KMR* experiment, where we obtained a positive *Matching Bias* ($MB = 0.87 \pm 0.13°$). This result suggested that, when subjects are requested to replicate movements' length, the tendency to overshoot the target is higher than the case in which our sensorimotor system has the goal to perceive punctual positions. Indeed, in this second case, subjects presented no tendency for movements' under/over estimation, as indicated by the *Matching Bias*, for which it resulted a value close to 0° ($MB = -0.14 \pm 0.14°$). Such difference was found to be significant by the Wilcoxon signed-rank test ($Z = 3.6546$, $p < 0.001$).

Finally, subjects' performance in *KMR* experiment resulted different from the *JPI* experiment also in term of *Matching Variability* (Fig. 4 panel D). Specifically, subjects' *Matching Errors* emerged to be less variable in the *JPI* experiment with a variability of $MV = 1.98 \pm 0.06°$, versus the variability of $MV = 2.19 \pm 0.05°$ in the *KMR* experiment. This result was confirmed by the Wilcoxon signed-rank test ($Z = 4.1569$, $p < 0.001$).

3.2. Differences among conditions

We then investigated whether, within the *JPI* and *KMR* experiment, there are differences among the five conditions. Fig. 5 shows the *MA*, *MP*, *MB* and *MV* for the *JPI* (grey) and *KMR* (black) group. The *Matching Accuracy* (Fig. 5 panel A) in the *JPI* experiment seems to be affected by the condition, as it is confirmed by the statistical analysis performed by the Friedman's test that revealed a significant main effect of condition [$\chi^2(N = 75, df = 2) = 25.0133$, $p < 0.001$]. Conversely, such main effect of condition did not seem to be relevant for the *KMR* experiments [$\chi^2(N = 75, df = 2) = 1.2088$, $p = 0.8766$].

The Friedman's test revealed a significant main effect of condition also for the *Matching Precision* (Fig. 5 panel B) for the *JPI* group [$\chi^2(N = 75, df = 2) = 23.2533$, $p < 0.001$], while such effect did not emerged in the *KMR* experiment [$\chi^2(N = 75, df = 2) = 3.3244$, $p = 0.5051$].

Similarly, the *Matching Bias* resulted to be significantly affected by a main effect of condition only in the *JPI* experiment, while, as shown from the black line of Fig. 5 panel C, in the *KMR* experiment, participants' *Matching Bias* did not seem to be influenced by the condition. Results of the Friedman's test support these observations: [$\chi^2(N = 75, df = 2) = 22.5244$, $p < 0.001$] and [$\chi^2(N = 75, df = 2) = 6.7620$, $p = 0.1514$] for the *MB* in the *JPI* and *KMR* group respectively. Finally, the results emerged so far for

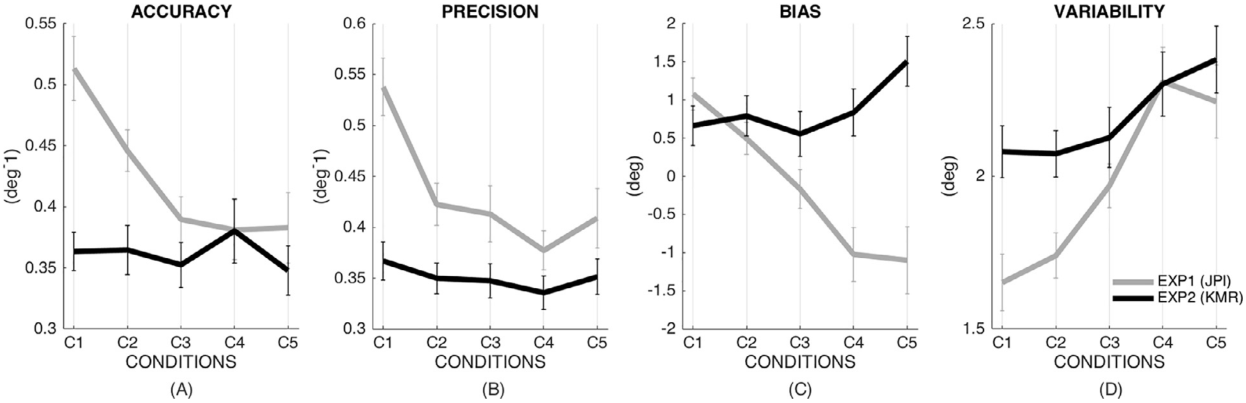

Fig. 5. *Matching Accuracy.*, *Matching Precision*, *Matching Bias* and *Matching Variability* in the Experiment 1 (*JPI*, grey) and Experiment 2 (*KMR*, black) for the five conditions. Averaged values over the three DoFs.

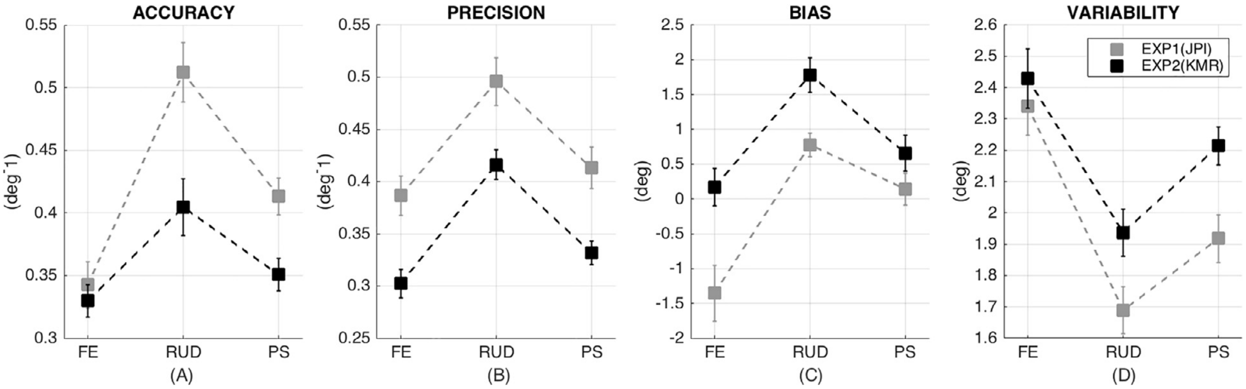

Fig. 6. *Matching Accuracy.*, *Matching Precision*, *Matching Bias* and *Matching Variability* of the three DoFs (Flexion/Extension: FE, Radial/Ulnar Deviation: RUD and Pronation/Supination: PS), in the Experiment 1 (*JPI*, grey) and Experiment 2 (*KMR*, black). Averaged values over the three DoFs.

MA, *MP* and *MB*, are analogous for those obtained for the *Matching Variability*, for which the Friedman's test found a significant main effect of condition only for the *JPI* group [$\chi^2(N = 75, df = 2) = 33.4755, p < 0.001$], while, for the *KMR* group the analysis of differences among conditions did not reach significance [$\chi^2(N = 75, df = 2) = 4.1422, p = 0.3871$].

To sum up these outcomes, it emerged that, in the *KMR* experiment the different conditions did not significantly affect the performance from all the four perspectives given by the performance indicators. Conversely, in the *JPI* experiment, when subjects have to match positions, it emerged to be significantly relevant the starting position of the active matching movement (changing among the five conditions), as confirmed by the positive result of the Friedman's test for significance, for all the four indicators of performance.

3.3. Behaviour of the three DoFs in the two experiments

We then investigated if the three DoFs behaved similarly in the two different experiments. The Friedman's test highlighted a significant main effect of the DoF: [$\chi^2(N = 75, df = 2) = 30.8266, p < 0.001$] for *MA*, [$\chi^2(N = 75, df = 2) = 17.3600, p < 0.001$] for *MP*, [$\chi^2(N = 75, df = 2) = 12.8266, p = 0.002$] for *MB*, and [$\chi^2(N = 75, df = 2) = 40.5066, p < 0.001$] for *MV*, in the experiment 1 (*JPI*) and [$\chi^2(N = 75, df = 2) = 4.1867, p = 0.1232$] for *MA*, [$\chi^2(N = 75, df = 2) = 31.5466, p < 0.001$] for *MP*, [$\chi^2(N = 75, df = 2) = 19.3067, p < 0.001$] for *MB*, and [$\chi^2(N = 75, df = 2) = 13.3067, p = 0.001$] for *MV* in the *KMR* experiment. As it can be seen from the p values, a main effect of DoFs was found for all of the four indicators, consistently in both the experiments, with a single exception for the *MA* in the *KMR* experiment for which, the main effect of DoF did not reach significance.

The four panels of Fig. 6 provide clear evidence of a consistent difference between experiment 1 (*JPI*) and experiment 2 (*KMR*) for the four indicators, for all of the three DoFs tested. The Wilcoxon signed-rank with the Bonferroni correction for multiple comparisons (significance $p < 0.015$), confirmed this result for most of the comparisons. Precisely, the difference in performance of the RUD DoF for the two experimental groups was found to be significant for all the four indicators: ($Z = 4.1029, p < 0.001$ for *MA*, $Z = 2.9254, p = 0.003$ for *MP*, $Z = 3.0099, p = 0.002$ for *MB* and $Z = 2.5927, p = 0.009$ for *MV*). The *MP* of the FE DoF resulted to be the only indicator significantly different in the two experiments ($Z = 4.4904, p < 0.001$) while the PS DoF resulted to have a significant difference in MA and MB between experiment 1 and 2 ($Z = 3.0099, p = 0.003$ for *MA*, $Z = 3.2581, p = 0.001$ for *MP*).

4. Discussion

The main goal of the study was to investigate whether the proprioceptive acuity in perceiving final positions or movements' length is similar, or whether in one of the two cases the proprioceptive system provides a better perception.

In two different experiments, two different versions of the joint position matching task were implemented on a wrist robotic device and performed by two different groups of 15 healthy participants. In the first experiment, blindfolded subjects were asked to perform matching movements towards a fixed target position, experienced with passive movements that started from different positions and had different lengths. In the second experiment, blindfolded subjects were requested to accurately match target positions that had different location in space but were passively shown trough movements of same length.

We found a clear evidence for better performances in terms of higher *Matching Accuracy* and *Matching Precision* in the *JPI* experiment, such as lower *Matching Variability* and no predominant preference for under or overshooting targets, as shown by the value of the *Matching Bias* close to 0°. These results suggest better abilities in proprioceptive identification of joint position rather than in kinaesthetic movement reproduction.

Particularly, our findings seem to demonstrate that, between position control and amplitude control, the first has a stronger preference to be adopted. This is consistent with results of previous studies (Bizzi et al., 1976; Latash & Gottlieb, 1992; Latash & Gottlieb, 1991; Polit & Bizzi, 1979) that argued for equilibrium or end-point positional control, which can allow achievement of final positions despite unknown starting locations and/or perturbations during the movement.

Conversely, our findings are in contrast with several dated studies suggesting preference for amplitude control (Bock & Eckmiller, 1986; Ghez et al., 1995).

In between, there are also results arguing that neurologically intact participants used a blended strategy in making whole arm reaching movements to targets, with both target distance and location influencing accuracy (Walsh, Russell, Imanaka, & James, 1979), and some evidences of both strategies (Hudson & Landy, 2012; van der Graaff et al., 2017).

Furthermore, serial strategies have also been proposed in which movements are achieved by initial vectorial control, and terminated under final positional or impedance control (Scheidt & Ghez, 2007; Yadav & Sainburg, 2011).

Overall, there is no doubt that, proprioceptive abilities in target matching depend significantly on whether subjects have to reproduce positions rather than length of movements, and our results support the hypothesis that our brain and our motor system are better in coding the first ones.

Several explanation could be identified behind the higher performance in joint position identification. Very simply, we could propose that the position information is simpler to code for the brain than the one regarding the whole movement, for its intrinsic static definition (Caminiti, Johnson, & Urbano, 1990; Mussa-Ivaldi, Giszter, & Bizzi, 1990; Wolpert & Ghahramani, 2000) and for the higher sensitivity of a time-dependent information to deterioration and noise. Indeed, we could assume that a time-dependent information is more subjected to deterioration and noise for two main reasons: firstly, when an information has to be collected in more and different time frames, as the case of matching movements, the noise to the sensory-motor system might become a sum of the noise collected all the time frames of the movement itself. Furthermore, we could speculate that, the higher the complexity of the information to be collected (a movement could be seen a sum of positions), the higher the probability for it to be affected by noise and uncertainty.

Besides this simplistic interpretation, a neuroscientific explanation can be provided to the decrement in performance emerged when subjects have to match movements and versus single positions, and it deals with the source of noise arising in this condition to the sensory-motor system. Sensory-motor integration is defined as the capability of the central nervous system to integrate different sources of stimuli and transform such inputs into motor actions. Particularly, peripheral pathways conveying sensory information project to cortical motor areas. The sensory-motor system is the one responsible for computing this sensorimotor transformation, between sensory inputs and motor commands, but the sensory signals it constantly deals with are generally corrupted by noise. Noise permeates every level of the nervous system, from sensory to motor responses generation, posing a fundamental problem for information processing (Faisal, Selen, & Wolpert, 2008). Recent studies have begun to reveal computational principles by which the central nervous system tries to minimise the sensory uncertainty (Bays & Wolpert, 2007) and movement variability arising from this internal noise. It is certain that, the most inaccurate and variable (noisy) signals are the sensory signals, that form the input, and the uncertainty in the estimation of the state is the highest respect to the other signals the brain has to deal with (Bard, Fleury, Teasdale, Paillard, & Nougier, 1995). The replication of the movement amplitude can be considered as noisier for two reasons: firstly, because of the shift in the centre of the reference frame that always differs from the neutral configuration, secondly, it is longer in time and therefore composed by the sum of noise collected in the time frames constituting the movement itself. Specifically, during this time, a complex set of signals is conveyed from the proprioceptors to the central nervous system where they give rise to the perception of the target position. Such signals consist in the mechanical interactions existing between them and the surrounding tissues (muscle, tendon, ligament, bones, or skin) but also in position, velocity, and force information that are mixed in a history-dependent manner for the entire movement duration. Conversely, we could speculate that, when a certain position is reached, it is less affected by these elements: to properly build the information about the length of the movement, all of the above mentioned information have to be collected and coded, for the duration of the entire movement; vice versa, if the sensory-motor system is requested to code the information about the final position, all the processes and information mentioned above, can be restricted to the time frame corresponding to the moment in which the position is acquired.

Moreover, in the recent years, quite a few studies tried to identify and model different motor control strategies that the brain can adopt in order to accomplish complex tasks (Morasso, Nomura, Suzuki, & Zenzeri, 2016; Saha & Morasso, 2012; Zenzeri, De Santis, & Morasso, 2014). On the two extreme cases, these multiple strategies can span from stiffness (Burdet, Osu, Franklin, Milner, & Kawato, 2001) to intermittent control (Loram, Gollee, Lakie, & Gawthrop, 2011; Loram, Cunningham, Zenzeri, & Gollee, 2016; Suzuki, Nomura, Casadio, & Morasso, 2012) passing through their combination. One crucial point that researchers are starting to speculate on Gollee, Gawthrop, Lakie, and Loram (2017) and Michimoto et al. (2016), is that the level of sensorimotor noise can induce the brain to switch among the different strategies. Our study revealed, in controlled and specific conditions, that the brain has preference for adopting joint position identification rather than kinaesthetic movement reproduction mechanisms. Given the fact that the knowledge of the target position is the input of the controllers, our specific finding can give indications and objective data to try to model and validate the switching among motor control strategies, obtaining in this way a deeper knowledge on the mechanisms of movements generation.

From a psychophysics perspective, a widely recognised approach has conceptualised the movement as a process involving three entities: starting position, distance moved, and terminal location (Walsh et al., 1979). If we accept this interpretation, it is licit to consider necessary for a proper movement replication the knowledge of all these three entities, versus the more simple condition when only the knowledge and perception of the final position is requested.

Furthermore, from a biomechanical perspective, we should consider that the inability to properly calibrate the motor response given the sensory input might be associated with the loss of calibration of the central control signals in terms of spatial coordinates (Flanagan, Ostry, & Feldman, 1993). Indeed, in Experiment 1, the starting positions of the *reaching movement* always corresponded with the neutral configuration (0° FE, 0° RUD and 0° PS), which is likely the one adopted as the centre of the reference frame built in the neural processing that involves the transformation from the sensory information to the motor command. It could be reasonable to identify the difficulty in properly coding the target position when the variable starting point varies, in the mismatch between the starting position and the reference frame built and adopted by each subject. Indeed, the starting position of the *reaching movement*, that in the *KMR* experiment did not always correspond to the neutral configuration but always changed, might have entailed higher errors and variability due to the re-calibration of the reference frame probably needed by subject within each trial.

Besides being due to changes in actual kinaesthetic signals arising from *reaching* and *matching movements*, the systematic pattern of accuracy decrement in target position reproduction, could also have a cognitive component. Several authors suggested indeed that the interference between distance and location seems to occur not only at a sensory or perceptual level but also at a more abstract or cognitive level of information processing (Kerr, 1978; Faisal et al., 2008) with a consistent influence on the strategy adopted for the sensory encoding and consequent movement planning (Imanaka & Abernethy, 1992; Walsh et al., 1979).

As regards possible limitation of the study and as interesting consideration for future developments of matching paradigms for proprioception testing, is it worth to consider that performing the *matching movement* actively might have been a confounding factor. In this work, we chose to implement an active matching task since passive tests for evaluation of joint position sense have been previously challenged (Prud'homme & Kalaska, 1994), contending that the proprioceptive system only functions properly when muscles contraction occurs for voluntary action or stretch reflexes (Windhorst, 2007). Previous contributions suggested that results of active tests (like the JPM) may have more relevance than passive ones because most of daily functions involves voluntary or reflex muscle control (Matthews, 1988); furthermore, a passive test may not result suitable in clinical practice because of the large amount of time needed to gather reliable measures, leading to a decrement in subjects' attention which can modify afferent signals (Hospod, Aimonetti, Roll, & Ribot-Ciscar, 2007) and introduce a time dependent quality of the result. Conversely, other scientists claim that tests based on passive motion most closely reflects afferent sensory feedback processing, while the matching methods, since they require active motion, are consequently influenced by additional sensorimotor processes (Elangovan, Herrmann, & Konczak, 2014).

Finally, a possible influence of memory in JPM test's outcomes should be discussed. In this study, we are confident to consider not significantly relevant the effect of memory in task performance for two main reasons: firstly, every trial, we introduced a random small shift on the target position of an amount ranging between 0° and ± 2°, to avoid learning and make impossible for participants to recall upon memory of the preceding trial; secondly, for previous validation performed during the same JPM test implemented on the same device (Marini et al., 2017).

To conclude, this study led to important results: (1) the design and validation of two reliable methods that allow to quantify precise kinematic outcomes when the interest is to compare joint position identification and kinematic movement reproduction; (2) the evidence that in specific controlled conditions the brain prefer to adopt joint position identification mechanisms rather than kinaesthetic movement reproduction; (3) the possibility to change experimental conditions in an artificial way in order to potentially force the brain to adopt one of the two strategies; (4) the emergence of new insights for the scientific debate in favour of the preference to use joint position identification mechanisms demonstrated in fully controlled experimental settings.

Availability of data and materials

Full data set and software analysis will be provided in case of request.

Competing interests

The authors declare that they have no competing interests.

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Consent for publication

Consent to publish was obtained from that adult participants.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, athttps://doi.org/10.1016/j.humov.2018.08.006.

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