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Insights into proprioceptive acuity assessed with a dynamic joint position reproduction task

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ABSTRACT

This study investigated proprioceptive acuity using the conventional joint position reproduction (JPR) task and a modified version, the Dynamic JPR task (D-JPR), during Concentric and Eccentric muscle contractions. Seventeen participants were recruited and received a tactile stimulus indicating the position cue at Initial (INI), Intermediate (INT), and Final (FIN) phases of movements, during either the concentric or eccentric phases. After the movement, they replicated the position where they received the stimulus. Angular error (AE) and movement velocity were analysed. AE was higher in the D-JPR than in JPR Task, and in Concentric than Eccentric contractions. Within the D-JPR Task, during Concentric contractions, AE was lower at FIN phase compared to INI and INT phases, and at INT phase compared to INI phase, whereas in Eccentric contraction AE was lower in FIN compared to INI phase. Significant correlations between movement velocity at the time of stimulus delivery and AE were found in both types of contractions. Proprioceptive acuity was affected by task type, muscle contraction, movement phase, and movement velocity, highlighting the need to consider these factors for accurate and ecological assessments of proprioception.

1. Introduction

Proprioception is the awareness of the body's mechanical and spatial state, including the position and movement of its musculoskeletal components from the integration of proprioceptive signals provided by muscle spindles, Golgi tendon organs, cutaneous receptors and joint receptors which the central nervous system (CNS) integrates to monitor body position, muscle effort, and the weight of objects being manipulated (Proske & Gandevia, 2012).

The accuracy of perceiving and processing proprioceptive signals is known as proprioceptive acuity, which includes the ability to detect joint position, movement and force (Proske & Gandevia, 2012). In particular, it measures how well an individual can sense body parts' position, movement and force. Proprioceptive acuity is essential for motor control (Heroux et al., 2022), and there are various methods to assess it. Regarding the ability to detect joint position (i.e., the joint position sense), Joint Position Reproduction task (JPR) and the Active Movement Extent Discrimination Assessment (AMEDA) can be listed among these methods (Han et al., 2016).

JPR protocols generally require memorizing a target joint angle to reproduce. The difference between the target and replicated joint angle is known as the angular error (AE) and serves as a measure of proprioceptive acuity. These protocols typically involve slow, passive, or active movements, performed freely or using isokinetic devices with a mechanical stop at the target position. Consequently, the ecological validity of this measure is limited, as it assesses proprioception only when a target position is reached and held for memorization, rather than during the execution of voluntary movements. In contrast, access to detailed, continuous proprioceptive information during movement is essential for efficiently executing actions.

Another concern involves the test's validity. When passive movements are used to reach the target position, fusimotor activity is lower compared to when active movements are performed to return to the target position, indicating that different types of sensory feedback are

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involved in these two phases (Gandevia et al., 1992). For these reasons, developing a methodology to assess proprioceptive acuity during movement is a crucial issue to be solved. A first tentative to enhance ecological validity by incorporating active movements was done with the AMEDA method (Waddington & Adams, 1999). In AMEDA, participants initially memorise different movement displacements from smallest to largest. They then move to a target position and identify it as one of the memorised positions. However, AMEDA results did not correlate with JPR results suggesting that joint position sense and movement discrimination are distinct aspects of proprioception (Yang et al., 2020). This highlights the need for assessments that specifically evaluate position sense during movement.

Another important aspect to assess is the effect of muscle contraction type—concentric or eccentric—on position sense, an area that remains underexplored (Clark et al., 2016; Haggerty et al., 2021), Differences in motor unit recruitment (Moritani et al., 1987), discharge rates (Nardone et al., 1989), corticospinal excitability (Canepa et al., 2021), and cortical activity (Perrey, 2018) have been observed when comparing these two modes suggesting that these variations may influence proprioceptive task performance.

This study aims to achieve three primary goals related to proprioceptive acuity assessment. Firstly, it will investigate whether detectable differences in AE exist when individuals perform a JPR test under static and dynamic conditions, focusing on the role of movement velocity. We hypothesise that AE will be higher in dynamic conditions compared to static conditions, particularly at higher movement speeds, due to reduced afferent sensitivity during movement (Angel & Malenka, 1982; Collins et al., 1998; Lee & White, 1974). This is crucial for understanding how the sense of position may be altered during movement execution. Secondly, it will assess whether AE varies with the type of contraction (concentric vs. eccentric). We hypothesise that AE will be lower during eccentric than concentric contractions, given the increased cortical involvement and attentional demands associated with eccentric muscle activity (Perrey, 2018). This helps to understand how contraction mode and proprioceptive acuity interact. Lastly, it will explore whether AE differs with joint angular position across various movement phases, such as 'onset,' 'middle,' and 'offset.' We hypothesise that AE will improve as movement progresses, with higher accuracy in the 'offset' phase compared to the 'onset' phase, due to increased joint receptor activity near the end of the range of motion (Proske, 2023).

2. Methods

2.1. Participants

Nineteen university students volunteered to participates to this study (28.16 ± 5.22 years; Male = 11). Sixteen were right-handed, and three were left-handed determined by the Edinburgh Handedness Inventory test (Oldfield, 1971). Seventeen participated in the Main experiment (27.35 ± 5.22 years; Male = 9; 14 right-handed) and twelve in the Control experiment (30.75 ± 4.77 years; Male = 6; 12 right-handed). The inclusion criteria were age over 18, and no history of neurological disorder and musculoskeletal injury. Participants did not receive any financial compensation for participating in the study. All participants received comprehensive information regarding the objectives and procedures of the study and provided their informed consent. The research was approved by the Comitato Etico per la Ricerca di Ateneo (N. 2023/84) of the University of Genoa and adhered to the principles outlined in the Declaration of Helsinki. All participants signed an informed consent before being enrolled in the study.

2.2. Experimental set up

Kinematic data were collected using two wearable Inertial Measurement Units (IMUs) of the BNO080 model, with a sample frequency of 25 Hz. The reliability of the device was previously verified; for technical details, refer to Stanzani et al (Stanzani et al., 2020). The IMU was calibrated according to the manufacturer's instructions and attached to the lateral arm and forearm of the participant with a Velcro strap to measure the elbow joint angle. Connected to a computer via Bluetooth, the IMU received sensor signals through integrated software that processed the data to obtain 3D sensor orientation. The kinematic analysis of the elbow joint angle focused on the fused YAW angle due to the positioning of the sensors. The computer was connected to a Digitimer constant current stimulator (DS7AH HV, Digitimer Ltd, UK) via a data acquisition (DAQ) card (NI USB-6009). A custom-made MatLab software was used to administer the experimental tasks and to process data. Specifically, the MatLab program received and saved the sensor data during all trials. Through this program, it was possible to deliver the tactile stimulus once the target angular position had been reached, and it was possible to record the joint angle reproduced by the participants. Before starting, to determine the positions for the tactile stimulus, participants were instructed to position themselves at 15°, 30°, 45°, 60°, 75°, and 90° of flexion, minimizing operator errors in sensor positioning. Tactile stimuli were delivered using a surface bipolar electrode attached with a velcro strap positioned at the inner part of the dominant wrist. The intensity of the stimulus was individually regulated to obtain a clear sensation to be reported by the participant. In addition, the stimulation intensity was limited within a comfortable interval for the participant so that no pain was perceived, and no movement was evoked. The stimulation magnitude ranged from 0.3 mA to 1.0 mA, with a pulse duration of 200 μs, employing a bipolar square wave.

2.3. Experimental design

Before undergoing the experimental tasks, participants completed demographic questionnaires on musculoskeletal injuries and neurological conditions, followed by the Edinburgh questionnaire to assess handedness (Oldfield, 1971). They then performed JPR tasks over three days: two for the Main experiment and one for the Control experiment.

Main experiment. The JPR tests (Fig. 1a) were performed with the dominant upper limb, requiring participants to replicate three joint positions in two tasks (JPR and Dynamic JPR, D-JPR) across two days. Participants reproduced positions during either Concentric or Eccentric contractions, with eyes closed to isolate proprioceptive signals.

In the D-JPR task, participants were seated and began with the elbow at 0° for concentric or at maximum flexion for eccentric contractions. They then performed flexion–extension (concentric) or extension-flexion (eccentric) movements. A tactile stimulus was applied during movement at the exact moment the participant's elbow angular position corresponded to one of three target positions (45°, 60°, or 90°) through an electro-stimulator (DS7AH HV, Digitimer Ltd, UK) positioned on the inner wrist. After completing the movement, participants returned to the start and attempted to reproduce the elbow position where they received the stimulus. In the standard JPR task, participants performed the same movement but paused immediately upon receiving the stimulus, held the position for 5 s, then completed the movement and repositioned to the stimulus angle (Han et al., 2016).

Concentric and eccentric trials were organised in two separate blocks, each containing 15 randomised trials for the three joint positions. In concentric contraction, 45°, 60°, and 90° were classified as initial (INI), intermediate (INT), and final (FIN) phases, respectively; in eccentric contraction, they corresponded to FIN, INT, and INI phases, respectively.

Before the test, participants completed a metronome training session to regulate their movement timing. This involved performing forearm flexion–extension for one minute, with the metronome set at 45 beats per minute (BPM) for the D-JPR condition and 10 BPM for the JPR condition. A different timing was chosen for different reasons. The D-JPR timing aimed to replicate natural movement velocity, while the JPR timing was adapted to mimic that used in a previous study (Han et al., 2016) allowing participants to hold the stimulation position for 5 s and

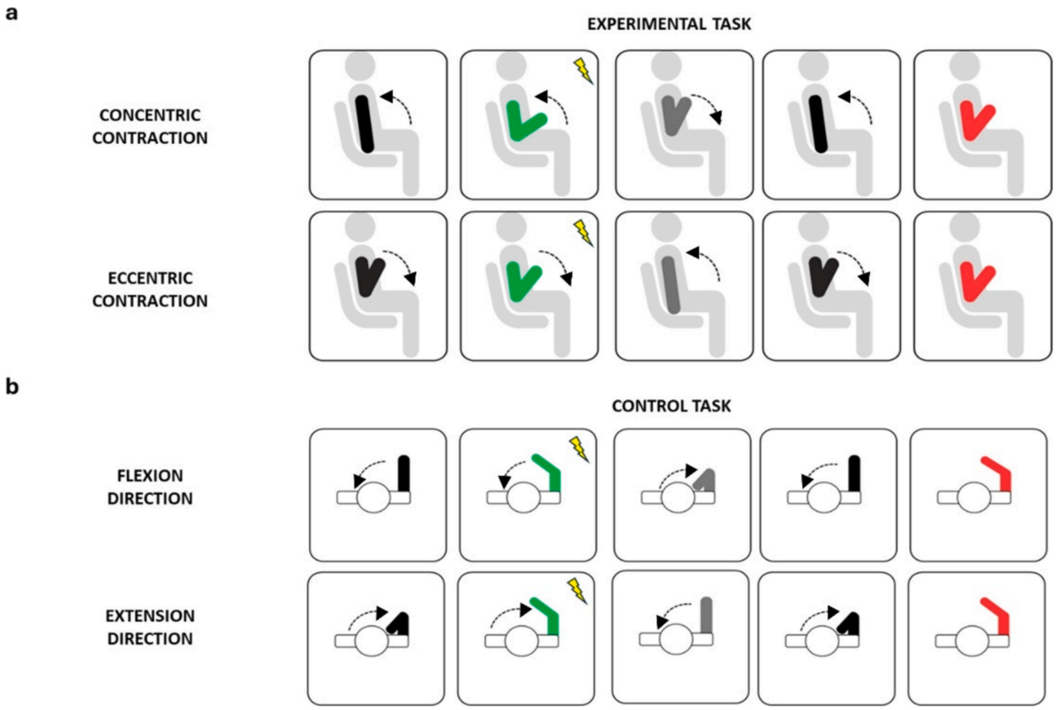

Fig. 1. Schematic representation of the Experimental Task (a) and Control Task (b). Schematic representation of the Experimental Task (a) and Control Task (b). The black arm indicates the initial movement phase during stimulation and reproduction; the green arm shows the phase where participants received the stimulus (continuing to the end position in the D-JPR task, while in the JPR task, the movement is paused for 5 s at the stimulated position); the grey arm represents the completion of the movement; the red arm indicates the reproduced position. The lightning symbol represents the instant when tactile stimulation was administered. Arrows indicate the direction of movements.

then end the movement.

Participants completed two tasks for each contraction type, with two types of contractions and three stimulus positions each (15 trials per position), totaling 180 trials. The order of tests was randomized before the study to minimize learning effects and enhance data validity. The different sessions were carried out at the same time of day for each participant, to avoid possible effects due to day-phase (Iester et al., 2023).

Control experiment. This experiment (Fig. 1b) assessed the influence of movement type (i.e. flexion and extension) on proprioceptive acuity using a D-JPR task performed in the horizontal plane. Participants, seated with their limbs supported and eyes closed, executed flexion–extension and extension-flexion movements. A tactile stimulus was applied at three elbow positions (45°, 60°, and 90°), corresponding to INI, INT, and FIN phases for flexion, and FIN, INT, and INI phases for extension. The tactile stimulus and experimental conditions mirrored those of the Main experiment. Participants completed two movement directions with three stimulus positions each (15 trials per position), totalling 90 trials.

2.4. Data analysis

Kinematic analysis. A custom MatLab routine was developed to Butterworth filter with a cutoff frequency set at 5 Hz was applied to filter data. The angular positions at the time of stimulus administration (stimulus position) and during the repositioning phase were acquired. The reproduced and stimulus positions were then extracted from the data. Furthermore, for the D-JPR tasks, the angular velocity profiles were also computed as the velocity at the time of stimulus administration (Vstim). This value was computed in each trial considering a time interval starting three samples before and ending three samples after the instant of the stimulus delivery.

2.5. Statistical analysis

Main experiment. The primary outcome of this experiment was the mean Angular Error (AE), which was calculated using the following formula:

$$AE = abs(angular\ stimulus\ position - reproduced\ angular\ position)$$

Trials with outlier values, defined as those falling outside the range of mean ± 2SD, were excluded from further analysis. The Shapiro-Wilk test was employed to assess the normality of the data distribution. In JPR task, AE distributions at INT and FIN were not normally distributed. Therefore, a linear mixed model analysis was conducted with PHASE (3 levels: INI, INT, and FIN), CONTRACTION TYPE (2 levels: Concentric and Eccentric), and TASK (2 levels: JPR and D-JPR) as fixed factors, and PARTICIPANTS as a random factor to evaluate the statistical significance of observed differences (Schielzeth et al., 2020). The Bonferroni post-hoc was applied in the case of significant interaction and to explore the significance of factors with more than two levels. A Spearman correlation analysis was performed to examine the relationship between Vstim and AE for each trial within the D-JPR TASK.

In the D-JPR task, to unveil the possible influence of movement velocity on AE, an ANCOVA was applied to AE values with PHASE (3 levels: INI, INT, and FIN), and CONTRACTION TYPE (with 2 levels: Concentric and Eccentric) as within-subjects factors, and Vstim as covariate.

Control experiment. AE was calculated using the same formula as in the Main experiment. Trials with outlier values, defined as those falling outside the range of mean ± 2SD, were excluded from further analysis. The Shapiro-Wilk test was employed to assess the normality of the data distribution. To evaluate the statistical significance of observed differences, a repeated measures ANOVA was conducted with PHASE (3 levels: INI, INT, and FIN), and DIRECTION (2 levels: Flexion and Extension) as within-subjects factors. The Bonferroni post-hoc was applied in case of significant interaction and to explore the significance of factors with more than two levels. Statistical significance was set at p < 0.05. Data are reported as mean values ± SD. All statistical analyses were conducted using SPSS Statistics 26 software.

3. Results

3.1. Main experiment

Analysis of AE showed a significant interaction CONTRACTION TYPE x TASK (F $_{(2,\ 176)}$ = 27.22; p < 0.001) (Fig. 2a). Post-hoc analysis showed a smaller AE in Eccentric compared to Concentric for both D-JPR (Eccentric 15.63 ± 8.95°, Concentric 28.69 ± 13.49°; p < 0.001) and JPR (Eccentric 8.89 ± 5.10°, Concentric 12.05 ± 6.38°; p = 0.020) tasks. Furthermore, participants exhibited lower AE in the JPR than in the D-JPR task in both Concentric (JPR 12.05 ± 6.38°, D-JPR 28.69 ± 13.49°; p < 0.001) and Eccentric (JPR 8.89 ± 5.10°, D-JPR 15.63 ± 8.95°; p < 0.001) contractions.

A significant interaction PHASE x TASK was observed (F $_{(2,\ 176)}$ = 17.37; p < 0.001) (Fig. 2b). In the JPR Task, no significant difference was observed in AE between INI (11.34 ± 6.80°), INT (10.80 ± 5.97°), and FIN (9.27 ± 4.95°). In the D-JPR Task, participants had a lower AE in the FIN phase (13.61 ± 6.77°) compared to INT (23.61 ± 14.53°; p < 0.001) and INI (29.26 ± 11.95°; p < 0.001), and in INT compared to INI (p = 0.002). AE in the D-JPR task was significantly higher than in JPR task for all phases (INI p < 0.001; INT p < 0.001; FIN p = 0.009).

A significant interaction effect PHASE x CONTRACTION TYPE (F $_{(2,\ 176)}$ = 5.10; p = 0.007) (Fig. 2c) was found. In the Concentric contractions, participants had a lower AE in the FIN phase (13.39 ± 7.01°) compared to INT (21.96 ± 12.81°; p < 0.001) and INI (25.76 ± 15.99°; p < 0.001), no significant difference was found compared INT to INI. In the eccentric contractions, participants had a lower AE in the FIN phase (9.49 ± 4.82°) compared to INI (14.83 ± 10.27°; p < 0.001). Furthermore, participants exhibited lower AE in the Eccentric than in Concentric contraction in INI (Eccentric 14.83 ± 10.27°, Concentric 25.76 ± 15.99°; p < 0.001), INT (Eccentric 12.46 ± 7.24°, Concentric 21.96 ± 12.81°; p < 0.001) and FIN (Eccentric 9.49 ± 4.82°, Concentric 13.39 ± 7.01°; p = 0.019).

A significant positive relationship was found between AE and Vstim in both Concentric (ϱ = 0.54, p < 0.001) and Eccentric (ϱ = 0.32, p < 0.001) contractions.

Concerning ANCOVA analysis, a significant CONTRACTION TYPE x PHASE interaction emerged (F $_{(2,\ 32)}$ = 5.97; p = 0.004) (Fig. 3). Post-hoc analysis revealed smaller AE in the Concentric at the FIN (17.45 ± 7.59°) compared to both INT (29.71 ± 7.63°, p < 0.001) and INI (36.31 ± 7.67°, p < 0.001), and in the INT compared to the INI (p = 0.039). For the Eccentric contraction, participants had a lower AE at the FIN (13.27 ± 7.75°) compared to the INI (19.94 ± 7.59°; p = 0.039). In the INI phase, participants had smaller AE in the Eccentric (19.94 ± 7.59°) compared to Concentric (36.31 ± 7.67°; p < 0.001) contraction. In the INT phase participants had a smaller AE in the Eccentric contraction (16.28 ± 7.59°; p < 0.001) compared to Concentric (29.71

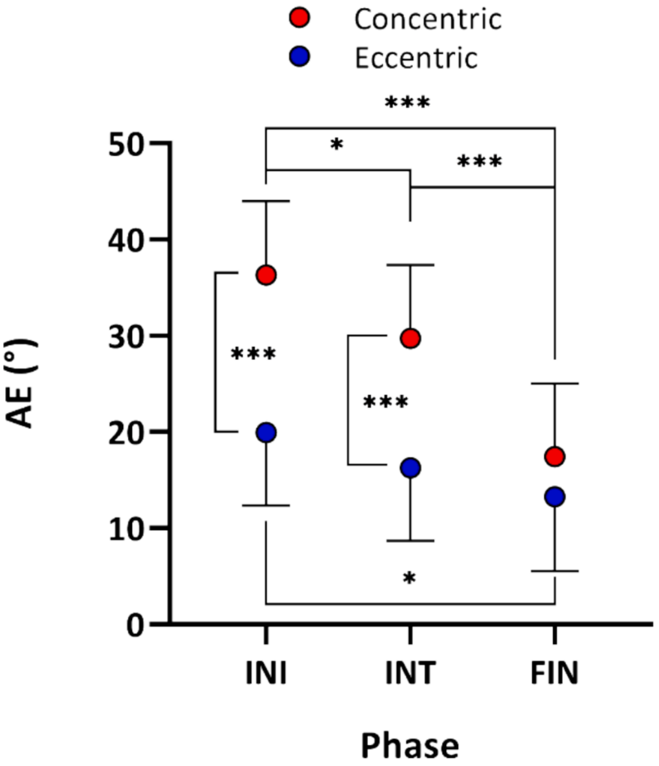

Fig. 3. ANCOVA analysis of Main Experiment in the Dynamic Task, showing the interaction between Phase (INI – initial, INT – intermediate, FIN – final) and Contraction Type (Concentric in red, Eccentric in blue). Circles indicate mean values, and error bars represent standard deviation. Significance levels are *p ≤ 0.05, **p ≤ 0.01, and ***p ≤ 0.001.

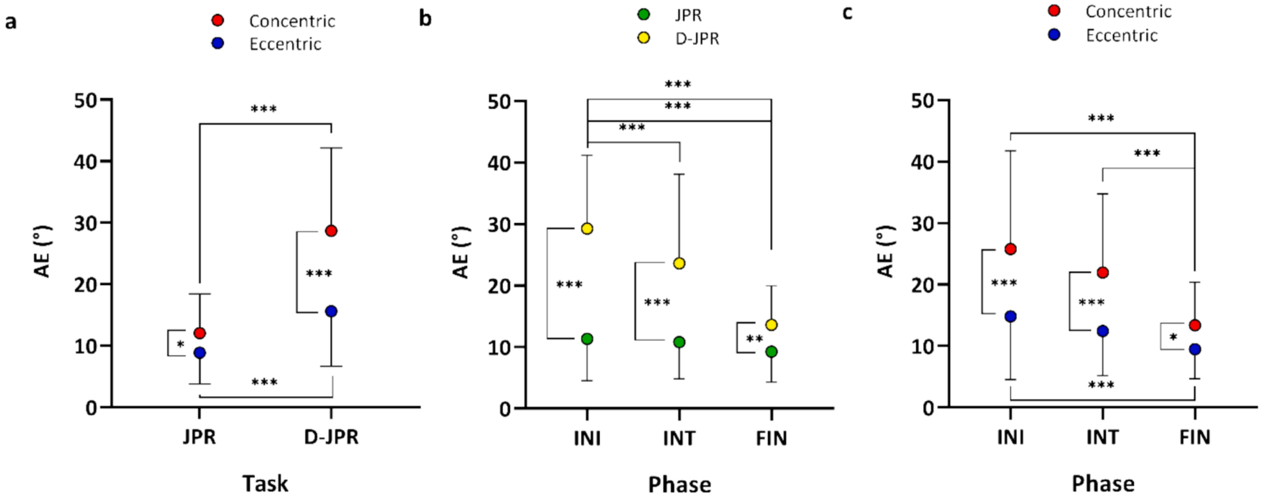

Fig. 2. Statistical analysis of Main Experiment showing: (a) Task × Contraction Type interaction (Concentric in red, Eccentric in blue); (b) Phase (INI – initial, INT – intermediate, FIN – final) × Task (Joint Position Reproduction-JPR in green, Dynamic-JPR – D-JPR in yellow) interaction; and (c) Phase × Contraction Type interaction. Circles denote mean values, while error bars indicate standard deviation. Significance levels are marked as *p ≤ 0.05, **p ≤ 0.01, and ***p ≤ 0.001.

± 7.63°; $p < 0.001$). No significant difference between Concentric (17.45 ± 7.59°) and Eccentric (13.27 ± 7.75°) contractions emerged in the FIN phase ($p = 0.11$).

3.2. Control experiment

A significant effect of PHASE was observed ($F_{(2,\ 22)} = 20.48$; $p < 0.001$). Post-hoc analysis indicated lower AE in reproducing the FIN phase (15.10 ± 6.10°) compared to the INT (24.95 ± 8.88°, $p < 0.001$), and INI (29.52 ± 13.80° $p = 0.002$).

4. Discussion

The main findings of this study were that proprioceptive acuity related to the joint position sense was significantly influenced by the dynamic nature of the task, the type of contraction, and the phase of the movement.

Proprioceptive acuity depends on the type of task: in the JPR task higher accuracy was recorded regardless of contraction type or movement phase. This suggests that executing a movement alters the perception of joint angular position, an effect that could stem from different levels of task complexity. Indeed, previous findings suggest that moving from a static to a dynamic state affects the perception of cutaneous stimuli, and afferent muscle feedback resulting in reduced sensitivity (Angel & Malenka, 1982; Collins et al., 1998; Lee & White, 1974). It could be suggested that, while static scenarios provide accurate proprioceptive information about joint angular position, the dynamic nature of the movement may interfere with accurate estimation, thus compromising accuracy. The level of complexity may also be related to the greater amount of information that the central nervous system receives and must process during dynamic conditions. Indeed, muscle spindles, which respond passively to stretch in static conditions, are actively modulated by gamma and beta motor neurons during contractions, enhancing spindle feedback (Kröger & Watkins, 2021). In addition, the interaction of muscle spindles with the collagen matrix surrounding muscle fibres may also influence proprioceptive feedback, particularly in dynamic scenarios (Fan et al., 2022). Our results also demonstrate a relationship between movement velocity at the time of stimulation and AE, indicating that higher velocities are associated with poorer proprioceptive acuity. This finding aligns with a previous study (Goble & Brown, 2009) in which participants were less accurate when the limb was passively set to the target position at higher speeds. Therefore, these findings underscore the importance of assessing proprioceptive acuity during dynamic tasks to increase the ecological validity of the test. Indeed, the use of D-JPR tasks may provide a more realistic description of proprioceptive function in everyday motor activities.

The present results also showed better accuracy during eccentric contractions. This finding contrasts with a previous study (Haggerty et al., 2021) in which a better accuracy in concentric contraction was found. The latter study observed a difference in angular error of 0.5° in the knee joint. However, the difference was very small and made the result questionable. A lower threshold for detecting movement has been observed in elbow extensor movements compared to flexor movements (Hall & McCloskey, 1983), which is attributed to a higher discharge rate of kinaesthetic signals. However, this explanation is not supported by the results of the Control experiment. In the Control experiment, participants performed flexion (i.e. when the muscle shortens) and extension (i.e. when the muscle lengthens) movements in the horizontal direction, namely moved the arm towards or away from the body, respectively. Results showed no differences between AE in flexion and extension movements. Notably, in the Main experiment participants performed the same movement, but in vertical direction, thus making concentric and eccentric contractions, causing differences in the proprioceptive acuity. This suggests a role of the muscle contraction type, regardless of movement direction. Furthermore, in the D-JPR task, it appears that also movement velocity was not the determining factor for the difference in AE in the initial and intermediate phases between concentric and eccentric contractions as the ANCOVA did not remove this difference in the interaction CONTRACTION TYPE x PHASE.

Previous studies that assessed the differences between concentric and eccentric contractions showed that eccentric contractions require greater cortical control during both planning and execution phases than concentric contraction (Perrey, 2018). Specifically, the pre-supplementary premotor area, prefrontal cortex, and anterior cingulate cortex, areas known to be implicated in attentional abilities (Weissman et al., 2005), exhibit heightened activity during eccentric contraction (Kwon & Park, 2011). This increased cortical activity could have increased attentional focus during the eccentric contraction improving the proprioceptive accuracy. Moreover, eccentric contractions involve greater force variability (Christou & Carlton, 2002), which poses challenges to motor control due to the need for precise coordination and adjustment to accommodate these fluctuations. Consequently, a more refined sense of position could act as a protective mechanism to prevent musculoskeletal injuries. This is particularly important considering that fewer motor units are involved at equivalent load levels (Duchateau & Enoka, 2008, 2016; Moritani et al., 1987).

A notable result is that accuracy improved as the movement neared the end position, with better accuracy in the final phase compared to the intermediate and initial phases, and the intermediate phase also exhibited greater accuracy than the initial phase. This difference was only evident in D-JPR tasks, both in eccentric and concentric contraction (Main experiment) and across movement directions (Control experiment). These discrepancies may stem from different activations of joint receptors among phases. Joint receptor activity increases as the movement approaches the joint limit (Burgess & Clark, 1969; Chen et al., 2021; Proske, 2023). Therefore, the different activity of joint receptors at different angles may explain the present results in the D-JPR task. In the JPR task, no significant differences were found among the movement phases. It should be noted that in the JPR task participants stopped moving as soon as the stimulus arrived, whereas in the D-JPR task continued to approach the joint limit. Thus, it can be speculated that joint receptor activity may not be as influential in the JPR task as in the dynamic task. Future studies should increase the number of positions to be reproduced, particularly those closer to the joint range limit, to explore potential differences in accuracy between JPR and D-JPR task.

In addition, a significant PHASE x CONTRACTION TYPE interaction was found by the ANCOVA analysis on the dynamic condition of Main experiment. For the Concentric contraction, a greater improvement in accuracy was observed from INI to INT and FIN. Although less pronounced, a significant improvement was observed in eccentric contractions, with a significant difference found only between the FIN and INI phases. Notably, AE in eccentric contractions was significantly lower in the INI and INT phases compared to concentric contractions, making further improvements harder to detect. Another important point is that this effect was absent in the Control experiment, as the PHASE x DIRECTION interaction was not significant. This indicates that the differences arose from the distinct nature of concentric and eccentric contractions rather than movement direction. One possible explanation is that the activation angle may differ between these contraction types. Greater fluctuation in force levels during Eccentric contraction compared to Concentric (Christou & Carlton, 2002) may influence joint receptor activity, resulting in a noiser signal. Thus, the discrimination between INT and both the other two phases could be less precise during the Eccentric contraction. This aspect needs further investigation for confirmation but suggests that when assessing proprioceptive acuity through D-JPR tasks, it is important to consider how different contraction modes affect the reproduction of various movement phases.

In conclusion, the results of this study shed insight into proprioceptive acuity in different experimental conditions, including JPR and D-JPR tasks, concentric and eccentric muscle contractions, and different movement phases. It found greater accuracy in JPR tasks and highlighted the impact of movement velocity on D-JPR tasks. Eccentric contractions demonstrated higher accuracy than concentric ones, suggesting distinct neural mechanisms at play. Differences in accuracy across movement phases emphasize the need to consider joint receptor activation patterns. These findings highlight call for further exploration of proprioceptive function in different contexts, with implications for rehabilitation and performance improvement, while also stressing the importance of experimental design factors in assessing proprioceptive acuity.

4.1. Limitations and future works

A limitation of the study is the exclusive use of behavioral measures to assess proprioceptive acuity. Although the observed behaviors provide important information, they are an indirect reflection of the neural and muscular processes underlying proprioceptive abilities. Integrating physiological measures, such as electromyography or brain activity recording, would allow direct investigation of the neural mechanisms underlying the observed changes in accuracy and allow behaviors to be correlated with physiological activity under different conditions. In addition, the study focused on a single muscle group. Future research is warranted to include analysis of other body regions to provide a more comprehensive view of proprioception. Finally, due to the limited sample size, it was not possible to make a reliable comparison between the sexes. Future studies with larger and more balanced samples are needed to investigate potential gender differences in proprioceptive accuracy and their underlying mechanisms.

CRediT authorship contribution statement

Pasquale Salerno: Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Mirko Job:** Writing – review & editing, Software. **Matteo Iurato:** Software. **Monica Biggio:** Conceptualization. **Marco Testa:** Writing – review & editing. **Marco Bove:** Writing – original draft, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. **Ambra Bisio:** Writing – original draft, Supervision, Software, Project administration, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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