

Low-Force Reproduction error is accompanied by greater cognitive demand

Alp Eşrefoğlu

Université Libre de Bruxelles (ULB)

Thomas Mangin

Université de Montréal

Benjamin Pageaux

Université de Montréal

Stéphane Baudry

`stephane.baudry@ulb.be`

Université Libre de Bruxelles (ULB)

Research Article

Keywords: sense of force, proprioception, dual task, signal clarity

Posted Date: August 20th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10689857/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

Sense of force depends on the ability to elaborate a reliable internal estimate of the force produced by a muscle group. When assessed with a force reproduction task, the reproduction accuracy is consistently poorer at low intensity [5% maximal voluntary contraction (MVC) force] than at moderate intensity (20% MVC), which may reflect reduced sensorimotor signal reliability (“clarity”) at 5%. We tested whether dividing attention during the force acquisition phase degrades more subsequent force reproduction at 5% than 20% MVC, with the rationale that lower clarity at low force level would require greater cognitive demands. Twenty healthy young adults performed wrist extensor force reproduction tasks at 5% and 20% MVC under a single-task condition (ST) and a dual-task condition (DT) in which they completed a concurrent a mental arithmetic task during the force acquisition phase. Reproduction accuracy was quantified using absolute error (AE) and signed error (SE). Perceived clarity of muscle sensation was assessed separately at each intensity using a visual analogue scale. DT increased AE at 5% [60.5 (30.8)% vs. 30.8 (18.1)%] but not at 20% MVC [22.6 (16.0)% vs. 15.5 (16.0)%]. SE showed the same pattern, with greater error at 5% in DT. Perceived clarity was lower at 5% than 20% MVC [41 (22) vs. 52 (23)] and predicted AE at 5% ($r^2 = 0.20$) but not 20% MVC. These findings suggest that the reproduction task imposes greater cognitive demand at low force levels, potentially due to less salient proprioceptive feedback.

INTRODUCTION

Accurate force production relies, in part, on the central nervous system’s ability to integrate sensory information from multiple peripheral sources, including muscle spindles, Golgi tendon organs, and cutaneous mechanoreceptors. These afferent signals contribute to proprioception, a multimodal construct encompassing the sense of limb position, movement, and force (Proske & Gandevia, 2012). In particular, the sense of force refers to the capacity to correctly perceive and reproduce a given level of force, and is commonly assessed using force reproduction tasks. Several studies have consistently reported greater force reproduction errors at low force levels (~ 5% of maximal voluntary contraction, MVC) compared with moderate force levels such as 20% MVC (Eşrefoğlu et al., 2023; Henry et al., 2022). Greater force reproduction errors at low force level has been observed across different muscle groups and experimental paradigms, and persists even in healthy older adults (Eşrefoğlu et al., 2023; Henry et al., 2022, 2025).

One possibility to explain the greater force reproduction error at 5% MVC is that low-force contractions are associated with poorer sensory resolution, leading to less accurate estimates of the force produced. Sensory signals at low force levels are likely weaker and more susceptible to contamination by neural noise, thereby reducing the signal-to-noise ratio available for central processing (Faisal et al., 2008; Henry et al., 2022). A reduction in the signal-to-noise ratio may reduce the signal clarity, defined as the reliability (precision) of the sensory evidence used to estimate the target force, determining the extent to which force-related information is discriminable from internal variability (“noise”) (Bays & Wolpert, 2007). The notion of clarity is grounded in the assumption that central nervous system performs state

estimation under uncertainty, and that the usefulness of a sensory cue depends on its reliability (Körding & Wolpert, 2004). If the force-related sensory evidence is less clear at 5% MVC, then encoding the target should require greater central processing to extract the relevant signal from noise, leading to increase the cognitive demand (Bays & Wolpert, 2007).

Dual-task paradigm, which consists of the concomitant completion of a primary and secondary tasks (e.g., a motor and a cognitive task), provides a tool to test whether low force level is associated with greater cognitive demand because dividing attention should impair performance most strongly when the primary task requires substantial attentional resources (Pashler, 1994). Performing a cognitive task simultaneously of an upper-limb joint repositioning task has been shown to decrease the accuracy of the repositioning, indicating an interference between the cognitive and the proprioceptive tasks (dual-task interference) (Ager et al., 2024). Such an interference has been linked to slower proprioceptive processing and altered detection thresholds in lower-limb paradigms (Jiang et al., 2023), and could increase when system relies more heavily on non-visual sensory information (Vermette et al., 2025).

This study aimed to determine whether the force reproduction task is accompanied by greater dual-task interference when performed at low compared with higher force level. To address this question, participants completed a force reproduction task at 5% and 20% MVC under either a single-task or a dual-task condition, in which a cognitive task was introduced during the force acquisition phase. Clarity of the sensations perceived in muscles during contractions was also rated. We hypothesized a greater dual-task interference at 5% MVC than at 20% MVC, as expressed with a larger reproduction error at 5% MVC. In addition, participants would report lower clarity of muscle sensations at low force level.

METHODS

Participants

Twenty healthy young adults participated in the study [mean (SD); age: 26 (3) years; body mass: 68.2 (10.3) kg; height: 174.0 (10.2) cm; 11 females; all right-handed]. Handedness was assessed using the Edinburgh handedness inventory (Oldfield, 1971). Individuals with Parkinson's disease, multiple sclerosis, diabetes, stroke, cardiac history or neurological damage, taking medications that could influence motor control [sedatives, hypnotics, antidepressants, and benzodiazepines; (Woolcott et al., 2009)], suffering from orthopaedic problems in the upper limbs or visual deficiency that cannot be corrected were not included. Participants were asked to refrain from doing intense physical activity for 72h before testing. All participants provided written informed consent prior to participation. Approval for the project was obtained from the Ethics Committee Erasme (#021/406), and all procedures used in this study conformed to the Declaration of Helsinki, except for preregistration.

The sample size was determined by practical constraints and corresponded to the maximum number of participants that could be recruited during the data-collection period (Lakens, 2022). This sample size is comparable to those commonly used in previous force reproduction and motor control experiments employing repeated-measures designs (Eşrefoğlu et al., 2023; Henry et al., 2022; Li et al., 2020). A

sensitivity analysis performed with G*Power 3.1.9.7 indicated that, with 20 participants, the study had 80% power to detect an interaction effect of approximately $f(u) = 0.331$ ($\eta^2_p = 0.098$) or larger in the planned 2×2 repeated-measures design.

Experimental setup

Participants were seated in a chair with the forearm of the right (dominant) arm placed on a custom-made ergometer. The wrist was in neutral position (0° of flexion, midway between pronation and supination), while the shoulder and elbow were flexed at about 25° and $40\text{--}50^\circ$ (elbow full extension: 0°), respectively. The dorsal surface of the hand was fixed against a pad (8 cm high and 3 cm wide) at the metacarpophalangeal joints. The pad was connected to a force transducer (model 4577A0, 2C3, voltage range: -5 to 5 V; Kistler, Winterthur, Switzerland) to record the force produced by the wrist extensor muscles. The force signal was A/D sampling at 200 Hz (Power 1401, 16-bit resolution, Cambridge Electronic Design, UK). A screen was placed in front of the participants to provide them with visual feedback of the wrist extension force produced. The very similar setup was previously described (Henry et al., 2022).

Maximal voluntary contraction

The MVC of the wrist extensors consisted of a gradual increase in force from zero to maximum within 2 s and sustained thereafter for 3–4 s. Three trials were performed, with participants resting for 90–120 s between trials to avoid fatigue. If the peak force of at least two of the three MVCs was within 5% of each other, the greatest value of these two MVCs was taken as the maximum. Otherwise, additional trials were performed until the 5% criterion was achieved. Participants never had to perform more than five MVCs per session to reach this criterion. The greatest MVC force was used thereafter to adjust the target displayed on the monitor during the tasks.

Force reproduction task

The force reproduction task consisted of a target phase followed by a reproduction phase. During the target phase, participants were required to match a given level of force for 15 s using visual feedback. The target force was displayed on a computer screen as a green horizontal line, while the force produced by the participant was represented by a red horizontal cursor moving vertically with changes in force. Participants were instructed to focus their attention on the sensation of the force generated by the wrist extensor muscles while maintaining the target force. The reproduction phase consisted of reproducing the target force for 15 s without visual feedback of either the force produced or the target force. The target and reproduction phases were separated by a 15-s interval during which participants were instructed to completely relax the forearm muscles. No information was provided regarding reproduction accuracy or performance on the concomitant cognitive task performed during the target phase in the dual task condition. Two successive force reproduction tasks were separated by at least 90 s to minimize fatigue. Before data collection, participants performed three 15-s familiarization contractions

for each contraction intensity and testing condition using visual feedback only. These practice contractions were not followed by a reproduction phase and were separated by 30- to 60-s rest intervals.

Cognitive task

During the target phase of the force reproduction task, in the dual task condition, participants concurrently performed an arithmetic task. They were presented with one two-digit number followed by four single-digit numbers at 3-s intervals (i.e., at the 2nd, 5th, 8th, 11th, and 14th seconds). Participants were instructed to mentally add all presented numbers as they appeared, without verbalizing or writing the calculation. Participants were prompted to report the total sum immediately after the end of the reproduction phase. Responses were scored as correct (1), incorrect (0).

Clarity SCORE

To assess the clarity of the sensation experienced in the muscles, participants performed force matching tasks where they were required to match, for a duration of 15 s, the target force (5 and 20% MVC) displayed as a green horizontal line on a screen with a red horizontal cursor representing the force they produced. The cursor's vertical movement corresponded to the force exerted, with upward displacement indicating an increase in force production. Participants were instructed to concentrate on the muscle sensation generated by their wrist extensors and the clarity of the sensation. At the end of each 15 s contraction interval, participants were instructed to quantify the clarity of sensations from their wrist extensor muscles using a Visual Analog Scale (VAS) on a tablet ("how clear were the muscle sensations generated by the contraction?"; left anchor = "not clear at all", right anchor = "extremely clear"). Three trials were performed at 5 and 20% MVC, and the average value for each intensity was considered for further analysis. The clarity of muscle sensation was assessed before the force reproduction task.

Experimental session

Prior to the recording phase, a pre-written script was read to all participants to present the different parts of the experimental session. After completing the MVC assessment, participants underwent a familiarization procedure aimed at acquainting them with the experimental setup, tasks and scales. Familiarization involved a series of force matching tasks lasting 5 s at various percentages of their MVC. Specifically, participants performed consecutive contractions at 2%, 25%, 50%, 75%, 50%, 25%, and 2% of their MVC. During these contractions, participants were instructed to match the force displayed on a computer screen, represented by a green horizontal line, with a red horizontal cursor indicating the force they exerted. Thereafter, participants performed the force matching tasks and assessed clarity of the sensation experienced in the muscles at 5 and 20% MVC. Then, the force reproduction task was performed at both contraction intensities (5% and 20% MVC) under two experimental conditions: (1) single-task, with no cognitive task (ST) and (2) dual task (DT), in which participants performed a concurrent arithmetic task during the target phase. No cognitive task was applied during the

reproduction phase. Participants completed three trials for each contraction intensity and condition, and trial order was fully randomized through the utilization of the JAMOVI software (version 2.6.44).

[INSERT FIGURE 1 HERE]

Data reduction

The force reproduction performance was assessed by computing the absolute error and the signed error (De Serres & Fang, 2004). Absolute error provides information about the overall error, regardless of its direction, reflecting thereby the magnitude of the error. Absolute error was calculated with the following formula, using the absolute value of the difference between the target force and the reproduction force:

$$\text{Absolute error (\%)} = 1/n \times \sum [| \text{reproduction force} - \text{target force} | / \text{target force} \times 100]$$

where reproduction force is the mean force produced during the last 5 s of this phase, target force is the mean force produced during the last 5 s of the target phase, and n is the number of trials ($n = 3$). The last 5 s of the target phase corresponded to the portion of the phase during which the force was stabilised around the target force.

Signed error provides information about the direction of the error: a negative value indicated that participants undershot the target whereas a positive value indicated that participants overshot the target. Signed error was calculated with the same formula as absolute error, using the real (signed) value of the difference between the reproduction force and the target force. The arithmetic task was analysed by counting the number of incorrect responses.

STATISTICAL ANALYSIS

The JAMOVI software (version 2.6.44) was used for statistical analysis. The D'Agostino and Pearson normality test confirmed that the distribution of each data set fitted a Gaussian function. For absolute error and signed error, two-way ANOVAs for repeated measures [intensity (5% vs. 20%) $\times$ condition (single task vs. dual task)] were used to analyse the effects of the independent variables on the force reproduction error. When the assumption of sphericity was violated, the Greenhouse-Geisser correction was applied. Partial Eta squared (η^2_p) was calculated for significant ANOVAs as an estimate of effect size with small ($\eta^2_p = 0.01$), medium ($\eta^2_p = 0.06$), and large ($\eta^2_p = 0.14$) effects (Cohen, 1988). Ninety-five percent confidence intervals were reported for η^2_p and Cohen's d . When appropriate, post-hoc comparisons were conducted on estimated marginal means (Holm test), and effect sizes (Cohen's d) were computed from observed group data. In addition, the clarity score was analysed using a Student t test for dependant samples. The arithmetic score was compared between the 5% and 20% contraction intensity with a Wilcoxon test. The coefficient of determination (r^2) extracted from Pearson product-moment correlations was calculated for the relation between the absolute error and clarity for each contraction intensity. As the clarity assessment did not provide information on the direction of the error, the r^2 was not computed for signed error. The level of statistical significance was set at $p \leq 0.05$ for all

comparisons. Values are expressed as mean (SD) in the text, except for arithmetic-task performance, which is expressed as median (IQR).

RESULTS

ARITHMETIC task

There was no difference between contraction intensities in the number of incorrect responses of the arithmetic task [5% MVC: 1.0 (1.0); 20% MVC: 0.00 (1.00); $p = 0.588$].

Force reproduction error

Absolute error. The absolute error was greater for the 5% than the 20% contraction intensity [intensity main effect: $F(1, 19) = 18.36, p < 0.001, \eta^2_p = 0.491, 95\% CI: 0.142, 0.677$] and was greater in the dual-task than the single-task condition [condition main effect: $F(1, 19) = 36.30, p < 0.001, \eta^2_p = 0.656, 95\% CI: 0.335, 0.783$]. The intensity $\times$ condition interaction was significant [$F(1, 19) = 8.68, p = 0.008, \eta^2_p = 0.314, 95\% CI: 0.025, 0.552$], and the associated post-hoc tests indicated that absolute error in the single-task condition was greater at 5% than 20% MVC [$p = 0.037, d = 0.662, 95\% CI: 0.169, 1.140$]. Absolute error was also greater in the dual-task than the single-task condition at 5% MVC [60.5 (30.8)% vs. 30.8 (18.1)%; $p < 0.001, d = 1.058, 95\% CI: 0.498, 1.600$], but not 20% MVC [22.6 (16.0)% vs. 15.5 (16.0)%; $p = 0.102, d = 0.547, 95\% CI: -0.070, 1.012$] (Fig. 2, top panel).

[INSERT FIGURE 2 HERE]

Signed error. The signed error was greater for the 5% than the 20% contraction intensity [intensity main effect: $F(1, 19) = 48.70, p < 0.001, \eta^2_p = 0.719, 95\% CI: 0.431, 0.823$] and was greater in the dual-task than the single-task condition [condition main effect: $F(1, 19) = 6.07, p = 0.023, \eta^2_p = 0.242, 95\% CI: 0.001, 0.496$]. The intensity $\times$ condition interaction was significant [$F(1, 19) = 11.83, p = 0.003, \eta^2_p = 0.384, 95\% CI: 0.061, 0.603$], and the associated post-hoc tests indicated that signed error in the single-task condition was greater at 5% than 20% MVC [$p < 0.001, d = 1.351, 95\% CI: 0.730, 1.953$]. Signed error was also greater in the dual-task than the single-task condition at 5% MVC [45.8 (55.9)% vs. 20.7 (29.6)%; $p = 0.019, d = 0.732, 95\% CI: 0.229, 1.220$], but not 20% MVC [-13.2 (25.3)% vs. -8.0 (21.0)%; $p = 0.472, d = -0.330, 95\% CI: -0.776, 0.125$] (Fig. 2, bottom panel).

Clarity

The clarity score was lower at 5% than 20% MVC [41 (22) mm vs. 52 (23) mm; $t(19) = -3.45, p = 0.002, d = -0.771, 95\% CI: -1.265, -0.262$] (Fig. 3).

[INSERT FIGURE 3 HERE]

For the 5% MVC reproduction task, the clarity score was negatively associated with absolute error ($r = -0.421, r^2 = 0.20, p = 0.032$), such that the greater was the clarity score, the lesser was absolute error

(Fig. 4, top panel). In contrast, no correlation was observed for the 20% MVC reproduction task ($r = 0.007$, $r^2 < 0.001$, $p = 0.960$) (Fig. 4, bottom panel).

[INSERT FIGURE 4 HERE]

DISCUSSION

The present study was designed to investigate whether force reproduction task at low intensity (5% MVC) induced greater dual-task interference than at higher force level (20% MVC). The rationale was that, if signal discrimination is more cognitively demanding at 5% MVC than at 20% MVC, the addition of the cognitive task would lead to a greater increase in force reproduction error at 5% MVC. We also assessed the perceived clarity of the force sensation during 5% and 20% MVC contraction to provide further arguments on the greater difficulty to discriminate the genuine signal at low force level. The results indicate i) a greater increase in both absolute and signed error in the dual task condition at 5 compared with 20% MVC, ii) a lower perceived clarity of the force signal at 5% than at 20% MVC, and iii) clarity being inversely related to absolute error only at 5% MVC. Taken together, these results suggest that the 5% MVC condition requires additional cognitive resources compared with 20% MVC, which may reflect a greater challenge to elaborate an estimate of low force levels.

Greater force reproduction error at 5% than 20% MVC

The greater reproduction error observed at 5 compared to 20% MVC is consistent with previous studies showing that the force reproduction error is more strongly affected by sensory manipulations, including tendon vibration, feedback modality, at 5% than at 20% (Eşrefoğlu et al., 2023; Henry et al., 2022, 2025). Force reproduction error may be greater at 5% than at 20% MVC because low-force contractions provide a less reliable sensory representation of force during the target phase. At 5% MVC, Golgi tendon organs are weakly loaded, and muscle spindle discharge is lower due to reduced α and γ motoneurons activation, likely limiting the amount of proprioceptive feedback (Eşrefoğlu et al., 2023; Henry et al., 2022). This potential weaker afferent signal could be further blurred by central noise, making the internal force estimate particularly uncertain. In contrast, at 20% MVC, increased tendon loading, higher spindle activity, and stronger cutaneous input improve the signal-to-noise ratio of proprioceptive and somaesthetic information, leading to a more stable force estimate and lower reproduction error.

Greater force reproduction error during dual-task at 5% MVC

The key finding of this study is that dividing attention during the target phase impaired subsequent force reproduction performance. This is in line with previous work showing that a cognitive task can impair the processing of proprioceptive inputs during an upper-limb repositioning task (Ager et al., 2024), a lower limb ipsilateral ankle matching task (Vermette et al., 2025) and movement-detection thresholds in the lower limb (Jiang et al., 2023). The greater dual-task effect at 5% compared to 20% MVC suggests that the encoding of a low target force is more cognitively demanding than the encoding of a moderate force, likely due to a less reliable internal representation of the target force. If force-related sensory signal is

less distinct at 5% MVC, encoding the target would require greater central processing to extract task-relevant information from noise, thereby increasing cognitive processing demands (Bays & Wolpert, 2007; Körding & Wolpert, 2006). Therefore, reproducing a force at 5% MVC appears to require greater central resources to extract the relevant force-related signal compared with higher force level. This interpretation may conceal with a lower signal-to-noise ratio at 5% MVC compared with 20% MVC, as suggested by the lower clarity at the low force level.

Clarity predicts error only at low force

Visual analogue scales allow to quantify internal perceptual states that lack direct physical observables (García-Pérez & Alcalá-Quintana, 2023). Subjective assessment via visual analogue scale is sensitive to changes in signal quality and uncertainty, capturing the individual's internal estimate of how distinct, stable, and informative a sensory signal feels during task execution (García-Pérez & Alcalá-Quintana, 2023). Therefore, the report of a lesser clarity at 5% MVC suggests that participant's internal assessment of signal quality was lower at 5% compared with 20% MVC. Accordingly, the lower clarity score at 5% MVC is compatible with the possibility that the sensory cues available in that condition was less salient (less easily discriminable), or less accurate than at 20% MVC (Eşrefoğlu et al., 2023; Henry et al., 2022, 2025). The inverse association between clarity and absolute error at 5% MVC supports that subjective signal quality was relevant in the low-force condition. In practical terms, participants who reported a clearer sensation at 5% MVC were also those who reproduced the target more accurately, whereas no such relationship was found at 20% MVC. This force-related effect is consistent with probabilistic models of sensorimotor control, according to which the influence of sensory reliability becomes most visible when uncertainty is high and the estimate is therefore more sensitive to imprecision (Bays & Wolpert, 2007; Körding & Wolpert, 2004, 2006).

Low-force error likely reflects more difficult signal discrimination

Taken together, the most parsimonious interpretation of these results is that the larger error in the force reproduction task at 5% MVC reflects, at least partly, a greater difficulty in discriminating the genuine force-related signal from background variability during sensorimotor processing. This explanation is well aligned with reviews showing that sensory and motor behaviour are fundamentally constrained by multiple sources of noise and uncertainty, and that accurate performance depends on how the nervous system filters, weights, and combines imperfect information (Bays & Wolpert, 2007; Faisal et al., 2008). It is also compatible with the view that force reproduction task relies on a task-dependent combination of centrally generated effort-related signals and peripheral afferent feedback, rather than on one source alone (Proske & Allen, 2019).

Limitations

Several limitations should be acknowledged. First, the sample included only healthy young adults, which limits the direct generalization of the findings to older adults or clinical populations. Nonetheless, a better understanding of the normal functioning of a system is essential to further apprehend the effects

of disease and pathology. Second, clarity was assessed with a subjective rating and only in the single-task condition, so the study cannot determine whether dual-tasking directly altered the perceived quality of the force-related feedback. However, the objective was to have complementary approaches to assess indirectly the difference in sensorimotor processing between 5% and 20% MVC with the dual-task allowing to provide information on the attentional demand of force estimate elaboration, and the clarity to figure out whether the signal was subjectively more or less salient. The convergent results from these two approaches strengthen the assumption that part of the greater force reproduction error at 5% MVC likely relies on a greater difficulty to discriminate the force feedback. Third, the protocol was restricted to wrist extensors and to two target intensities, so the generalizability of the results across muscles and force levels remains to be established. Fourth, the study did not include direct neurophysiological measures of peripheral afferent processing or central estimation, meaning that the proposed sensorimotor explanation remains inferential. Finally, attentional allocation between the arithmetic task and force acquisition was not directly assessed. Although arithmetic performance did not differ between the 5% and 20% MVC conditions, suggesting comparable engagement in the arithmetic task across force levels, we cannot determine the extent to which participants prioritized one task over the other. Future studies should include measures of task prioritization or attentional allocation to better characterize the mechanisms underlying dual-task interference during force encoding.

Conclusion

In conclusion, the present study indicates that the greater force-reproduction error observed at 5% MVC is associated with a larger dual-task interference, lower perceived clarity of the force related feedback, and a selective relationship between clarity of the force related feedback and force reproduction error, which is absent at 20% MVC. These converging findings suggest that encoding low force level is likely constrained by reduced sensory signal reliability.

Declarations

Conflict of interest

The authors have no conflict of interest to declare

Funding

Benjamin Pageaux was supported by the Chercheur Boursier Junior 1 from the Fonds de recherche du Québec – Santé. This project was part of an international collaboration between Benjamin Pageaux and Stéphane Baudry supported by the Xle Commission mixte permanente Québec–Wallonie-Bruxelles.

Author Contribution

A.E.: Investigation, Data curation, Formal analysis, Writing – original draft, Conceptualization, Methodology, Validation, Visualization, Writing – review & editing. T.M., B.P., and S.B.: Conceptualization, Methodology, Validation, Visualization, Writing – review & editing.

Data Availability

The data are available upon relevant and justified request.

References

1. Ager AL, Cools AM, Borms D, Roy J-S (2024) How does a motor or cognitive dual-task affect our sense of upper limb proprioception? PLoS ONE 19(3):e0299856. <https://doi.org/10.1371/journal.pone.0299856>
2. Bays PM, Wolpert DM (2007) Computational principles of sensorimotor control that minimize uncertainty and variability. J Physiol 578(2):387–396. <https://doi.org/10.1113/jphysiol.2006.120121>
3. Cohen J (1988) Statistical Power Analysis for the Behavioral Sciences. Routledge & CRC. <https://www.routledge.com/Statistical-Power-Analysis-for-the-Behavioral-Sciences/Cohen/p/book/9780805802832>
4. De Serres SJ, Fang NZ (2004) The accuracy of perception of a pinch grip force in older adults. Can J Physiol Pharmacol 82(8–9):693–701. <https://doi.org/10.1139/y04-085>
5. Eşrefoğlu A, Henry M, Baudry S (2023) Influence of Proprioceptive Inputs and Force Feedback Modality on Force Reproduction Performance. J Mot Behav 1–11. <https://doi.org/10.1080/00222895.2023.2280260>
6. Faisal AA, Selen LPJ, Wolpert DM (2008) Noise in the nervous system. Nat Rev Neurosci 9(4):292–303. <https://doi.org/10.1038/nrn2258>
7. García-Pérez MA, Alcalá-Quintana R (2023) Accuracy and precision of responses to visual analog scales : Inter- and intra-individual variability. Behav Res Methods 55(8):4369–4381. <https://doi.org/10.3758/s13428-022-02021-0>
8. Henry M, Darendeli A, Tvrdy T, Daneshgar S, Enoka RM (2025) Influence of age and feedback modality on the proprioceptive sense of force : Insights from motor unit recordings. J Neurophysiol 133(4):1103–1115. <https://doi.org/10.1152/jn.00486.2024>
9. Henry M, Eşrefoğlu A, Duchateau J, Baudry S (2022) Effects of tendon vibration and age on force reproduction task performed with wrist flexors. Exp Brain Res 240(3):941–951. <https://doi.org/10.1007/s00221-022-06311-z>
10. Jiang L, Kasahara S, Ishida T, Wei Y, Chiba A, Samukawa M, Tohyama H (2023) Dual-Task Interference Slows Down Proprioception. Motor Control 27(3):465–479. <https://doi.org/10.1123/mc.2022-0075>

11. Körding KP, Wolpert DM (2004) Bayesian integration in sensorimotor learning. *Nature* 427(6971):244–247. <https://doi.org/10.1038/nature02169>
12. Körding KP, Wolpert DM (2006) Bayesian decision theory in sensorimotor control. *Trends Cogn Sci* 10(7):319–326. <https://doi.org/10.1016/j.tics.2006.05.003>
13. Lakens D (2022) Sample Size Justification. *Collabra: Psychol* 8(1):33267. <https://doi.org/10.1525/collabra.33267>
14. Li L, Li Y, Gong R, Fu H (2020) Effect of wrist position on grip force sense in healthy adults. *Human Factors Ergon Manufacturing Service Industries* 30(4):237–247. <https://doi.org/10.1002/hfm.20836>
15. Oldfield RC (1971) The assessment and analysis of handedness : The Edinburgh inventory. *Neuropsychologia* 9(1):97–113. [https://doi.org/10.1016/0028-3932\(71\)90067-4](https://doi.org/10.1016/0028-3932(71)90067-4)
16. Pashler H (1994) Dual-task interference in simple tasks : Data and theory. *Psychol Bull* 116(2):220–244. <https://doi.org/10.1037/0033-2909.116.2.220>
17. Proske U, Allen T (2019) The neural basis of the senses of effort, force and heaviness. *Exp Brain Res* 237(3):589–599. <https://doi.org/10.1007/s00221-018-5460-7>
18. Proske U, Gandevia SC (2012) The proprioceptive senses : Their roles in signaling body shape, body position and movement, and muscle force. *Physiol Rev* 92(4):1651–1697. <https://doi.org/10.1152/physrev.00048.2011>
19. Vermette MJ, Paré E, Prince F, Messier J (2025) Paying attention to proprioception : Age affects ankle proprioception and the attentional demand of proprioceptive processing in sedentary adults. *GeroScience* 47(4):5803–5823. <https://doi.org/10.1007/s11357-025-01609-6>
20. Woolcott JC, Richardson KJ, Wiens MO, Patel B, Marin J, Khan KM, Marra CA (2009) Meta-analysis of the Impact of 9 Medication Classes on Falls in Elderly Persons. *Arch Intern Med* 169(21):1952–1960. <https://doi.org/10.1001/archinternmed.2009.357>

Figures

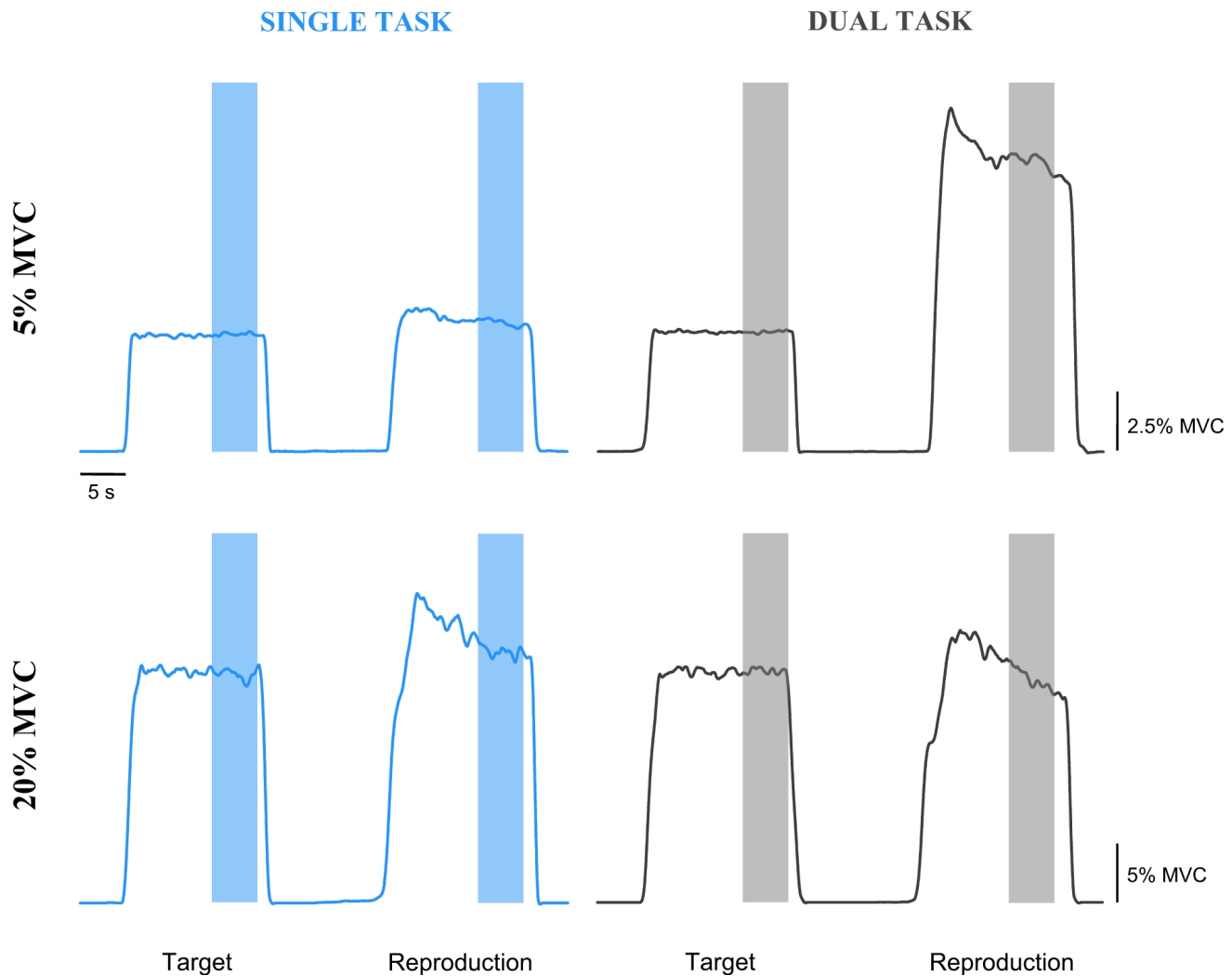


Figure 1

Original traces of the force produced by one participant of the force reproduction task performed with the wrist extensors in single-task condition (left panels) and dual-task condition (right panel) at 5% (top panels) and 20% of the force produced during a maximal voluntary contraction (MVC). During the target phase, participants were required to match a given level of force for 15 s using visual feedback while the reproduction phase consisted of reproducing the target force for 15 s without visual feedback of either the force produced or the target force. In dual-task condition, participants performed an arithmetic task during the target phase (see the text for more details). The shaded zones represent the epoch during which force were measured.

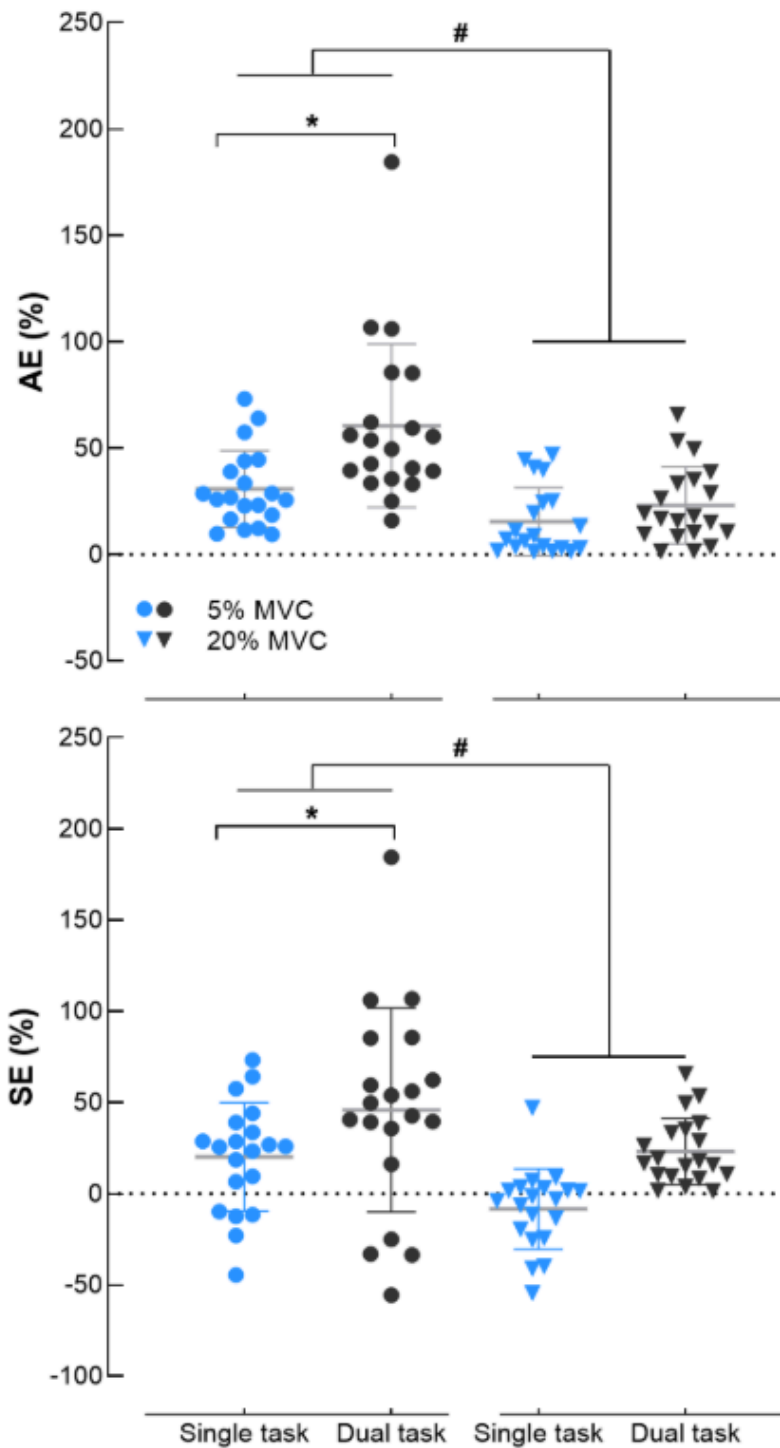


Figure 2

Absolute error (AE, top panel) and signed error (SE, bottom panel) during force reproduction task performed at 5% and 20% of maximal voluntary contraction (MVC) under single task (blue symbols) and dual-task (dark symbols) conditions. Individual data points represent single participants; horizontal bars indicate the group mean. The dotted horizontal line corresponds to zero error. Disk denote 5% MVC and

inverted triangles denote 20% MVC. * denotes statistical difference between ST and DT and # denotes difference between 5% and 20% MVC ($p < 0.05$).

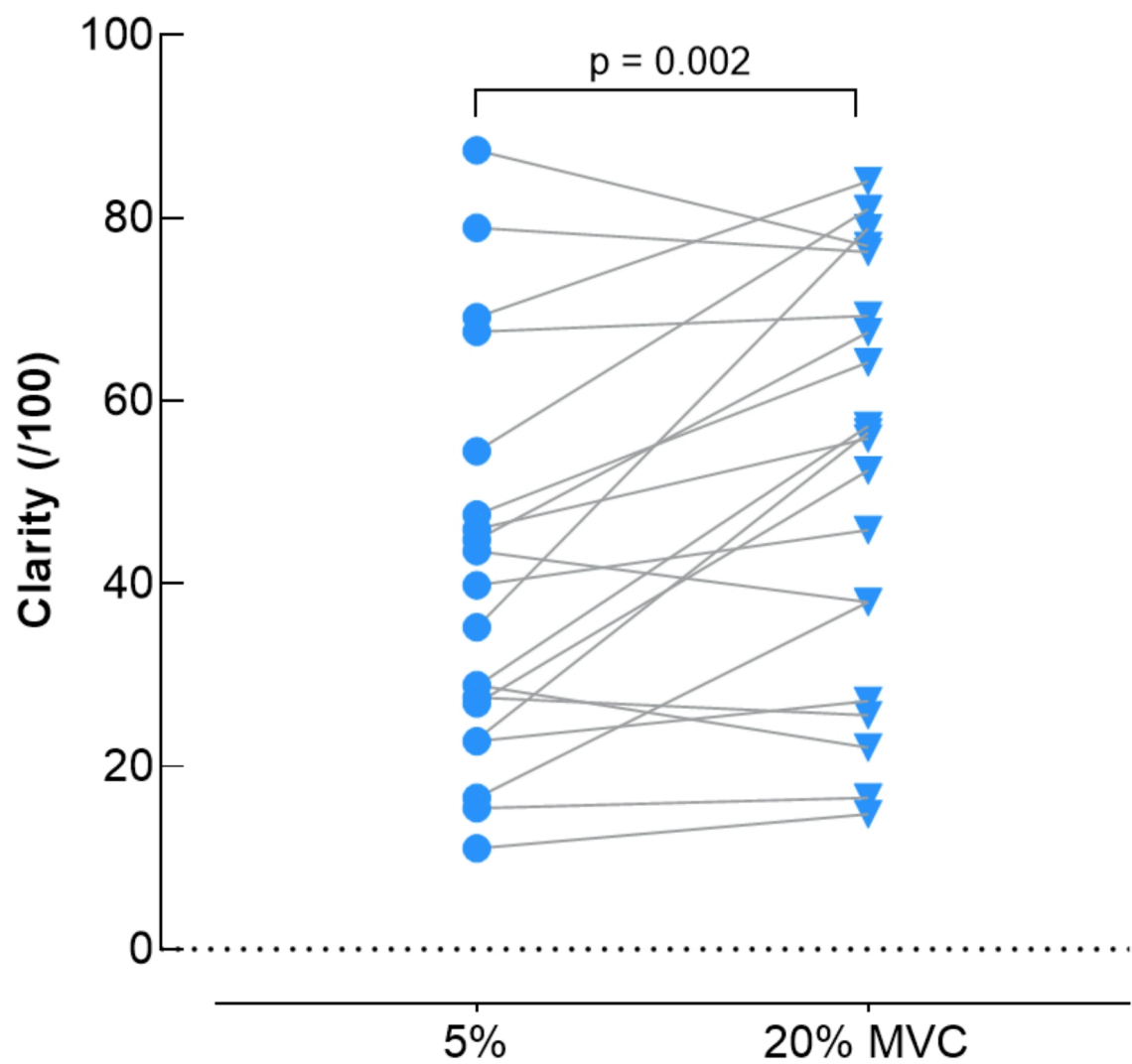


Figure 3

Perceived signal clarity during force matching task performed at 5% (disk) and 20% (inverted triangle) of maximal voluntary contraction (MVC). Individual data points represent single participants; paired data are connected by grey lines. Clarity was rated on a 10-point scale (/100). A significant increase in perceived clarity was observed at 20% compared with 5% MVC ($p = 0.002$).

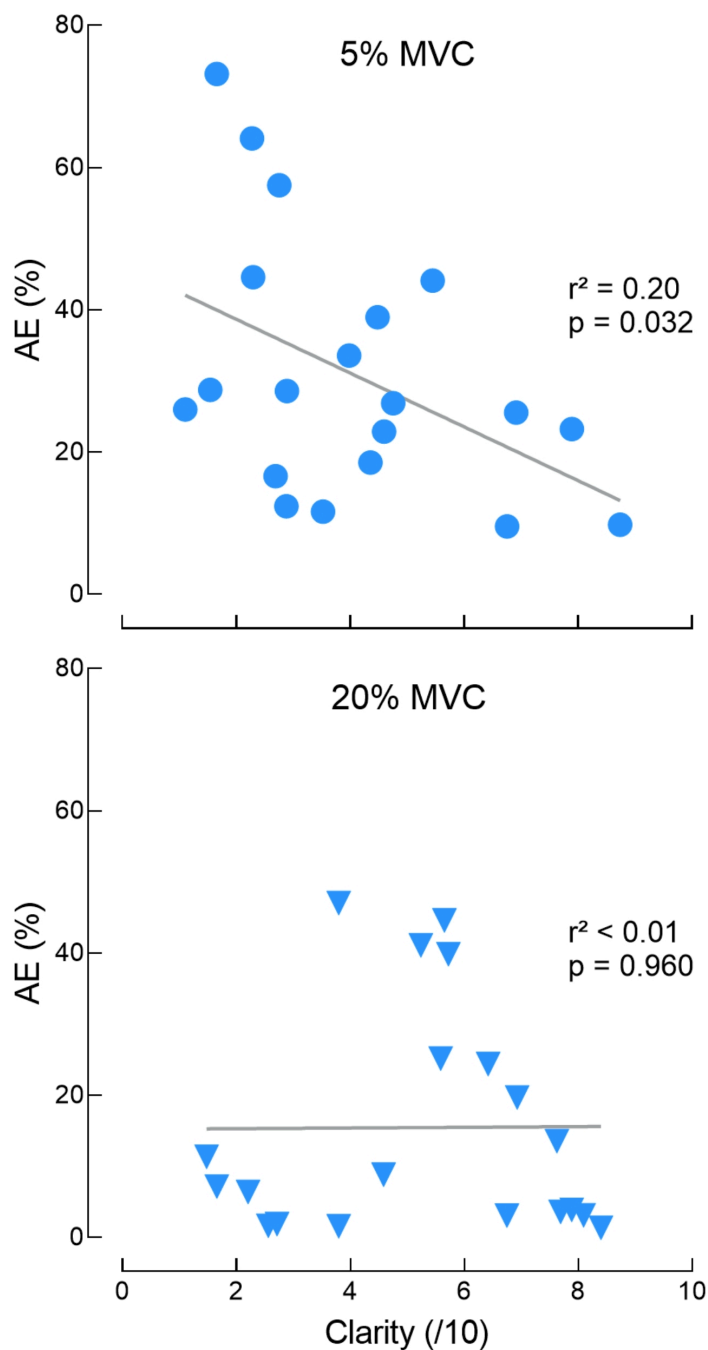


Figure 4

Relationship between absolute error (AE) during force reproduction task at 5% MVC (top panel) and 20% MVC (bottom panel) and perceived signal clarity. Individual data points represent single participants. Grey lines indicate the linear regression. At 5% MVC, AE decreased with increasing clarity ($r^2 = 0.20$, $p = 0.032$), whereas no relationship was observed at 20% MVC ($r^2 < 0.01$, $p = 0.960$). Clarity was rated on a 10-point scale (/10); AE is expressed as a percentage of the target force.

