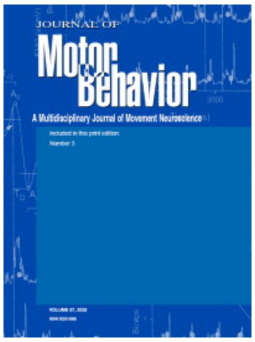

Journal of Motor Behavior

ISSN: 0022-2895 (Print) 1940-1027 (Online) Journal homepage: www.tandfonline.com/journals/vjmb20

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To cite this article: João Henriques Oliveira, João Sá Gomes, Philipp Bauer, Pedro Pezarat-Correia & João Rocha Vaz (2025) Torque Regularity is not Affected by the Nature of Visual Feedback During Hold Type of Isometric Contractions in Adults, Journal of Motor Behavior, 57:3, 269-277, DOI: 10.1080/00222895.2025.2469725

To link to this article: https://doi.org/10.1080/00222895.2025.2469725

Published online: 05 Mar 2025.

Journal of Motor Behavior, Vol. 57, No. 3, 2025

RESEARCH ARTICLE

Torque Regularity is not Affected by the Nature of Visual Feedback During Hold Type of Isometric Contractions in Adults

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ABSTRACT. The literature that investigated the influence of visual feedback properties on the magnitude and temporal structure of variability suggests that increases in the precision of visual information of the torque output (through manipulation of visual gain and its intermittency) lead the neuromuscular system to produce torque in a more steady and complex manner. However, less is known about the influence of the nature of visual feedback on torque variability. The present study aimed to investigate the effect of two different feedback natures, one from the angular position and the other from the torque produced, on the magnitude and temporal structure of torque variability during submaximal hold isometric tasks. Twenty healthy and young participants performed a knee extension isometric task, consisting in sustaining an applied resistance equivalent to 40% of their Maximal Voluntary Isometric Contraction for 30 s with visual feedback from angular position (H_{angle}) and with visual feedback from torque (H_{torque}). The magnitude of torque variability was calculated through the coefficient of variation. Sample Entropy was used to analyze the temporal structure of torque fluctuations, i.e., torque complexity. We observed no significant differences between conditions (H_{angle} vs H_{torque}) in both magnitude ($p = 0.117$) and the temporal structure of torque fluctuations ($p = 0.940$). Our results demonstrated that torque regulation seems not to be affected by the nature of the visual feedback during hold submaximal isometric tasks, suggesting a participation of sensorimotor system due to the nature of the task. Researchers should take this into account to take methodological decisions when using hold submaximal isometric tasks to investigate possible changes in motor control.

Keywords: complexity, variability, entropy, force control, visual feedback

Introduction

Torque output is characterized by natural non-random fluctuations present in the temporal structure of its time series, i.e., complexity, that is believed to contain hidden information about the intricate interplay between the multiple components of the neuromuscular system which generate complex patterns of torque output (Forrest et al., 2014; Slifkin & Newell, 1999; Vaillancourt & Newell, 2002, 2003). Therefore, torque complexity is believed to reflect the ability of the neuromuscular system to adapt motor output to the task demands and changes in the environment, representing the dynamic balance between stability and adaptability that characterizes healthy physiological systems (Lipsitz & Goldberger, 1992; Vaillancourt & Newell, 2003). Consequently, torque complexity is considered an important measure of motor control and an indicator of functionality of the neuromuscular system (Pethick et al., 2016, 2018). Interestingly, the literature suggests that the aging process (Fiogbé et al., 2021; Vaillancourt & Newell, 2003), pathology (Vaillancourt & Newell, 2002) and neuromuscular fatigue (Oliveira et al., 2022; Pethick et al., 2015, 2018, 2019b, 2019a, 2021) contribute to a decrease in the ability of the neuromuscular system to adapt its output, i.e., a loss of complexity.

Traditionally, the magnitude and temporal structure of torque fluctuations are assessed through targeted submaximal isometric tasks at a percentage of maximal voluntary isometric contraction (MVIC) (Clark et al., 2023; Enoka & Farina, 2021). The maintenance of an isometric torque level against a static object requires both feedforward information about the required torque and feedback information about the level of torque output being produced. Usually, this feedback consists in a visual indication of torque output, which can be used to adjust the torque production to meet the task requirements (Vaillancourt et al., 2006). Indeed, visual feedback is known to be essential when attempting to hold force steady (Lee Hong & Newell, 2008; Prodoehl et al., 2010) since its removal leads to a decrease in the absolute torque production, and to changes in the magnitude of variability, revealing a decrease in the individuals' capacity to meet the task requirements and to produce steady torque outputs following the withdrawal of visual feedback (Baweja et al., 2009; Vaillancourt & Russell, 2002).

Furthermore, the properties of visual feedback have been implicated to influence both the magnitude of variability, measured by standard deviation (SD) and coefficient of variation (CV), and the temporal structure of torque variability, assessed through entropy measures such as approximate entropy (ApEn) or sample entropy

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(SampEn) (Newell & Mcdonald, 1994; Slifkin et al., 2000; Sosnoff & Newell, 2006; Tracy et al., 2007). For instance, visual gain, i.e., the number of pixels on the screen per unit of torque, has been suggested to affect both the magnitude and time-dependent properties of variability in the torque output (Hu et al., 2011; Lee Hong & Newell, 2008; Newell & Mcdonald, 1994; Prodoehl et al., 2010; Sosnoff & Newell, 2006). Interestingly, it has been shown that improving the precision of visual feedback, by increasing its gain (i.e., the amount of visual information provided), improves individual's performance, measured through root mean square error (Beuter et al., 1995; Hong et al., 2008; Prodoehl et al., 2010). The gain of visual feedback has also been shown to influence both the magnitude and the temporal structure of force variability (Lee Hong & Newell, 2008; Prodoehl et al., 2010). Likewise, it has been demonstrated that the visual angle (i.e., the ratio between the vertical length on the screen per unit of force amplitude and the participant's eye distance to the screen) also mediates the control of force production (Vaillancourt et al., 2006). Furthermore, the literature has demonstrated that increasing the intermittency of visual feedback is associated to increases in the magnitude of torque fluctuations as well as to an increase in torque regularity (Hu et al., 2012; Lafe et al., 2016; Slifkin et al., 2000; Sosnoff et al., 2005; Sosnoff & Newell, 2005). Moreover, it was observed that visual gain and intermittency of visual feedback have compounding and compensatory effects on the time-dependent properties of torque variability (Hong et al., 2008).

In summary, it has been suggested that the more precise the visual information of the torque output is, the more the neuromuscular system is able to use that information to produce force in a steadier (i.e. with decreased magnitude of variability) but more complex manner (Hong et al., 2008; Lee Hong & Newell, 2008; Prodoehl et al., 2010; Slifkin et al., 2000). Thus, increasing the precision of the visual feedback information allows for more precise updating of the feedback processes involved in the visual control loop of torque production, increasing the number of solutions available to neuromuscular system to tune the torque production, resulting in a more complex isometric torque output (Sosnoff & Newell, 2005).

Although the effect of visual feedback properties on torque variability and complexity is well studied, less is known about the influence of the source/origin of visual feedback on both magnitude and temporal structure of torque fluctuations. In the traditional submaximal isometric tasks, the torque is produced against an immovable resistance and, therefore, an individual only has to control the torque production to achieve and sustain the targeted torque level since the position is fixed (force control tasks). Conversely, when an equivalent torque level has to be sustained in a determined angular position (position control tasks), which is closer to a real-world environment, the individual has to control both joint position and torque production (Enoka & Farina, 2021). Interestingly, it has been demonstrated that the time to task failure is considerably lower in position control tasks where the individuals must hold a submaximal load in a determined joint angle (hold isometric task) compared to force control tasks in which individuals have to push against an immovable resistance to match an equivalent torque level (Hunter et al., 2002; Rudroff et al., 2007, 2010). Moreover, Bauer and colleagues (2023) have demonstrated that torque complexity significantly differs between hold-type and push-type isometric contractions. Importantly, they also observed that adding visual feedback did not change torque regulation assessed through both torque complexity and variability. However, in these hold isometric tasks, the effect of providing visual feedback from different sources (joint angular position or torque level) on the magnitude and temporal structure of torque variability has not yet been determined.

In this type of tasks, the joint position is a consequence of the level of torque produced since the lever arm of isokinetic dynamometer moves whenever the individuals produce more or less torque than the targeted one. Therefore, it could be considered that the feedback from torque would provide direct information about the force produced by individuals' neuromuscular system to achieve the task goal and, hence, is more precise than the feedback from joint angle which would provide information about the individuals' joint angle and, indirectly influence the force produced to sustain the targeted task load. Thus, considering the literature mentioned above, the nature of feedback received by individuals could influence how their neuromuscular system regulates the torque production and, therefore, the torque complexity. Moreover, if the nature of feedback influences the torque regulation, it could be helpful in terms of methodological considerations for future research.

Thus, the aim of the present study is to address this gap by investigating the difference between the use of visual feedback of joint angular position and of torque level on the magnitude and temporal structure of torque fluctuations during submaximal hold isometric contractions. Considering the existing literature suggesting that the more precise the visual information provided to the individuals is, the steadier and more complex (less regular) the torque output produced by their neuromuscular system is (Hong et al., 2008; Lee Hong & Newell, 2008; Prodoehl et al., 2010; Slifkin et al., 2000), we hypothesized that torque feedback will result in a more complex torque output when compared to joint position feedback. We also hypothesized that the magnitude of variability would be lower during torque feedback as compared to joint position feedback.

Materials and Methods

Participants

Twenty young and healthy male adults aged 18-35 years (age: 24.6 ± 3.5yrs; height: 1.77 ± 0.07m; body mass:

74.6 ± 13.3Kg; body mass index: 23.7 ± 3.3 kg/m^2) without any neurological disorder or lower limb disabilities were recruited by word of mouth and participated in the present study. Each participant attended one data collection session and, prior to participation, signed an informed consent previously approved by the Ethics Committee of the Faculty of Human Kinetics (approval number #3/2022) and in conformity with the Declaration of Helsinki.

Experimental Design and Protocol

The participants were required to visit the laboratory to perform a maximal and a submaximal task in Biodex System 3 Pro isokinetic dynamometer (Biodex Medical System 3, Shirley, NY), initialized and calibrated according to the manufacturer's instructions. The chair of isokinetic dynamometer was adjusted to guarantee the alignment between the lateral epicondyle of the femur and the axis of rotation of the lever arm. The full extension was defined as the 0°, and the relative hip and knee angles were set at 90°. The lower leg of the participants' dominant member was attached to the lever arm above the malleoli with a velcro strap. Moreover, to prevent excessive movement and the use of hip extensors during the experimental tasks, straps were secured across participants' shoulders and waist. Furthermore, to guarantee proper warm-up and familiarization with testing procedures, a range of submaximal isometric, isokinetic and isotonic knee extensions were performed by participants.

To determine their Peak Torque (PT), defined as the highest torque value obtained during a MVIC task, participants were asked to perform three MVIC lasting 3 to 5 s each, being instructed to exert their maximum force as fast as possible with strong verbal encouragement. These contractions were separated by 60 s of rest, and continued until three consecutive peak torques were within 5% of each other.

For the submaximal trials, participants were asked to perform a hold isometric task, in two different conditions: with visual feedback from angular position (H_{angle}) and with visual feedback from torque (H_{torque}). The order of conditions was randomized. The submaximal task consisted in sustaining a resistance equivalent to 40% of their MVIC for 30 s at 70° of flexion. The visual feedback was provided through an angular position or torque line, depending on the testing condition (H_{angle} vs H_{torque}), displayed on a monitor (HP L1908W 19'', 1400 × 900 Widescreen), placed at 1.5 meters from participants, as depicted in Figure 1.

For the H_{angle} condition, participants were instructed to align their instantaneous angular position line with the target angle of 70° of knee flexion (testing angle) by sustaining the applied force equivalent to 40%MVIC. In the H_{torque} condition participants were asked to match their instantaneous torque with the target value equivalent to resistance applied by the isokinetic dynamometer (40%MVIC). In both conditions the isotonic mode of the

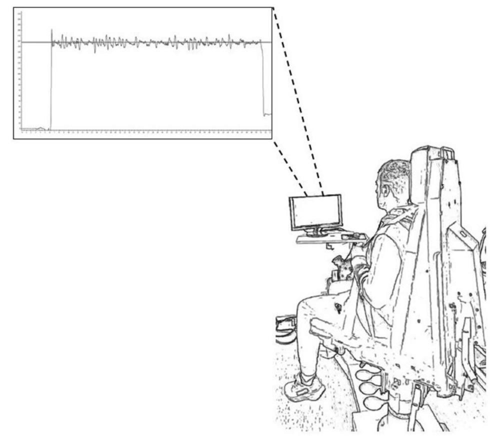

FIGURE 1. Representation of the experimental design.

isokinetic dynamometer was used, and the researcher assisted the participants at the start of each trial in moving the lever arm of the isokinetic dynamometer to the 70° target angle. Participants performed two trials for each condition with a 60-second period in between and were instructed to maintain the articular position while sustain the applied resistance through the entire duration of each trial. If the knee flexion angle varied by more than 10° from the target angle for three times or when the participant was unable to restore the angle back once lost, the trial was interrupted immediately and repeated. Data was sampled through Biopac MP100 (Biopac Systems Inc., California, USA) interfaced with a personal computer, at 1000 Hz. Data was collected in Acknowledge (Version 3.9.1. Biopac Systems, Inc., California, USA) and further exported to Matlab® R2023a (The MathWorks Inc., Natick, MA, USA).

Data Analysis

All data was analyzed using code written in Matlab® R2023a (The MathWorks, Natick, MA, USA). Torque signals were first low-pass filtered (Butterworth 10 Hz, 4th order), and, to guarantee that the analyzed signals only accounted for the time the participant matched the targeted MVIC%, were cropped to remove the ascending and descending components of the hold isometric contractions. After a power spectral analysis demonstrated the ∼9Hz as the maximal frequency of interest across all participants, the signals were downsampled to 50 Hz for further analysis, following the Stergiou (2004) recommendation of a sampling frequency five times greater than the highest frequency of interest in the time series. Then, the magnitude of variability, through the coefficient of variation (CV), and temporal structure of variability were calculated. Sample Entropy (SampEn)

TABLE 1. Temporal structure (SampEn) and magnitude (CV) of torque variability in function of nature of visual feedback (H_{angle} vs. H_{torque}).

	Mean torque (N.m)		SampEn		CV	
	H_{angle}	H_{torque}	H_{angle}	H_{torque}	H_{angle}	H_{torque}
Mean ± SD	132.4 ± 21.5	132.6 ± 21.0	1.20 ± 0.22	1.19 ± 0.19	5.19 ± 1.10	5.0 ± 1.07
95% CI	120.9–141.5	121.5–141.5	1.11–1.30	1.12–1.28	4.70–5.66	4.56–5.49

Data are presented as mean, standard deviation (SD) and confidence intervals (CI).

(Richman & Moorman, 2000) was used to determine the temporal structure of the torque output. SampEn determines the inverse probability that short sequences of data points are repeated throughout a temporal sequence of points, and, therefore, is a measure of the regularity of a signal. Lower SampEn values are associated with time series characterized by repeatable sequences of data points, i.e. a regular output. On the other hand, higher SampEn values are associated with time series characterized by the absence of this repeatability of sequences of data points, i.e. irregular outputs. Therefore, a perfectly repeatable time series has a SampEn value equal to zero, and a perfectly random time series has a SampEn value converging toward infinity (Richman & Moorman, 2000). SampEn is adapted from an earlier method of approximate entropy (ApEn). Unlike ApEn, SampEn is less sensitive to the data length and eliminates the bias of self-similar matches (Richman & Moorman, 2000). In this study, a pattern length (m) of 2, error tolerance (r) of 0.2 and data length (N) of 1500 data points (i.e., 50 Hz x 30 sec) were selected and used in the determination of SampEn values (Raffalt et al., 2023; Yentes et al., 2013). The reliability of entropy measures was shown to be optimal when these input values are identical for all trials and participants (Cavanaugh et al., 2005).

The Coefficient of Variation (CV), a common linear measure that translates the magnitude of variability within the torque output was calculated through the standard deviation normalized to the mean. Mean torque (MT) was also calculated to assure the targeted torque was reached equally across conditions. SampEn, CV and MT were extracted from the exact same previously cropped signal. For statistical purposes, the average of the two trials in each condition was used.

Statistical Analysis

All statistical analyses were carried out using Jamovi (Version 1.6. Sydney, Australia). Standard descriptive statistics (mean and standard deviation) were used to summarize the data. All data were tested for normality using Shapiro-Wilk tests. A paired samples *t*-test was used to investigate the difference between feedback nature in the magnitude and temporal structure of torque variability (CV and SampEn, respectively). When normality was violated, a Wilcoxon signed-ranks test was used. Cohen's d was calculated as a measure of effect size, as $d = \frac{t}{\sqrt{N}}$, where t stands for the statistical value and N for the number of observations. Statistical significance was set at $p < 0.05$.

Results

All data are summarized on Table 1.

Mean Torque

No significant differences were found between conditions ($t_{(19)} = -0.963$; $p = 0.348$; d=-0.215;MTH_{angle}= 132.4 N.m, MTH_{torque}=132.6 N.m).

Sample Entropy

Regarding temporal structure of torque fluctuations, assessed through SampEn, we observed no significant differences between conditions ($W = 107.5$; $p = 0.940$; $d = 0.024$; $SampEnH_{angle}$=1.20, $SampEnH_{torque}$=1.19)—Figure 2.

Coefficient of Variation

Relatively to the magnitude of variability, we found no significant differences between conditions for CV ($W = 147.5$; $p = 0.117$; $d = 0.405$; CVH_{angle}=5.19, CVH_{torque}=5.00) as depicted in Figure 2.

Discussion

This study aimed to investigate the effect of the nature of visual feedback on the magnitude and temporal structure of torque variability during submaximal hold isometric tasks. We hypothesized torque feedback would lead to a steadier (i.e., decreased magnitude) but more complex, i.e. less regular, torque production. This hypothesis was not verified since we observed no significant differences between conditions (H_{angle} vs H_{torque}) in both the magnitude, measured by CV, and the temporal structure of torque fluctuations, assessed through SampEn.

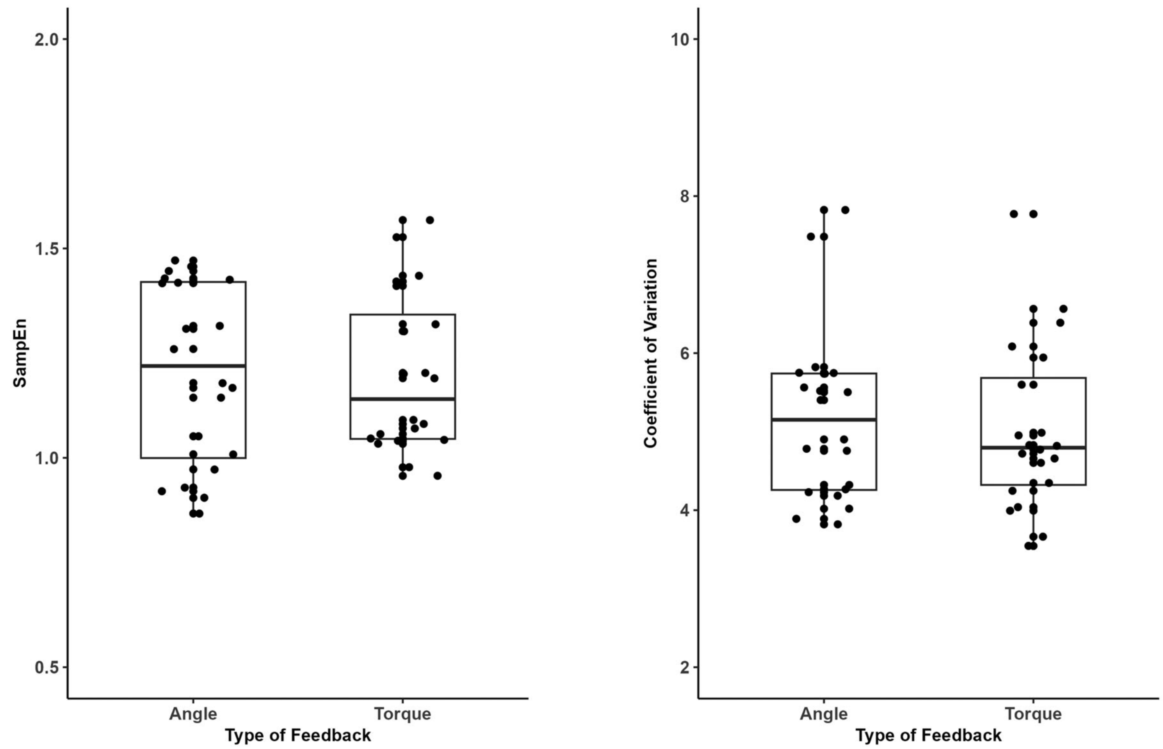

FIGURE 2. Torque sample entropy and coefficient of variation in function of the type of feedback. Data are presented as individual values.

Previous literature suggests that providing more precise visual information, through the increase of the gain and/or the reduction of the visual feedback intermittency, leads to a decrease in the magnitude and an increase in the complexity of torque production by the neuromuscular system (Hong et al., 2008; Lee Hong & Newell, 2008; Prodoehl et al., 2010; Slifkin et al., 2000). However, this was not observed in the present study since giving more accurate visual information through torque feedback (H_{torque}) did not translate into more complex and steadier torque control when compared to joint position feedback (H_{angle}). The nature of the submaximal isometric task could be a possible explanation to our results. In hold isometric tasks, participants must hold an applied submaximal load in a determined joint angle. Thus, in the case of knee extension, whenever participants produce a torque level below the target torque, the lever arm of dynamometer moves toward flexion. Conversely, when participants produce a torque level higher than the target torque, the arm of the dynamometer moves toward the extension. Therefore, in this type of tasks, the joint position is closely related to the level of torque produced. In this sense, the adjustments that participants must make to the joint position in the H_{angle} condition in order to maintain the target angle of the task depend on how they adjust the torque production to correspond to the task goal. Therefore, considering the close relationship between the joint position and the torque level produced in hold submaximal tasks, it seems that the nature of feedback provided to individuals does not affect the neuromuscular ability to adapt the motor output to correspond to the task demands, i.e. its adaptability, reflected by torque complexity (Vaillancourt & Newell, 2003).

Furthermore, the literature suggests that, when motor actions are performed, there is redundancy in the task goal which can be achieved by an infinite number of motor solutions, and that the coordination patterns are influenced by the constraints from the task, individual and environment (Bernstein, 1967; Newell, 1986; Ranganathan et al., 2020). The experimental paradigm used in the present study comprises both task and environmental constraints. At the task level, the 40% MVIC torque level to be sustained and the 70° of knee flexion served as constraints. Moreover, the visual feedback provided represents an environmental constraint.

The organization of motor coordination patterns is influenced by the interactive effect of the different constraints' categories (Hu & Newell, 2011a) and each constraint is weighted based on the relative influence of the constraint in the organization of the coordination patterns (Hu & Newell, 2011b), suggesting a constraint hierarchy, i.e., a set of prioritized requirements defining the task to be performed (Rosenbaum et al., 2001). It has also been suggested that if the task requires an individuals to maintain a given posture (e.g., maintaining the joint position during hold isometric contractions in our experiment), to attend to a given stimulus such as visual feedback, the stability of the task is prioritized over other constraints as it is a crucial condition to accomplish the task goal (Lee et al., 2018). In our experimental apparatus, the hold nature of the isometric task can be seen as constraint prioritized by the participants to assure the task goal, i.e., not losing the 70° knee flexion position. Thus, the motor control underlying the proposed task is likely being dictated by the sensorimotor system and adding visual feedback of different nature turns irrelevant. In other words, in our experiment, it could be hypothesized that the individuals have prioritized the stability of knee joint position to achieve the task goal, reducing their focus of attention from the visual feedback provided. Therefore, although the nature of the task-related feedback provided varied (torque vs joint angle), the mode how the participants explore the system's redundancy, i.e. the multiple solutions available to perform the task (sustain the 40%MVIC at 70° of knee flexion for 30 s) in order to select the best solutions to ensure its accomplishment, may have resulted in the selection of similar or synergistic solutions and, consequently, in similar temporal structures of torque output in both conditions. Conversely, if the contraction type would have been a push mode where the dynamometer lever arm is fixed, this constraint would likely be less relevant as the focus would then go to the torque level feedback, but no joint angle position feedback would be possible as there would be no need for controlling it. This rationale supports our findings and shows how potentially minor details in task experiment can have a great impact in the used motor control strategies. In addition, we have previously showed that adding additional visual feedback to a hold type of task did not change motor control as assessed through both the magnitude and temporal structure of variability (Bauer et al., 2023). Moreover, Bauer et al. (2023) have demonstrated that hold-type isometric contractions differ from the traditional push-type isometric contractions in terms of torque complexity, highlighting the relevance of task nature for torque regulation.

Altogether, the present and previous findings support that, due to the nature of the task, individuals prioritized the stability of the task and the achievement of the task goal, that potentially led them to adjust the motor output based on the sensorimotor information, that is, information provided by the articular receptors, mechanoreceptors (e.g., Golgi tendon organ and muscle spindles), and reflex pathways, attributing less weight to the environmental constraints such as the visual feedback. Interestingly, Fitzpatrick et al. (1994) have demonstrated in their study that proprioceptive signals from receptors in the leg muscles were sufficient to maintain a stable upright position, highlighting the importance of the information provided by the sensorimotor system to maintain the task stability. Furthermore, previous studies suggest that monosynaptic proprioceptive feedback has a time delay of 25-50ms, considerably lower than the visual feedback path (~200ms) (Mugge et al., 2013). This faster information processing could be the reason for the neuromuscular system to rely on proprioceptive information to regulate torque production when the focus was set to the task stability, which together with what was mentioned above, can help explaining the results obtained, and reflects the importance the sensorimotor system for torque regulation. Although this discussion seems neurophysiological logical, we did not address its through direct measures of it and, therefore, this discussion is partly speculative. Furthermore, despite the randomization of the conditions, a potential learning effect could have been observed and influenced the results since participants experienced both feedback natures. Moreover, considering that the literature suggests the existence of sex differences regarding torque complexity and variability (Brown et al., 2010; Harrison et al., 2023; Jakobi et al., 2018), future research should investigate if the nature of feedback would impact differently males and females.

To the best of our knowledge, this was the first study that investigated the nature of feedback (joint angular position or torque level) in the magnitude and temporal structure of torque fluctuations during submaximal hold isometric contractions. Our results suggest that torque regulation seems not to be affected by the nature of the visual feedback during hold submaximal isometric tasks, indicating that online force control processes of the lower limbs may not necessarily be able to adapt to various modulations of visual feedback during this type of tasks. We hypothesized that, due to the hold nature of the task, the participants could have prioritized the stability of the task, reducing their focus of attention to the visual feedback provided which could have increased the participation of the sensorimotor system on force regulation. This could have practical implications for the researchers who want to use this type of hold submaximal isometric tasks, closely related to the real-world environment, to investigate possible changes in motor control, particularly at the level of methodological decisions.

ACKNOWLEDGMENTS

We would like to thank all our participants for their voluntary contribution that allowed this research and made the present findings possible.

Authors' Contributions

João H. Oliveira: Conceptualization, Methodology, Software, Validation, Formal Analysis, Investigation, Writing—Original Draft, Writing—Review and Editing, Visualization, Project administration; João R. Vaz: Conceptualization, Methodology; Software, Validation, Formal Analysis, Resources, Data Curation, Writing—Original Draft, Writing—Review and Editing, Visualization, Supervision, Project administration; João S. Gomes: Validation, Investigation, Writing—Review and Editing, Visualization; Pedro Pezarat Correia: Conceptualization, Methodology, Resources, Writing—Review and Editing, Visualization, Supervision, Project administration; Philipp Bauer: Validation, Writing—Review and Editing, Visualization.

Ethics Approval

Approval was obtained from the ethics committee of Faculty of Human Kinetics (approval number #3/2022). The procedures used in this study adhere to the tenets of the Declaration of Helsinki

Informed Consent

Written informed consent was obtained from all individual participants included in the study.

Disclosure Statement

The authors have no competing interests to declare that are relevant to the content of this article.

Funding

João R. Vaz and Pedro Pezarat-Correia were partly supported by the Fundação para a Ciência e Tecnologia under grant number UIDB/00447/2020 to CIPER - Centro Interdisciplinar para o Estudo da Performance Humana (unit:447). João R. Vaz was partly funded by Fundação para a Ciência e Tecnologia through Egas Moniz Center for Interdisciplinary Research (CiiEM) under grant number UIDB/04585/2020. João H. Oliveira, João S. Gomes and Philipp Bauer were supported with PhD scholarships from Fundação para a Ciência e Tecnologia with grant numbers 2021.08271.BD, 2022.10952.BD and UI/BD/154379/2023, respectively.

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Data Availability Statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

REFERENCES

Bauer, P., Gomes, J. S., Oliveira, J., Santos, P., Pezarat-Correia, P., & Vaz, J. R. (2023). Torque regulation is influenced by the nature of the isometric contraction. *Sensors (Basel, Switzerland)*, *23*(2), 726. https://doi.org/10.3390/s23020726

Baweja, H. S., Patel, B. K., Martinkewiz, J. D., Vu, J., & Christou, E. A. (2009). Removal of visual feedback alters muscle activity and reduces force variability during constant isometric contractions. *Experimental Brain Research*, *197*(1), 35–47. https://doi.org/10.1007/s00221-009-1883-5

Bernstein, N. A. (1967). *The co-ordination and regulation of movements*. Pergamon Press.

Beuter, A., Haverkamp, H., Glass, L., & Carrière, L. (1995). Effect of manipulating visual feedback parameters on eye and finger movements. *The International Journal of Neuroscience*, *83*(3-4), 281–294. https://doi.org/10.3109/00207459508986345

Brown, R. E., Edwards, D. L., & Jakobi, J. M. (2010). Sex differences in force steadiness in three positions of the forearm. *European Journal of Applied Physiology*, *110*(6), 1251–1257. https://doi.org/10.1007/s00421-010-1600-x

Cavanaugh, J. T., Guskiewicz, K. M., & Stergiou, N. (2005). A nonlinear dynamic approach for evaluating postural control: New directions for the management of sport-related cerebral concussion. *Sports Medicine (Auckland, N.Z.)*, *35*(11), 935–950. https://doi.org/10.2165/00007256-200535110-00002

Clark, N. C., Pethick, J., & Falla, D. (2023). Measuring complexity of muscle force control: Theoretical principles and clinical relevance in musculoskeletal research and practice. *Musculoskeletal Science & Practice*, *64*, 102725. https://doi.org/10.1016/j.msksp.2023.102725

Enoka, R. M., & Farina, D. (2021). Force steadiness: From motor units to voluntary actions. *Physiology (Bethesda, Md.)*, *36*(2), 114–130. https://doi.org/10.1152/physiol.00027.2020

Fiogbé, E., Vassimon-Barroso, V., Catai, A. M., de Melo, R. C., Quitério, R. J., Porta, A., & Takahashi, A. C. M. (2021). Complexity of knee extensor torque: Effect of aging and contraction intensity. *Journal of Strength and Conditioning Research*, *35*(4), 1050–1057. https://doi.org/10.1519/JSC.0000000000002888

Fitzpatrick, R., Rogers, D. K., & McCloskey, D. I. (1994). Stable human standing with lower-limb muscle afferents providing the only sensory input. *The Journal of Physiology*, *480*(Pt 2), 395–403. https://doi.org/10.1113/jphysiol.1994.sp020369

Forrest, S. M., Challis, J. H., & Winter, S. L. (2014). The effect of signal acquisition and processing choices on ApEn values: Towards a "gold standard" for distinguishing effort levels from isometric force records. *Medical Engineering & Physics*, *36*(6), 676–683. https://doi.org/10.1016/j.medengphy.2014.02.017

Harrison, S., Clark, N. C., Ansdell, P., & Pethick, J. (2023). Sex differences in knee extensor torque control. *Journal of Electromyography and Kinesiology: Official Journal of the International Society of Electrophysiological Kinesiology*, *72*, 102806. https://doi.org/10.1016/j.jelekin.2023.102806

Hu, X., & Newell, K. M. (2011a). Adaptation to bimanual asymmetric weights in isometric force coordination. *Neuroscience Letters*, *490*(2), 121–125. https://doi.org/10.1016/j.neulet.2010.12.040

Hu, X., & Newell, K. M. (2011b). Modeling constraints to redundancy in bimanual force coordination. *Journal of Neurophysiology*, *105*(5), 2169–2180. https://doi.org/10.1152/jn.01086.2010

Hu, X., Loncharich, M., & Newell, K. M. (2011). Visual information interacts with neuromuscular factors in the coordination of bimanual isometric force. *Experimental Brain Research*, *209*(1), 129–138. https://doi.org/10.1007/s00221-010-2528-4

Hu, X., Mazich, M. M., & Newell, K. M. (2012). Time gain infuences adaptive visual-motor isometric force control. *Experimental Brain Research*, *218*(1), 73–80. https://doi.org/10.1007/s00221-012-3006-y

Hunter, S. K., Ryan, D. L., Ortega, J. D., & Enoka, R. M. (2002). Task differences with the same load torque alter the endurance time of submaximal fatiguing contractions in humans. *Journal of Neurophysiology*, *88*(6), 3087–3096. https://doi.org/10.1152/jn.00232.2002

Jakobi, J. M., Haynes, E. M. K., & Smart, R. R. (2018). Is there sufficient evidence to explain the cause of sexually dimorphic behaviour in force steadiness? *Applied Physiology, Nutrition, and Metabolism = Physiologie Appliquee, Nutrition Et Metabolisme*, *43*(11), 1207–1214. https://doi.org/10.1139/apnm-2018-0196

L., Hong, S., Brown, A. J., & Newell, K. M. (2008). Compensatory properties of visual information in the control of isometric force. *Perception & Psychophysics*, *70*(2), 306–313. https://doi.org/10.3758/pp.70.2.306

Lafe, C. W., Matheus, Pacheco, M., & Newell, K. M. (2016). Bimanual coordination and the intermittency of visual information in isometric force tracking. *Experimental Brain Research*, *234*(7), 2025–2034. https://doi.org/10.1007/s00221-016-4606-8

Lee Hong, S., & Newell, K. M. (2008). Visual information gain and the regulation of constant force levels. *Experimental Brain Research*, *189*(1), 61–69. https://doi.org/10.1007/s00221-008-1403-z

Lee, I. C., Pacheco, M. M., & Newell, K. M. (2018). Constraints specific influences of vision, touch and surface compliance in postural dynamics. *Gait & Posture*, *59*, 117–121. https://doi.org/10.1016/j.gaitpost.2017.09.014

Lipsitz, L. A., & Goldberger, A. L. (1992). Loss of 'complexity' and aging: Potential applications of fractals and chaos theory to senescence. *JAMA*, *267*, 1806–1809.

Mugge, W., Abbink, D. A., Schouten, A. C., van der Helm, F. C. T., Arendzen, J. H., & Meskers, C. G. M. (2013). Force control in the absence of visual and tactile feedback. *Experimental Brain Research*, *224*(4), 635–645. https://doi.org/10.1007/s00221-012-3341-z

Newell, K. M. (1986). Constraints on the development of coordination. In M.G. Wade and H.T.A. (Eds.). *Motor development in children: Aspects of coordination and control*. Martinus Nijhoff.

Newell, K. M., & Mcdonald, P. V. (1994). Information, coordination modes and control in a prehensile force task. *Human Movement Science*, *13*(3-4), 375–391. https://doi.org/10.1016/0167-9457(94)90046-9

Oliveira, J., Casanova, N., Gomes, J. S., Pezarat-Correia, P., Freitas, S., & Vaz, J. R. (2022). Changes in torque complexity and maximal torque after a fatiguing exercise protocol. *Sports Biomechanics*, *23*(12), 2873–2885. https://doi.org/10.1080/14763141.2022.2067588

Pethick, J., Winter, S. L., & Burnley, M. (2015). Fatigue reduces the complexity of knee extensor torque fluctuations during maximal and submaximal intermittent isometric contractions in man. *The Journal of Physiology*, *593*(8), 2085–2096. https://doi.org/10.1113/jphysiol.2015.284380

Pethick, J., Winter, S. L., & Burnley, M. (2016). Loss of knee extensor torque complexity during fatiguing isometric muscle contractions occurs exclusively above the critical torque. *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology*, *310*(11), R1144–R1153. https://doi.org/10.1152/ajpregu.00019.2016

Pethick, J., Winter, S. L., & Burnley, M. (2018). Effects of ipsilateral and contralateral fatigue and muscle blood flow occlusion on the complexity of knee-extensor torque output in humans. *Experimental Physiology*, *103*(7), 956–967. https://doi.org/10.1113/EP086960

Pethick, J., Winter, S. L., & Burnley, M. (2019a). Fatigue reduces the complexity of knee extensor torque during fatiguing sustained isometric contractions. *European Journal of Sport Science*, *19*(10), 1349–1358. https://doi.org/10.1080/17461391.2019.1599450

Pethick, J., Winter, S. L., & Burnley, M. (2019b). Relationship between muscle metabolic rate and muscle torque complexity during fatiguing intermittent isometric contractions in humans. *Physiological Reports*, *7*(18), e14240. https://doi.org/10.14814/phy2.14240

Pethick, J., Winter, S. L., & Burnley, M. (2021). Physiological complexity: Influence of ageing, disease and neuromuscular fatigue on muscle force and torque fluctuations. *Experimental Physiology*, *106*(10), 2046–2059. https://doi.org/10.1113/EP089711

Prodoehl, J., David, A. E., & Vaillancourt, E. (2010). Effects of visual gain on force control at the elbow and ankle. *Experimental Brain Research*, *200*(1), 67–79. https://doi.org/10.1007/s00221-009-1966-3

Raffalt, P. C., Yentes, J. M., Freitas, S. R., & Vaz, J. R. (2023). Calculating sample entropy from isometric torque signals: Methodological considerations and recommendations. *Frontiers in Physiology*, *14*, 1173702. https://doi.org/10.3389/fphys.2023.1173702

Ranganathan, R., Lee, M. H., & Newell, K. M. (2020). Repetition without repetition: challenges in understanding behavioral flexibility in motor skill. *Frontiers in Psychology*, *11*, 2018. https://doi.org/10.3389/fpsyg.2020.02018

Richman, J. S., & Moorman, J. R. (2000). Physiological time-series analysis using approximate entropy and sample entropy maturity in premature infants Physiological time-series analysis using approximate entropy and sample entropy. *American Journal of Physiology. Heart and Circulatory Physiology*, *278*(6), H2039–H2049. https://doi.org/10.1152/ajpheart.2000.278.6.H2039

Rosenbaum, D. A., Meulenbroek, R. J., Vaughan, J., & Jansen, C. (2001). Posture-based motion planning: Applications to grasping. *Psychological Review*, *108*(4), 709–734. https://doi.org/10.1037/0033-295X

Rudroff, T., Christou, E. A., Poston, B., Bojsen-Møller, J., & Enoka, R. M. (2007). Time to failure of a sustained contraction is predicted by target torque and initial electromyographic bursts in elbow flexor muscles. *Muscle & Nerve*, *35*(5), 657–666. https://doi.org/10.1002/mus.20752

Rudroff, T., Justice, J. N., Matthews, S., Zuo, R., & Enoka, R. M. (2010). Muscle activity differs with load compliance during fatiguing contractions with the knee extensor muscles. *Experimental Brain Research*, *203*(2), 307–316. https://doi.org/10.1007/s00221-010-2233-3

Slifkin, A. B., & Newell, K. M. (1999). Noise, information transmission, and force variability. *Journal of Experimental Psychology. Human Perception and Performance*, *25*(3), 837–851. https://doi.org/10.1037/0096-1523.25.3.837

Slifkin, A. B., Vaillancourt, D. E., & Newell, K. M. (2000). Intermittency in the control of continuous force production. *Journal of Neurophysiology*, *84*(4), 1708–1718. https://doi.org/10.1152/jn.2000.84.4.1708

Sosnoff, J. J., & Newell, K. M. (2006). Information processing limitations with aging in the visual scaling of isometric force. *Experimental Brain Research*, *170*(3), 423–432. https://doi.org/10.1007/s00221-005-0225-5

Sosnoff, J. J., & Newell, K. M., 67. (2005). Intermittent visual information and the multiple time scales of visual motor control of continuous isometric force production. *Perception & Psychophysics*, *67*(2), 335–344. https://doi.org/10.3758/bf03206496

Sosnoff, J. J., Jordan, K., & Newell, K. M. (2005). Information and force level interact in regulating force output during two and three digit grip configurations. *Experimental Brain Research*, *167*(1), 76–85. https://doi.org/10.1007/s00221-005-0009-y

Stergiou, N. (2004). *Innovative analyses of human movement*. Human Kinetics Publishers.

Tracy, B. L., Dinenno, D. v., Jorgensen, B., & Welsh, S. J. (2007). Aging, visuomotor correction, and force fluctuations in large muscles. *Medicine and Science in Sports and Exercise*, *39*(3), 469–479. https://doi.org/10.1249/mss.0b013e31802d3ad3

Vaillancourt, D. E., & Newell, K. M. (2002). Changing complexity in human behavior and physiology through aging and disease. *Neurobiology of Aging*, *23*(1), 1–11. https://doi.org/10.1016/s0197-4580(01)00247-0

Vaillancourt, D. E., & Newell, K. M. (2003). Ageing and the time and frequency structure of force output variability. *Journal of Applied Physiology (Bethesda, Md.: 1985)*, *94*(3), 903–912. https://doi.org/10.1152/japplphysiol.00166.2002

Vaillancourt, D. E., & Russell, D. M. (2002). Temporal capacity of short-term visuomotor memory in continuous force production. *Experimental Brain Research*, *145*(3), 275–285. https://doi.org/10.1007/s00221-002-1081-1

Vaillancourt, D. E., Haibach, P. S., & Newell, K. M. (2006). Visual angle is the critical variable mediating gain-related effects in manual control. *Experimental Brain Research*, *173*(4), 742–750. https://doi.org/10.1007/s00221-006-0454-2

Yentes, J. M., Hunt, N., Schmid, K. K., Kaipust, J. P., McGrath, D., & Stergiou, N. (2013). The appropriate use of approximate entropy and sample entropy with short data sets. *Annals of Biomedical Engineering*, *41*(2), 349–365. https://doi.org/10.1007/s10439-012-0668-3

Received October 15, 2024
Revised January 13, 2025
Accepted February 14, 2025