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Fatigue in elite fencing: effects of a simulated competition

Giorgio Varesco[1], Benjamin Pageaux[2,3,4], Thomas Cattagni[1], Aurélie Sarcher[1], Guillaume Martinent[5], Julie Doron[1] & Marc Jubeau[1]

[1] Nantes Université, Laboratory Movement – Interactions – Performance (MIP), UR 4334, F-44000 Nantes, France.

[2] Université de Montréal, École de kinésiologie et des sciences de l'activité physique (EKSAP), Montréal, Canada.

[3] Centre de recherche de l'Institut universitaire de gériatrie de Montréal (CRIUGM), Montréal, Canada.

[4] Centre interdisciplinaire de recherche sur le cerveau et l'apprentissage (CIRCA), Montréal, Canada.

[5] University of Claude Bernard Lyon 1, Univ Lyon, Laboratory on vulnerabilities and innovation in sport, Lyon, France.

*Corresponding author: Giorgio Varesco
Laboratoire MIP - Nantes Université
23, rue du Recteur Schmitt Bât F0 - BP 92235
44322 NANTES
Giorgio.varesco@univ-nantes.fr

Authors ORCID ID :
0000-0001-9385-6972 Giorgio Varesco
0000-0001-9302-5183 Benjamin Pageaux
0000-0002-6650-8339 Thomas Cattagni
0000-0002-6408-6291 Aurélie Sarcher
0000-0002-4151-2286 Guillaume Martinent
0000-0002-3967-709X Julie Doron
0000-0002-4878-7813 Marc Jubeau

ABSTRACT

The fatigue induced by fencing remains scarcely investigated. The literature suggests limited fatigability despite the high perceived effort experienced during a fencing competition. In this study, we aimed to investigate both objective (neuromuscular performance fatigability) and subjective (perceived fatigue, effort and workload) manifestations of fatigue in elite fencers following a 5-bouts simulated competition. Changes in countermovement jump height, knee extensors maximal isometric torque, rate of torque development, voluntary activation, and contractile response to muscular electrical stimulation were measured in 29 elite fencers [12 epee (6 women), 11 saber (5 women), and 6 foil]. Perceived fatigue and effort were evaluated with visual analog scales, and the perceived workload was evaluated with the $\mathrm{NASA}_{\mathrm{TLX}}$ scale. The knee extensors neuromuscular function remained unaltered after a single bout. During the competition, maximal torque and rate of torque development decreased by 1.6% ($P=0.017$) and 2.4% ($P<0.001$) per bout, respectively. Perceived fatigue increased during the competition (12% per bout) with higher values at the beginning of the bouts, and similar values at the end of the bouts (time × bout interaction: $P<0.001$). Perceived effort increased during the bouts (10% per bout, $P<0.001$) and during the competition (3% per bout, $P=0.011$). Perceived mental demand was the sole $\mathrm{NASA}_{\mathrm{TLX}}$ dimension increasing during the competition (2%, $P=0.024$). These results suggest limited impairments in the knee extensor neuromuscular function after a fencing competition, and that elite fencers needed to increase the allocation of mental rather than physical resources to the task to counterbalance the deleterious effect of fatigue on performance.

250 words

Keywords: mental fatigue, rate of force development, interpolated twitch technique, combat sport, escrime.

1. INTRODUCTION

Fencing is one of the oldest combat sports and is part of the modern summer Olympic games since its first edition in 1896. It includes three disciplines, characterized by different weapons: the epee, the foil, and the saber [for a detailed review, see [1]]. Typically, an international competition of fencing lasts more than 9 hours for the finalists, with a net match time of about 10% (*i.e.,* 17 to 48 minutes in total), with 15 up to 180 minutes of rest between matches, or "bouts".[1] The 5-6 bouts included in the competition are divided into rounds. Rounds are characterized by intense "*assaults*" followed by resting periods of similar or greater duration [epee: work to rest ratio = 9s:8s,[2] foil = 5s:15s,[1] saber = 3s:15s.[3]]. The number of bouts and the duration of the rounds depend on the specific rules for each weapon.

As other combat sports, fencing practice induces fatigue.[4] Fatigue is a symptom traditionally associated with increased feelings of tiredness and lack of energy that can be caused by physical, mental or combined physical and mental exertion.[5,6] Following a task (*e.g.,* a fencing bout), an increase in fatigue could be identified by objective and subjective manifestations, impairing or not cognitive and physical performance.[6,7] It is thus important to distinguish fatigue from its objective and subjective manifestations related to a specific task.

The objective manifestation of fatigue in relation to a task can be assessed across various systems of the human body. For a given absolute work performed, the decrease in performance on the task or of a specific system is considered a measure of its fatigability.[8] When evaluating fatigability in fencing, previous studies focused mainly on the changes over time in oxygen consumption or blood lactate concentration, reporting no change in these variables along the competition (*e.g.*,[2,9,10]). Limited evidence is available on the performance of the neuromuscular system.[4] Considering the frequent fast displacements of athletes in fencing, it is of crucial importance to focus on the fatigability of the lower limbs, as previously suggested.[9,11] A previous study evaluating countermovement jump height (CMJ) observed no change following a fencing competition.[4] It is worth noting that CMJ does not specifically isolate one muscle group and includes a coordination aspect, requiring complementary evaluations for a finer monitoring of the lower limbs' fatigability.[4] Such measures should include the evaluation of maximal force, voluntary activation, contractile function and the rate of force development, particularly important because of the fast actions performed in fencing.[12]

Subjective manifestations of fatigue refer to the individual report of her/his experience of fatigue and associated feelings (i.e., tiredness and lack of energy). During a fatiguing task, it is possible to observe changes in the athlete's perception of her/his engagement in a task to perform,[6] namely the perception of effort.[13–15] Due to the high cognitive and physical demands associated with fencing competition, fencers have previously reported ratings of perceived effort ranging from "somewhat hard" to "very hard",[2,4,10] with stable ratings along a competition.[4] However, as the authors monitored the rating of perceived effort solely after each bout of a competition, it remains unknown how effort perception changes during a bout.

This contraposition observed in the literature between high perceived effort despite no fatigability observed during a fencing competition deserves further investigation. One possible explanation could be that fencing bouts, being recognized as a highly technical and tactical discipline,[1,2,16] would be characterized by an intense mental workload, impacting more the subjective manifestation of fatigue rather than the physiological ones, which would recover quickly. Also, elite athletes are trained so their physical condition can cope well with the competition demands, as already suggested.[4] If true, it would be necessary, other than perceived effort, to better study the characteristics and kinetic of the mental workload of the task along a fencing competition to provide useful information to coaches and sports scientists.

Thus, the present study aimed at investigating the fatigue induced by a simulated competition in elite fencers of the three weapons: epee, foil, and saber. We evaluated changes in objective and subjective manifestations of fatigue, measured with changes in i) the knee extensors neuromuscular performance and ii) the perceptions of fatigue, effort and workload. In line with previous literature demonstrating limited alterations in neuromuscular function, we hypothesized that a simulated competition would have an important mental demand, that would be associated with marked subjective manifestations of fatigue and limited fatigability of the neuromuscular function.

2. METHODS

2.1 Participants

Twenty-nine elite fencers that were part of the national fencing team in 2022 across the three fencing weapons were included in the study: 12 from epee (6 women), 11 from saber (5 women), and 6 from foil (men only). Participants' competition period ranged from November until July. During that period, they trained on average 5±0.5 days/week and for 5±1 hours/day. The average time dedicated to technical training was 3±1 hours/day, while the rest consisted of strength and conditioning. All participants gave their written informed consent before their participation. The study was approved by the ethics committee of Nantes University (n°08042021).

2.2 Study design

This study used a within-subject design with the participants tested in two separate sessions, where the simulated competition took place (the French Institute of Sport center in Paris, and the Federation center in Nevers). In the first session, the day before the simulated competition, participants were familiarized with all experimental procedures described thereafter. They also performed a first baseline assessment of the knee extensor neuromuscular function. The knee extensors' neuromuscular function of the lunge leg was evaluated (*i.e.,* the frontal leg, which corresponds to the side where the athlete held the weapon: right leg *n*=23, left leg *n*=6). In the second session, participants completed a simulated fencing competition, with the neuromuscular function of the knee extensors evaluated before and after the first bout, and after the competition, as well as self-report of various psychological variables.

2.2.1 Simulated competitions

The simulated competition took place between February and May 2022. The competition included 5 bouts of 15 points to simulate the direct elimination stage of an actual international competition. Such competition format is perceived as more demanding than the 5-points initial rounds, known as "*Poule*"[2,10]. Five simulated competitions were used to test the different teams involved in the study (epee men and women, saber men and women, and foil men). Participants used their fencing kit that conforms to the Fédération Internationale d'Escrime (FIE) regulations. Official scoring equipment was used and professional referees contributed to each competition. The opponents in the competition were of similar level. Competitions complied with the FIE rules, except that a fencer losing a bout was not directly eliminated and kept competing against other bouts' losers in a parallel competition to ensure that all fencers performed the same number of bouts. Fencing indoor stadium temperature and humidity were similar across all competitions (22°C, 40% RH). Two fencing platforms were used, and to ensure that a maximum of two athletes at a time reported to the neuromuscular testing stand, the bouts on the first platform started 10 to 20 min earlier than the bouts on the second platform. We ensured that the recovery period between bouts was similar across all athletes. The result of every bout disputed (victory or defeat) was recorded for each athlete.

2.2.2 Experimental procedures

At the beginning of the first session, a standardized warm-up was first performed, consisting of 5 min of light pedaling on a cycle ergometer and six 5-s knee extensors voluntary isometric contractions (interspersed by 5 s). Contractions were performed on the isometric dynamometer, starting from a self-selected torque and progressively increasing until the maximal torque was exerted. Following 1 min of rest, muscle electrical stimulation intensity was determined. Then, participants were familiarized with the neuromuscular evaluation procedures (see below). At the end of the session, a full neuromuscular evaluation was performed. On the second session (simulated competition day), participants first underwent a briefing to make sure the testing protocol was clear and to read the instructions for the self-reported scales and questionnaires. Before the start of the simulated competition, the athletes were instructed to perform a warm-up identical to what they routinely do before a world-cup competition. Then, they performed one knee extensor neuromuscular evaluation. Neuromuscular testing was repeated at the end of the first bout and the end of the last bout. Maximal torque and CMJ height were also tested after the third bout (see below). Self-reported scales were administered at each bout.

2.3 Fatigability of the knee extensor neuromuscular function

The neuromuscular evaluation was designed to include surrogate measures of maximal power (CMJ), force (maximal isometric contractions) and rapidity (rate of torque development) of the lower limbs. Three CMJs were used to assess jump height, one 5-s maximal voluntary isometric contractions of the knee-extensors for the assessment of maximal torque, and eight 1-s rapid isometric contractions to measure rate of torque development.[17] During and 2 s after the maximal isometric contraction, 100-Hz stimulations were elicited to measure voluntary activation and contractile function. Contractions were separated by 5-10 s.

Because sometimes the athletes that participated in the study faced each other, the order of testing (neuromuscular evaluation or CMJs) was randomized before the end of each bout for the athletes, so that one athlete performed the CMJs while his/her opponent performed the knee extensors neuromuscular evaluation. Before the beginning of the competition, participants were equipped with the stimulation electrodes and cables that were kept under the fencing kit for the first bout. Through pilots, we observed that electrode holds tend to move or detach from the skin if kept for too many bouts, because of the sweating and attrition with the pants. Thus, after the first bout, it was decided to remove stimulation electrodes and reapply them before the last bout. To check the kinetic of eventual neuromuscular impairments during the competition, a maximal contraction and 3 CMJs were also performed after the third bout. Because of time constraints and athletes' availability, it was not possible to reapply and remove all electrodes to perform stimulations, nor to perform the series of rapid contractions after the third bout. At the end of the first, third and fifth bouts, participants were asked to report to the neuromuscular testing stand immediately after the completion of the scales and questionnaire. Detailed information on the neuromuscular testing procedures and materials is available in Appendix A.

2.4 Subjective measurements

Two visual analog scales were used to measure the perception of fatigue and effort, as well as the NASA Task-Load-Index ($NASA_{TLX}$) questionnaire for measuring the perceived workload of each bout.[18,19] The visual analog scale for perceived fatigue was administered immediately before, during the 1-min break between rounds, and at the end of every bout of the simulated competition. The visual analog scale for perceived effort was administered during the 1-min break between rounds, and the end of every bout of the simulated competition. The $NASA_{TLX}$ was administered at the end of each bout. Participants were instructed to complete the questionnaires as soon as possible after the end of each phase. To be noted that the $NASA_{TLX}$ also includes an item called "effort", that answers to the question "How hard did you have to work to accomplish your level of performance?".[18] Detailed information on the testing procedures and materials is available in Appendix A.

2.5 Statistical analysis

Statistical analyses were carried out in R statistical environment.[20] Information on model fitting and assumptions is presented in the Appendix A. To evaluate the overtime changes of the variables (CMJ, maximal torque, rate of torque development, voluntary activation, potentiated doublet, $NASA_{TLX}$ scores, and visual analog scales), linear mixed-effects models were fitted to the data using the restricted mean likelihood method in the lme4 package.[21] The glmmTMB package[22] was used assuming a beta distribution when data could not be modelled with a normal distribution, due to possible ceiling effect and skewed data density (that was the case for the mental demand dimension of the $NASA_{TLX}$). P-values were extracted from all F-tests using Satterthwaite's degrees of freedom method (lmerTest package[23]). Two different analyses were performed for the physiological variables: (i) to evaluate the effect of one bout by entering in the model data obtained *pre* and *post* the first bout of the simulated competition (time encoded as *pre* = 0, *post* = 1) and (ii) to evaluate the evolution of fatigability over time, all data obtained *post* bouts were used (time encoded as *post first bout* = 0, *post third bout* = 2, *post fifth bout* = 4). For the visual analog scales, only one model was built with the data from all bouts. Besides the time effect, we also evaluated the effect of weapon, sex, and bout's result for each variable. When a significant main effect or interaction was observed, Tukey post-hoc correction was applied to pairwise comparisons. For all tests, the significance threshold was set at α=0.05.

3. RESULTS

Participants' characteristics at baseline for each of the teams are presented in table 1. Stimulations were performed on 24 athletes (6 epee men, 5 epee women, 6 saber men, 2 saber women, and 5 foil), while 5 athletes refused the procedure due to the discomfort caused by the stimulation. For voluntary activation, because only participants that at the testing session presented values >70% at *pre* were considered, data were available for 14 participants (2 epee men, 3 epee women, 3 saber men, 2 saber women, 4 foil men). Because the bout ends when one of the two opponents scores 15 hits, some bouts did not last 3 rounds (detailed information is presented in Appendix D).

****Table 1 about here****

3.1 Fatigability of the neuromuscular system

3.1.1 Effect of a single bout

No significant main effects of weapon and bout results were found for the neuromuscular variables (all P>0.05). Thus, those effects were removed from the models for the subsequent analyses. CMJ increased from *pre* to *post*-bout, however, this change was within the standard error of the measure. Men performed higher jumps heights than women [Intercept (I, β±SE) = 41.4±1 cm, $t_{(1,29)}$=40.9, P<0.001; $time_{(0,1)}$=1±0.4 cm, $t_{(1,27)}$=2.5, P=0.02; $sex_{(women)}$=-10.2±1.6 cm, $t_{(1,27)}$=-6.3, P<0.001]. For maximal torque, two outliers were detected: The first (saber man) reported an increase from 311 N·m to 367 N·m, and the second (saber woman) reported a steep drop in maximal torque values (346 N·m to 258 N·m). Maximal torque decreased from *pre* to *post*, but this change was within the standard error of the measure of the intercept, and it was greater for men than women [I=307.71±16 N·m, $t_{(1,26)}$=19.2, P<0.001; $time_{(0,1)}$=-10.40±4.7 N·m, $t_{(1,25)}$=-2.2, P=0.036; $sex_{(women)}$=-57.7±26.12 N·m, $t_{(1,25)}$=-2.2, P=0.037]. For the rate of torque development, one outlier was identified (epee woman) showing a steep increase in the rate of torque development values (662.5 to 1165.7 N·m·s^{-1}). The rate of torque development did not change over time (P=0.08), with greater values for men compared to women [I=1041.8±54.8 N·m·s^{-1}, $t_{(1,26)}$=19, P<0.001; $sex_{(women)}$=-217.5±92 N·m·s^{-1}, $t_{(1,26)}$=-2.4, P=0.026]. The amplitude of the potentiated doublet was unchanged after the bout (P=0.87) and was not different across sexes (P=0.17), with I=130.6±7.2 N·m ($t_{(1,23)}$=18; P<0.001). For voluntary activation, one participant (epee man) was excluded due to invalid data at *post*. Voluntary activation (n=13) was similar across sexes (P=0.79) but decreased with time [I=84±2%, $t_{(1,22)}$=44.6, P<0.001; $time_{(0,1)}$=-5±2%, $t_{(1,14)}$)=-2.5, P=0.028]. Percentage differences from *pre* to *post* are presented in Figure 1.

****Figure 1 about here****

3.1.2 Effect of a simulated competition

No main effects of weapon and bout result were found for the neuromuscular variables (all P>0.05). Those effects were thus removed from the models for subsequent analyses. For CMJ, one outlier was identified (epee man) showing a steep decrease in CMJ across the competition (from 49 to 36 cm). CMJ did not show significant changes across the competition (P=0.059), being greater for men than women [I=42.5±0.9 cm, $t_{(1,25)}$=47.4, P<0.001; $\text{sex}_{(\text{women})}$=-9.7±1.5 cm, $t_{(1,25)}$=-6.6, P<0.001, Figure 2A]. Maximal torque did not show a significant sex main effect (P=0.082), but it decreased along the competition [I=274.14±12.9 N·m, $t_{(1,31)}$=21.2, P<0.001; $\text{bout}_{(0,4)}$=-4.44±1.8 N·m, $t_{(1,52)}$=-2.5, P=0.017, Figure 2B]. One outlier was found for the rate of force development (saber man), showing a steep increase in the rate of torque development values from the end of the first bout (554.56 N·m·s^{-1}) to the end of the competition (881.93 N·m·s^{-1}). The rate of torque development was greater for men than women and decreased along the competition [I=1033.6±49.8 N·m·s^{-1}, $t_{(1,29)}$=20.8, P<0.001; $\text{bout}_{(0,4)}$=-24.3±6.0 N·m·s^{-1}, $t_{(1,25)}$=-4.0, P<0.001; $\text{sex}_{(\text{women})}$=-176.9±79.9 N·m·s^{-1}, $t_{(1,27)}$=-2.2, P=0.036, Figure 2C]. One outlier was detected for the potentiated doublet (epee man, the same as CMJ), which showed a steep decrease from the end of the first bout (150.1 N·m) to the end of the competition (52.1 N·m). The amplitude of the potentiated doublet did not change from the end of the first bout to the end of the competition (P=0.73) nor the difference between sexes was observed (P=0.37), [I=129.3±7.0 N·m·s^{-1}, $t_{(1,24)}$=18.5, P<0.001, Figure 2D]. For voluntary activation, one outlier was detected (epee man), who showed a steep decrease in voluntary activation values from the end of the first bout (83%) to the end of the competition (53%). Voluntary activation did not change between sexes (P=0.39) or across the competition (P=0.53); [I=79.9±1.5 N·m·s^{-1}, $t_{(1,14)}$=53, P<0.001, Figure 2E].

****Figure 2 about here****

3.2 **Subjective measurements**

3.2.1 Perception of Fatigue and Effort

No main effects of weapon and bout results were found for fatigue (P=0.60; P=0.25) and effort (P=0.12; P=0.14). For fatigue, no significant sex effect was found (P=0.57). Significant bout × time interaction was found for fatigue. As the competition progressed, *pre* bout fatigue increased, with lower differences at *post* between bouts [I=4.83±0.35 cm, $t_{(1,41)}$=12.2, P<0.001; $\text{time}_{(0,3)}$=0.70±0.1 cm, $t_{(1,422)}$=7.05, P<0.001, $\text{bout}_{(0,4)}$=0.58±0.07 cm, $t_{(1,422)}$=8.47, P<0.001, $\text{time}_{(0,3)}\times\text{bout}_{(0,4)}$=-0.14±0.04 cm, $t_{(1,422)}$=-3.33, P<0.001, Figure 3A]. For effort, significant time and bout main effects were found, indicating an increase in effort along the bout and throughout the competition [I=5.45±0.31 cm, $t_{(1,46)}$=17.5, P<0.001; $\text{time}_{(0,2)}$=0.54±0.12 cm, $t_{(1,300)}$=4.42, P<0.001, $\text{bout}_{(0,4)}$=0.16±0.06 cm, $t_{(1,297)}$=2.55, P=0.011, Figure 3B].

****Figure 3 about here****

3.2.2 Perceived Workload

Because mental demand was modelled assuming beta distribution due to skewed data, glmmTMB was used to model all linear-mixed models for $NASA_{TLX}$ dimensions to be consistent in data reporting. Effort presented no weapon (P=0.22), sex (P=0.51) or bout (P=0.38) main effects. The effort was reported as greater in the case of victory [I=61±3 A.U., z=20.24, P<0.001; $result_{(victory)}$=7±3 A.U., z=2.14, P=0.03]. Physical demand presented no weapon (P=0.21), sex (P=0.30), bout (P=0.07) or result (P=0.20) main effect [I=65±3 A.U. z=23.95, P<0.001]. Mental demand presented one outlier (saber woman), who reported a very low score (5 A.U. over 100 A.U.) in the last bout (ended with a defeat). Mental demand did not present weapon (P=0.55) or sex (P=0.35) main effects, but it increased throughout the competition and was greater in case of victory [beta-distribution (mental demand*100^{-1}), logit estimates: I=0.53±0.21, z=2.52, P<0.001; $bout_{(0,4)}$=0.11±0.5, z=2.26, P=0.024; $result_{(victory)}$=0.30±0.15, z=2.04, P=0.042]. For mental demand, estimates were computed using the ggpredict package for R[24] and presented in Figure 5. Frustration did not present weapon (P=0.45), sex (P=0.43) or bout (P=0.06) main effects but it was scored higher when the bout was lost [I=63±4 A.U., z=15.86, P<0.001; $result_{(victory)}$=-22±4 A.U., z=-5.84, P<0.001]. Perceived performance did not present weapon (P=0.65), sex (P=0.68) or bout (P=0.81) main effects, but was perceived as greater when the bout was won [I=38±3 A.U., z=11.4, P<0.001; $result_{(victory)}$=-24±4 A.U., z=-6.87, P<0.001]. Temporal pressure did not show weapon (P=0.08), sex (P=0.50), bout (P=0.53) or result (P=0.31) main effects [I=52±4 A.U., z=14.26, P<0.001]. The effect of the bout's result (victory or defeat) is presented in Appendix E using the estimated density function for the $NASA_{TLX}$ scores. We observed a generalizable high mental and physical demand and considerable effort in the task.

****Figure 4 about here****

4. DISCUSSION

In the present study, we aimed to evaluate fatigue induced by a simulated competition in fencing. The strengths and novelties of our study were the inclusion of elite athletes for all three fencing weapons and the consideration of objective and subjective manifestations of fatigue.

The main results reveal: (i) a meaningful impairment in knee extensor neuromuscular function highlighted with an impaired rate of torque development after the simulated competition; (ii) an increase in perceived effort, fatigue, and mental demand across the competition. Results also indicate that (iii) fencing is characterized by an important effort required to win a bout. These results support our hypothesis, demonstrating that a simulated competition has a limited impact on the knee extensors' neuromuscular function, but induces an increase in the perception of fatigue associated with an important perceived mental demand that increases along the competition.

4.1 Characteristics of a fencing bout

Fencers perceived high levels of effort, mental and physical demands. Following a single bout, the reported high levels of effort and physical demand were not associated with fatigability of the knee extensor. The important physical demand is likely due to the rapid and successive recruitment of motor units and motor control demand of the task needed to attack or defend. However, the short duration of assaults and the recovery in-between was likely sufficient to avoid fatigability of the knee extensors in elite fencers. Furthermore, as effort refers to the engagement of physical and cognitive resources to perform in a task,[13–15] the high level of effort reported by the fencers is likely due to the concomitant high level of physical and cognitive demands of fencing. To the physical demand previously described, it is possible to add the high mental demand associated with continuous attention to the movement of the opponent, as well as the rapid and continuous information processing needed to take accurate decisions.

Regarding our data on the neuromuscular function, after a single fencing bout we observed an increase in CMJ height and a concomitant decrease in maximal torque and voluntary activation. However, regarding CMJ height and maximal torque, the changes were inferior to the standard errors estimated by the model, suggesting that these changes might not be meaningful. Indeed, by plotting the percentage changes from *pre* to *post* bouts (see Figure 4), all the points clustered around zero. It is important to note that maximal torque was 12% lower at baseline the day of the competition compared to the familiarization (Appendix B). Potentiated doublet and rate of torque development were similar between days. Therefore, we cannot rule out the possible underestimation of maximal strength loss after the first bout in the present study. It is likely that, on the day of the simulated competition, athletes were prioritizing their engagement in the fencing bouts rather than in the maximal voluntary contraction, despite the instructions and encouragements provided by the researchers. The significant drop in voluntary activation observed was probably dragged by four participants who showed a steep decrease. Furthermore, the low reliability and agreement analyses for maximal torque and voluntary activation presented in Appendix B suggest that caution must be taken when interpreting these changes.

Regarding the possible increase in CMJ, similar results has been previously documented in fencing.[4] CMJ showed an excellent reliability and agreement, and this increase might be due to the post-activation performance enhancement of the first bout that counterbalanced the possible fatigue-related impairments.[25] It is, therefore, possible that fencers' warm-up routine could be improved to take advantage of the post-activation performance enhancement phenomenon. Future studies should explore the potential benefits of various warm-up routines inducing post-activation performance enhancement on fencing performance.

4.2 Evolution of fatigue during a fencing simulated competition

The results of our study suggest that, to cope with the competition-related demands and maintain optimal performance, or counterbalance the effect of increasing fatigue across the bouts and the competition, fencers needed to increase the allocation of mental rather than physical resources to the task. To support this statement, limited impairments in neuromuscular function were observed, *i.e.*, the rate of force development was the sole neuromuscular variable impaired by the simulated competition.

4.2.1 Fatigability of the knee extensors' neuromuscular function

During the simulated competition, we observed a slight decrease in maximal torque and rate of torque development (-1.6% and -2.4% per bout, respectively), which was not accompanied by changes in potentiated doublet or voluntary activation. Furthermore, CMJ height did not decrease. This was not surprising as some authors previously suggested that CMJ height might not be a sensitive index of fatigue in fencing.[4] Although the decreased maximal torque of ~17.8 N·m for the simulated competition might be considered as limited, the decreased rate of torque development was ~100 $N \cdot m.s^{-1}$ (~10%). This loss in rate of torque development could be relevant, considering that recently it has been reported a loss of ~15% following an intense downhill running session using similar methods.[26] As fencing involves rapid and intense contractions during the bouts, the rate of torque development could be a more appropriate measure than maximal torque to detect alteration in neuromuscular function induced by fencing.[12] The decrease in the rate of torque development would indicate an impairment in the ability to rapidly develop muscle force along a competition day. This aspect is of interest to strength and conditioning coaches and shows that fencing causes some impairments in the knee extensors' neuromuscular function that could not be detected using CMJs. Consequently, we suggest that strength and conditioning coaches should focus predominantly on the ability to rapidly produce force as a marker of fatigability in the context of fencing.

4.2.2 Perceptions of fatigue, effort and workload

During the simulated competition, fencers began each successive bout with a higher level of fatigue compared to the previous one. Also, effort slightly increased during the competition, with similar kinetic across bouts. This is the first study that studied both fatigue and effort in fencing. Previously, only effort was measured, and solely at the end of the bouts and not during. No differences between post-bouts were found during the direct elimination phase of the competition.[4,10] Indeed, the effort item on the $NASA_{TLX}$

(administered only after each bout) showed in no significant time effect. As effort differs from fatigue and other exercise-related perceptions [for more information see[14] and[15]], it is likely that, by rating separately fatigue and effort, as well as acquiring data between and within bouts, we were able to detect small changes in these two parameters. Differences with the literature could also be due to the greater sample size in this study, leading to a higher statistical power [29 *vs.* 9,[4] and 8.[10]]. Importantly, the mental demand increased during the competition, and a higher mental demand was perceived in case of victory. The observed increase in fatigue, effort and mental demand during the competition suggests that fatigue induced by a fencing competition could have a strong cognitive component, traditionally referred to as cognitive or mental fatigue.[5] As changes in these perceptions are subjective manifestations of cognitive fatigue, future studies should quantify objective manifestations such as changes in cognitive performance – *i.e.*, cognitive fatigability – to further extend this observation.

4.3 Weapon- and sex-related differences

We did not observe any effect of the fencing weapon on the variables studied. Despite this result could be underpowered due to the low number of participants per weapon, it also indicates that no evident pattern emerged. Regarding sex-related differences, except for the neuromuscular variables at baseline, we did not observe any sex-related differences in fatigability, effort, fatigue, and workload. This suggests that the impact of the simulated competition on both neuromuscular and perceptual/subjective variables was similar between men and women competing against peers matched for sex and fencing level. This does not exclude a difference in the absolute intensity of the task across groups. Indeed, the lack of an objective external workload (e.g., distance covered during the assaults) held us to perform a standardized comparison across sexes.

4.4 Limitations

The main limitation of the present study was that not all athletes during the simulated competition fulfilled the instructions of performing maximal contractions during neuromuscular testing or did not tolerate the associated electrical stimulation, reducing the maximal torque exerted in case of stimulations. Contrary to maximal torque and voluntary activation that are dependent on the voluntary engagement of the fencers, the potentiated doublet obtained at rest, in the absence of voluntary engagement of the fencers, was similar between days. However, we are confident that our analysis addressed this limitation: although the 70% threshold was arbitrary, participants showing values >70% of voluntary activation were clustered when plotted against the other indices of fatigability such as maximal torque, rate of torque development or potentiated doublet (data presented in Appendix C). Another limitation was the imbalanced number of men and women and across weapons, limiting our analysis when evaluating sex and weapon differences.

4.5 Conclusions and Future Perspectives

In conclusion, our results suggest that elite fencers cope well with the physical demand of a competition. However, the increased in the perceptions of fatigue, effort, and mental demand overtime suggest the need to increase the mental resources mobilized across bouts, to cope with the mental demand of a competition. The present study offers future perspectives. It would be of interest to reproduce this protocol with different levels of fencers to test the effects of fencing expertise on fatigue. Our results also imply that future interventions aiming to improve fencing performance should consider training the mental skills of fencers, to help them cope with the important mental demand of the competition. Furthermore, as we observed that frustration was greater, and perceived performance lower, in case of defeat, interventions aiming to manage stress and frustration following a lost bout or *assault,* could also be of great interest to coaches and fencers.

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We would like to thank Maëlle Bracco, Pierre Bagot and Maël Goisbault for their help during the simulated competitions. We also thank the Federation Francaise d'Escrime, the Institut National du Sport, de l'Expertise et de la Performance and the CPF Nevers for their logistic support and help for the simulated competitions. We sincerely thank all the coaches and the athletes for their participation.

Competing interests

The authors declare that they have no competing interests.

Data statement

The research data will be kept confidential until the end of the Olympic Games in Paris 2024.

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References

1. Roi GS, Bianchedi D. The Science of Fencing: Implications for Performance and Injury Prevention. *Sports Med*. 2008;38(6):465-481. doi:10.2165/00007256-200838060-00003

2. Bottoms L, Sinclair J, Rome P, Gregory K, Price M. Development of a lab based epee fencing protocol. *Int J Perform Anal Sport*. 2013;13(1):11-22. doi:10.1080/24748668.2013.11868628

3. Aquili A, Tancredi V, Triossi T, et al. Performance Analysis in Saber. *J Strength Cond Res*. 2013;27(3):624-630. doi:10.1519/JSC.0b013e318257803f

4. Turner AN, Kilduff LP, Marshall GJG, et al. Competition Intensity and Fatigue in Elite Fencing. *J Strength Cond Res*. 2017;31(11):3128-3136. doi:10.1519/JSC.0000000000001758

5. Pageaux B, Lepers R. Fatigue induced by physical and mental exertion increases perception of effort and impairs subsequent endurance performance. *Front Physiol*. 2016;7(NOV). doi:10.3389/fphys.2016.00587

6. Dong L, Pageaux B, Romeas T, Berryman N. The effects of fatigue on perceptual-cognitive performance among open-skill sport athletes: A scoping review. *Int Rev Sport Exerc Psychol*. Published online November 6, 2022:1-52. doi:10.1080/1750984X.2022.2135126

7. Schmit C, Brisswalter J. Executive functioning during prolonged exercise: a fatigue-based neurocognitive perspective. *Int Rev Sport Exerc Psychol*. 2020;13(1):21-39. doi:10.1080/1750984X.2018.1483527

8. Skau S, Sundberg K, Kuhn HG. A Proposal for a Unifying Set of Definitions of Fatigue. *Front Psychol*. 2021;12(October). doi:10.3389/fpsyg.2021.739764

9. Turner A, James N, Dimitriou L, et al. Determinants of olympic fencing performance and implications for strength and conditioning training. *J Strength Cond Res*. 2014;28(10):3001-3011. doi:10.1519/JSC.0000000000000478

10. Oates LW, Campbell IG, Iglesias X, Price MJ, Muniz-Pumares D, Bottoms LM. The physiological demands of elite epée fencers during competition. *Int J Perform Anal Sport*. 2019;19(1):76-89. doi:10.1080/24748668.2018.1563858

11. Turner AN, Marshall G, Noto A, Chavda S, Atlay N, Kirby D. Staying out of range: Increasing attacking distance in fencing. *Int J Sports Physiol Perform*. 2017;12(10):1319-1323. doi:10.1123/ijspp.2016-0680

12. D'Emanuele S, Maffiuletti NA, Tarperi C, Rainoldi A, Schena F, Boccia G. Rate of Force Development as an Indicator of Neuromuscular Fatigue: A Scoping Review. *Front Hum Neurosci*. 2021;15(July):1-11. doi:10.3389/fnhum.2021.701916

13. Preston J, Wegner D. Elbow grease: The experience of effort in action. In: *Morsella E, Bargh JA, Gollwitzer PM Oxford Handbook of Human Action.* Oxford University Press; 2009:469-486.

14. Pageaux B. Perception of effort in Exercise Science: Definition, measurement and perspectives. *Eur J Sport Sci*. 2016;16(8):885-894. doi:10.1080/17461391.2016.1188992

15. Bergevin M, Steele J, Payen de la Garanderie M, et al. Pharmacological Blockade of Muscle Afferents and Perception of Effort: A Systematic Review with Meta-analysis. *Sports Med*. Published online November 1, 2022. doi:10.1007/s40279-022-01762-4

16. Sorel A, Plantard P, Bideau N, Pontonnier C. Studying fencing lunge accuracy and response time in uncertain conditions with an innovative simulator. *PLoS ONE*. 2019;14(7):1-17. doi:10.1371/journal.pone.0218959

17. Maffiuletti NA, Aagaard P, Blazevich AJ, Folland J, Tillin N, Duchateau J. Rate of force development: physiological and methodological considerations. *Eur J Appl Physiol*. 2016;116(6):1091-1116. doi:10.1007/s00421-016-3346-6

18. Hart SG, Staveland LE. Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. In: *Advances in Psychology*. Vol 52. Elsevier; 1988:139-183. doi:10.1016/S0166-4115(08)62386-9

19. Rubio S, Diaz E, Martin J, Puente JM. Evaluation of Subjective Mental Workload: A Comparison of SWAT, NASA-TLX, and Workload Profile Methods. *Appl Psychol*. 2004;53(1):61-86. doi:10.1111/j.1464-0597.2004.00161.x

20. R Core Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. *Httpwww R-Proj Org*. Published online 2013.

21. Bates D. lme4: Linear mixed-effects models using S4 classes. R package version 0.999375-37. *Httpwww R-Proj Org*. Published online 2010.

22. Magnusson A, Skaug H, Nielsen A, et al. glmmTMB: generalized linear mixed models using template model builder. *R Package Version 01*. 2017;3.

23. Kuznetsova A, Brockhoff PB, Christensen RHB. Package ‘lmertest.’ *R Package Version*. 2015;2(0):734.

24. Lüdecke D, Aust F, Crawley S, Ben-Shachar M. Package ‘ggeffects.’ *Create Tidy Data Fram Marg Eff “ggplot” Model Outputs*. 2020;23.

25. Blazevich AJ, Babault N. Post-activation Potentiation Versus Post-activation Performance Enhancement in Humans: Historical Perspective, Underlying Mechanisms, and Current Issues. *Front Physiol Wwwfrontiersinorg*. 2019;10(1359). doi:10.3389/fphys.2019.01359

26. Varesco G, Coratella G, Rozand V, et al. Downhill running affects the late but not the early phase of the rate of force development. *Eur J Appl Physiol*. Published online 2022:11. doi:doi.org/10.1007/s00421-022-04990-8

Tables caption

Table 1. *Data are presented as mean ± SD unless otherwise specified. For voluntary activation, data were available for 14 participants (2 epee men, 3 epee women, 3 saber men, 2 saber women, and 4 foil men). CMJ = countermovement jump; IQR = interquartile range. The ranking represents the world ranking position of athletes at the moment of the study.*

Figures caption

Figure 1. *Effects of a single fencing bout on the knee extensors' neuromuscular function in men (blue) and women (red), presented as a percentage difference from pre (Panel A). Vertical lines represent the mean ± SD. For voluntary activation, values at post were subtracted from values at pre and presented as median ± IQR (Panel B). CMJ = countermovement jump.*

Figure 2. *Evolution of the knee extensors' neuromuscular function post-bout in men (blue) and women (red) across a fencing simulated competition. Vertical lines represent the mean ± SD. For voluntary activation, vertical lines represent the median ± IQR. CMJ= countermovement jump; *significant sex-related difference ($P < 0.05$). $^{\#}$significant effect of bout ($P < 0.05$). The dotted line indicates the estimates from the mixed model (bout effect).*

Figure 3. *Evolution of the perceived fatigue (Panel A) and perceived effort (Panel B) across a fencing simulated competition. Both perceptions were reported with a visual analog scale Data are presented as mean ± SD. *significant effect of time ($P < 0.05$). $^{\#}$significant effect of bout ($P < 0.05$). $^{\$}$significant bout × time interaction ($P < 0.05$). The dotted line indicates the estimates from the mixed model. For panel A, only the effect of time was presented for clarity. In panel B, only the bout main effect is presented.*

Figure 4. *Evolution of the perceived mental demand measured with the NASA TLX scale. Data are presented as median ± interquartile range. The dotted line indicates the estimates from the mixed model.*

Tables

Table 1. *Participants' characteristics were divided by team measured during the familiarization session.*

	Epee		**Saber**		**Foil**
	Men (n=6)	*Women (n=6)*	*Men (n=6)*	*Women (n=5)*	*Men (n=6)*
Age (yr)	29 ± 5	27 ± 4	23 ± 2	23 ± 2	23 ± 2
Height (cm)	184 ± 8	178 ± 8	181 ± 4	177 ± 4	187 ± 6
Body mass (kg)	82 ± 11	66 ± 3	77 ± 8	68 ± 6	81 ± 6
Ranking (median and range)	12 [4, 115]	31 [4, 88]	111 [53, 311]	43 [25, 281]	56 [37, 104]
CMJ (cm)	43 ± 8	30 ± 3	41 ± 5	34 ± 5	39 ± 4
Maximal torque (N·m)	330 ± 64	318 ± 63	302 ± 54	271 ± 62	339 ± 75
Rate of force development (N·m·s^{-1})	1222 ± 99	1021 ± 202	1050 ± 288	1103 ± 276	1168 ± 161
Potentiated doublet (N·m)	128 ± 43	104 ± 22	120 ± 24	135 ± 36	162 ± 25
Voluntary activation (%) (median ± IQR)	90 ± 2	93 ± 1	83 ± 9	91 ± 1	92 ± 6

Figures

Figure 1.

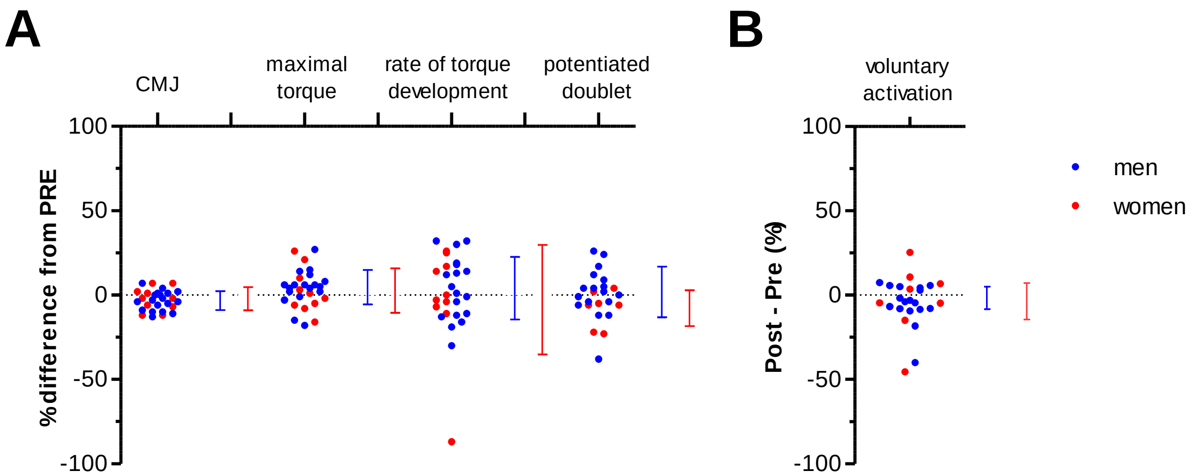
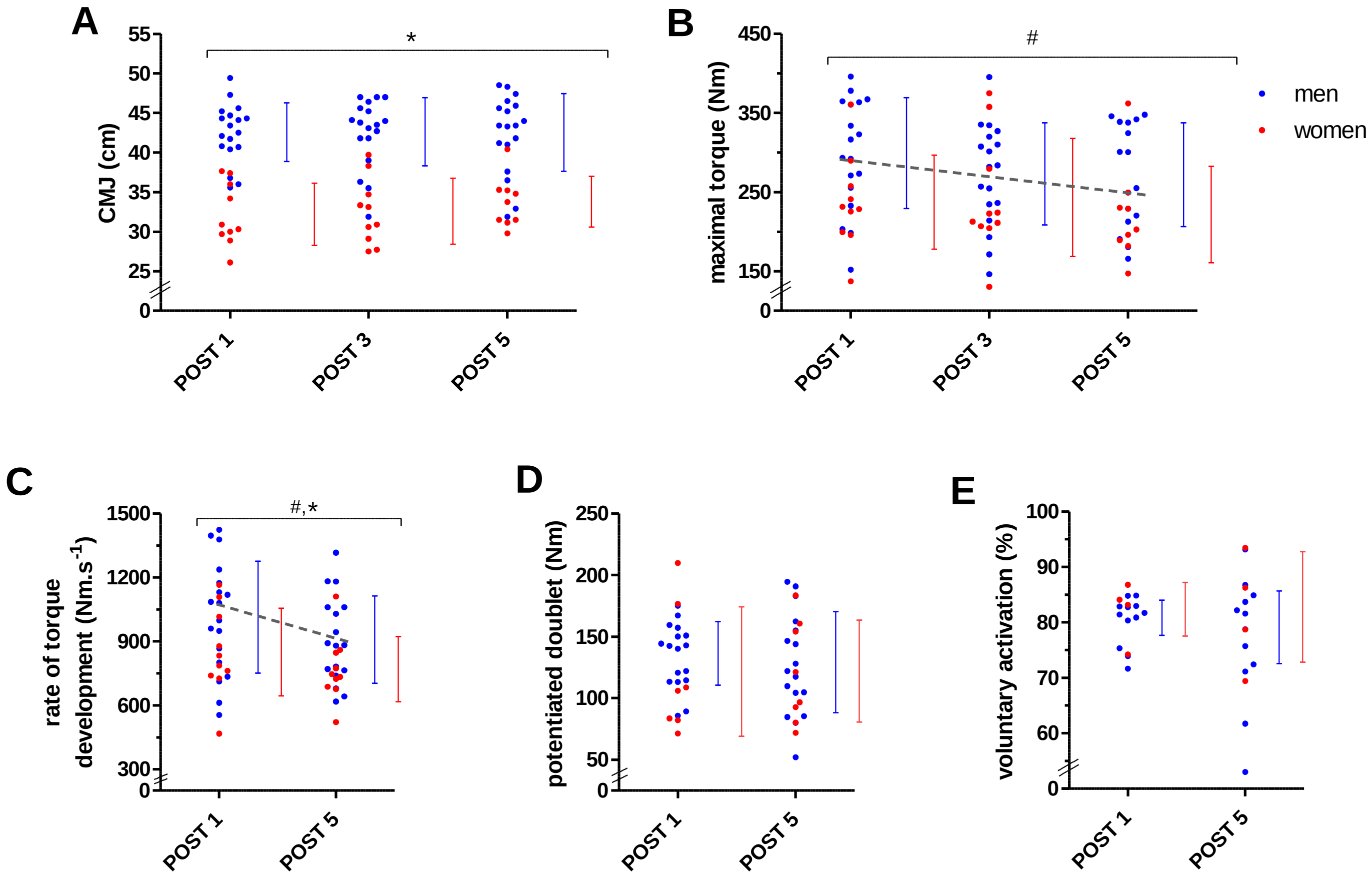
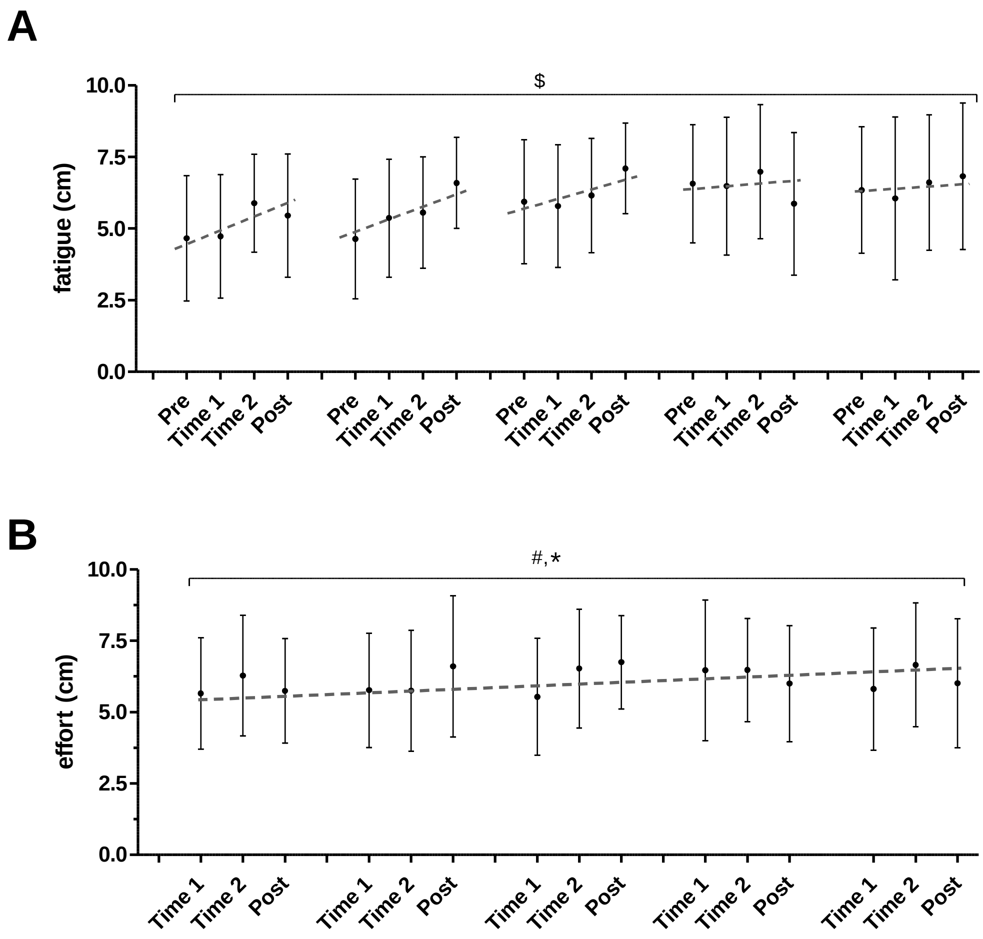


Figure 2.



545 **Figure 3**



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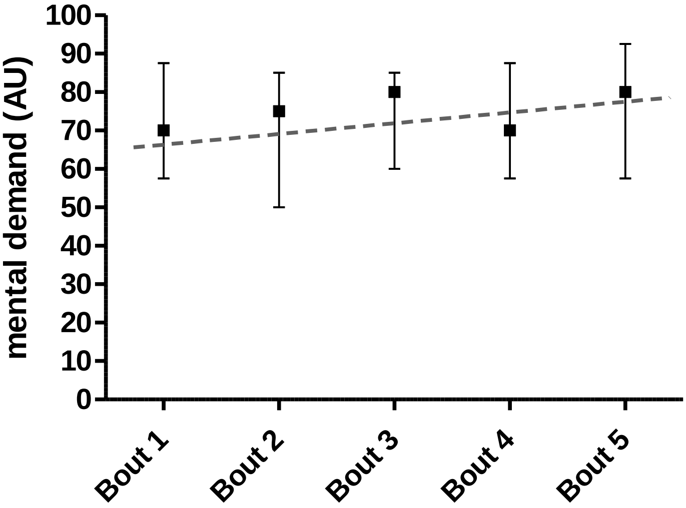
547 **Figure 4.**



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APPENDIX A

Detailed methodology for the assessment of the neuromuscular function

A.1 Countermovement jumps height

For each measure of the CMJ, participants performed a set of 3 jumps (separated by ~10 s) to assess jump height. CMJs were performed with hands on the hips. The highest value recorded for each set was retained for further analyses.

A.2 Maximal torque, voluntary activation and contractile function

For all maximal contractions, participants were instructed to extend the knee "as hard as possible". During the contraction, the twitch interpolation technique was used to measure the voluntary activation and contractile function (except after the third match). The interpolated twitch technique included a first supramaximal 100-Hz doublet that was superimposed when torque reached a plateau (superimposed doublet), and a second doublet (potentiated doublet) that was delivered at rest two seconds after the maximal contraction. Stimulation intensity was determined at rest by increasing the stimulation intensity by 10 mA starting from 30 mA until the twitch torque response plateaued. The 130% of the intensity producing the greatest peak torque response was used to ensure supramaximal twitch response (average stimulation intensity = 181±28 mA). For the analysis, the maximal torque achieved during the maximal contraction was determined as the highest peak torque recorded before the superimposed doublet. Voluntary activation was calculated using the formula of Strojnik and Komi:[1]

$$Voluntary\ activation\ (\%) = 100 - \left[\frac{Superimposed\ doublet\ \times \left(\frac{Torque_{pre\ stim}}{Maximal\ Torque}\right) \times 100}{Potentiated\ doublet}\right]$$

where $\mathrm{Torque}_{\mathrm{pre\ stim}}$ is the voluntary torque level just before the stimulation. To minimize measurement error, all participants that showed <70% of voluntary activation at baseline were discarded.[2] Changes in potentiated doublet were used as an index of changes in contractile function.

A.3 Rate of torque development

Participants were instructed to extend the knee "as fast as possible" for all rapid contractions. The contraction was repeated in case of countermovement or pre-tension, determined by a torque ≤2 N·m and ≥2 N·m right before the rapid contraction onset, respectively. The rapid contractions were also repeated if the force level was <70% of the maximal torque measured during the maximal isometric contraction that preceded the series of rapid contractions.[3,4] Visual feedback of torque responses was provided on a computer monitor. The analysis for the rate of torque development was performed as previously described.[3,4] Briefly, the best five rapid contractions were determined based on the peak rate of torque development, i.e. the steepest 10-ms segment on the force-time curve. These five contractions were averaged for further analysis, while the others were discarded. For each contraction, a nonlinear least-square model was fitted on the first 200 ms torque data from the onset. The slope coefficient calculated from the model was used to quantify the rate of torque development, indicating the rapid force production ability. The onset was automatically defined as the point at which force raised over the average resting baseline by 2 N·m. This onset was also checked visually by an experienced investigator.

A.4 Experimental apparatus

Participants sat upright on an isometric chair with the knee and the torque meter rotational axes aligned (ARS dynamometry, SP2, Ltd., Ljubljana, Slovenia), the hip and the knee positioned at 90° and 120° extension, respectively (180°=full extension), and the leg attached just above to the malleoli using a non-compliant strap. Hips and chest were securely strapped to maintain the position during contractions. The position was recorded and reproduced for each athlete between days. Torque data were sampled at 2 kHz using a PowerLab system (16/30-ML880/P, ADInstruments, Bella Vista, Australia), and transmitted to the computer through Labchart 8 interface (ADInstruments). For the electrical stimulations, two self-adhesive surface electrodes (80×130 mm, Stimex electrodes, Pierenkemper, Wetzlar, Germany) were placed over the rectus femoris and over the vastus medialis portions to allow the stimulation of the quadriceps femoris muscle.[5] Electrical stimuli of 2-ms duration and 400 V output voltage were delivered via a constant-current stimulator (DS7A; Digitimer, Welwyn Garden City, Hertfordshire, UK), similarly to what was previously reported to improve accuracy in the measured outcomes.[5] The position of each participant on the chair was registered and reproduced between neuromuscular function evaluations. The electrodes position was marked on the skin with a permanent marker to be kept consistent between tests. The performance during CMJs, i.e. jump height, was measured using an optoelectronic system (OptojumpNEXT, Microgate, Bolzano, Italy) and exported using its native software (Optojump v.1.12.23, Microgate). The knee-extensors neuromuscular data were analyzed offline using Labchart 8 and exported to excel (Excel v.2206, Microsoft, Redmond, Washington) and R-studio (v. 2022.07.1.554, Boston, MA) to perform calculations and statistical analysis.

Detailed methodology for the assessment of the subjective variables

A.5 Perception of Fatigue and Effort

The question for the visual analog scale for fatigue was ‘How fatigued are you right now?’, and the anchors were ‘Not fatigued at all’ and ‘extremely fatigued’. The question of the visual analog scale for effort was ‘How much effort did you put into performing in the round you just completed?’, and the anchors were ‘no effort’ and ‘maximal effort’. Data from the visual analog scales were manually measured (from 0 to 10 cm).

A.6 Perceived workload

Administering the NASA_{TLX} questionnaire involves participants rating each of the six dimensions (Mental demand, Physical demand, Temporal demand, Effort, Performance and Frustration level) on scales from "Low" to "High", or from "Good" to "Poor" in the case of Performance.[6] The raw score for each of the six items could be multiplied by the weight obtained from an additional questionnaire to generate an overall workload score. However, being highly time-consuming, this procedure has been skipped across several studies. [6] Because participants needed to report to the neuromuscular testing stand as soon as possible once the bout was over, we administered only the rating questionnaire. Data were obtained for each dimension of the NASA_{TLX} expressed as a scale from 0 to 100, with each one of the 20 squares corresponding to 5-points. For clarity, data for the item "performance" were reversed, so "0" corresponded to the worst performance possible and "100" to a perfect performance.

Detailed methodology for statistics

A.7 Statistical analysis: model fitting and assumptions

Given the dependence of the data for the participants, a random intercept for participants was built into each model. The empirical test of the model assumptions was performed via model residuals graphical analysis of the Q-Q plots, that allowed also the detection of eventual outliers. Shapiro-Wilk test was used to ensure that the assumption of normality was respected for the residuals and random effects. Simulated residuals [DHARMa package[7]] were used when adopting glmmTMB. The build models were reduced when no main effect of time, weapon, sex, or result was observed, accordingly to the Occam razor principle, and compared using Akaike Information Criteria (AIC). Day-by-day reliability and agreement were evaluated for CMJ, maximal torque, rate of torque development, voluntary activation and potentiated doublet (familiarization session data vs. pre-competition data of the testing session; procedures and results are available in Appendix B). Finally, to evaluate if maximal torque and rate of torque development were linked to voluntary activation, these variables were modelled in the function of all voluntary activation data obtained (i.e. not filtered for values at rest >70%; detailed analysis and results presented in Appendix C).

References Appendix A

1. Strojnik V, Komi PV. Neuromuscular fatigue after maximal stretch-shortening cycle exercise. *J Appl Physiol*. 1998;84(1):344-350. doi:10.1152/jappl.1998.84.1.344

2. Place N, Maffiuletti NA, Martin A, Lepers R. Assessment of the reliability of central and peripheral fatigue after sustained maximal voluntary contraction of the quadriceps muscle. *Muscle Nerve*. 2007;35(4):486-495. doi:10.1002/mus.20714

3. Varesco G, Espeit L, Feasson L, Lapole T, Rozand V. Rate of force development and rapid muscle activation characteristics of knee extensors in very old men. *Exp Gerontol*. 2019;124(June):110640. doi:10.1016/j.exger.2019.110640

4. Varesco G, Coratella G, Rozand V, et al. Downhill running affects the late but not the early phase of the rate of force development. *Eur J Appl Physiol*. Published online 2022:11. doi:doi.org/10.1007/s00421-022-04990-8

5. Zarkou A, Stackhouse S, Binder-Macleod SA, Lee SCK. Comparison of techniques to determine human skeletal muscle voluntary activation. *J Electromyogr Kinesiol*. 2017;36:8-15. doi:10.1016/j.jelekin.2017.05.011

6. Hart SG. Nasa-Task Load Index (NASA_TLX); 20 years later. *Proc Hum Factors Ergon Soc Annu Meet.* 2006;50(6):5. doi:10.1177/154193120605000909

7. Hartig F. DHARMa: residual diagnostics for hierarchical (multi-level/mixed) regression models. R package v. 0.2. 0. *httpwww CRAN R-Proj Org*. Published online 2018.

APPENDIX B

Reliability analysis and results

Day-by-day reliability and agreement were evaluated for CMJ, maximal torque, rate of torque development, voluntary activation, and potentiated doublet (familiarization session data vs. pre-competition data of the testing session) using intra-class correlation coefficients [ICCs (A,1); Two-way mixed model[1]; irr package[2]] and coefficients of variation (CVs), respectively, both presented with 95% confidence intervals (95% CI). Based on the ICC estimate, values between 0 and 0.50 were considered poor, 0.50–0.75 Moderate, 0.75–0.90 good, and >0.90 excellent.[1] As a rule of thumb, CVs were considered high and low, respectively, for values greater and lower than 10%.

Agreement and reliability for CMJ were high and excellent, respectively [CV = 3% (2%; 4%); ICCA,1 = 0.96 (0.93; 0.98);], being not different between days (P=0.94). Maximal torque was different across days (P=0.02), being greater during the familiarization session than the day of the bout at baseline (313 ± 64 N·m vs. 275 ± 61 N·m), consequently, the agreement was on average low [CV = 11% (8%; 14%)] and reliability moderate [ICCA,1 = 0.68 (0.07; 0.88)]. The rate of torque development was not different between days (P=0.05), with low agreement [CV = 15% (10%, 20%)] and moderate reliability [ICCA,1 = 0.50 (0.14; 0.73)]. Agreement and reliability for potentiated doublet were high and good, respectively [CV = 9% (5%; 12%); ICCA,1 = 0.83 (0.66; 0.92);], being not different between days (P=0.88). Voluntary activation was different across days (91 ± 5% vs. 84 ± 6%; P=0.008), the agreement was high [CV = 6% (3%, 9%)] and reliability was poor [ICCA,1 = 0.05 (0; 0.45)].

References for Appendix B

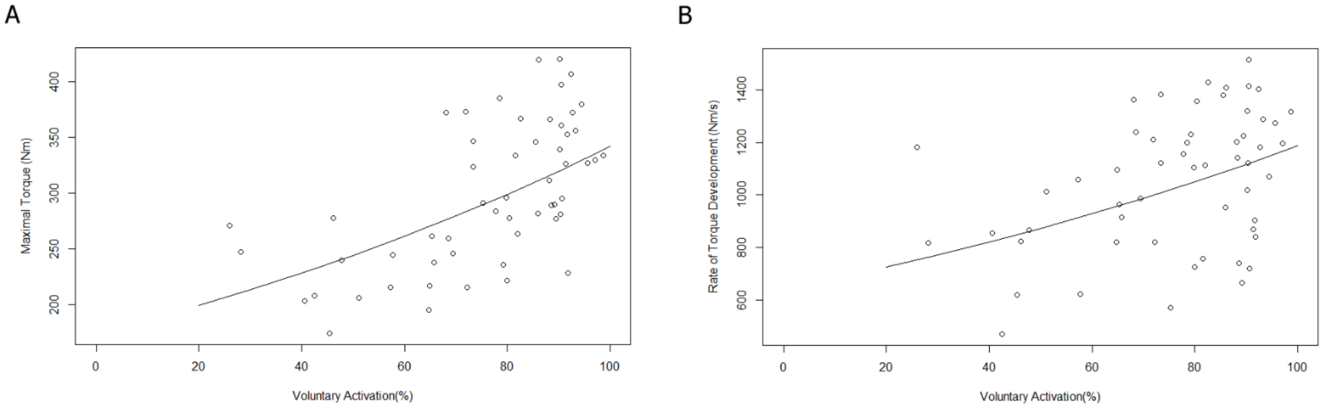
1. Koo TK, Li MY. A Guideline of Selecting and Reporting Intraclass Correlation Coefficients for Reliability Research. J Chiropr Med. 2016;15(2):155-163. doi:10.1016/j.jcm.2016.02.012

2. Gamer M, Lemon J, Fellows I, Singh P. irr: Various coefficients of interrater reliability and agreement [Computer software]. Httpwww CRAN R-Proj Org - package Irr. Published online 2012.

APPENDIX C

Association between maximal torque, rate of torque development and voluntary activation

To evaluate if maximal torque and rate of torque development were linked to low voluntary activation, maximal torque and rate of torque development obtained were modelled in the function of all voluntary activation data obtained (*i.e.* not filtered for values at rest >70%). We found a significant exponential function for both maximal torque ($P<0.001$) and rate of torque development (all $P=0.002$), and a Pearson'R coefficients (obtained on log-transformed data) of 0.57 ($t_{(0,53)} = 5.1$, $P < 0.001$; strong correlation) and 0.37 ($t_{(0,53)} = 2.9$, $P = 0.006$; moderate correlation) respectively (figure below). Additionally, potentiated doublet and voluntary activation were not correlated ($R = 0.09$; $t_{(0,53)} = 0.6$, $P = 0.52$). This would indicate that low reliability in maximal torque and rate of torque development (see Appendix A) was associated with low voluntary activation in participants, which could be either due to measurement error such as submaximal volitional effort during contractions (in the case of values <70%, for example) or to a real deficit in voluntary activation.



APPENDIX D

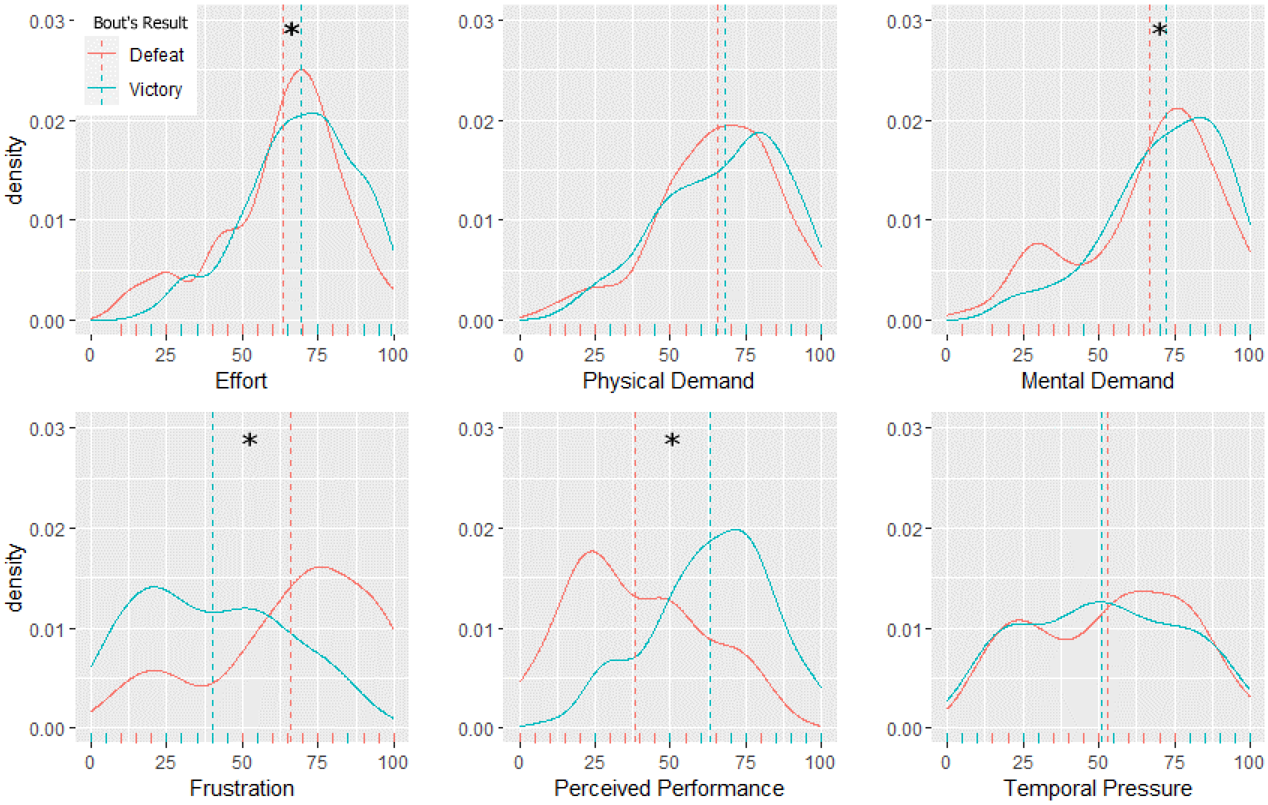
Simulated competition: number of athletes that disputed each round.

TOTAL = 29 athletes	**Bout 1**			**Bout 2**			**Bout3**			**Bout 4***			**Bout 5[#]**		
Round	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**
Athletes (n)	29	29	15	29	29	13	29	29	15	28	26	11	25	22	7

*Notes:*one athlete did not dispute the 4th bout due to pain. [#]four athletes did not dispute the 5th bout due to pain.*

APPENDIX E

Effect of victory or defeat on the NASA$_{TLX}$ dimensions



The estimated density function for each dimension of the NASA$_{TLX}$ (all bouts pulled together) separated by the result of the match. Dotted lines represent the mean.=difference in density distribution between victory and defeat ($P < 0.05$).*