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# Fatigue in elite fencing: Effects of a simulated competition

Giorgio Varesco<sup>1</sup>  | Benjamin Pageaux<sup>2,3,4</sup>  | Thomas Cattagni<sup>1</sup>  |  
Aurélie Sarcher<sup>1</sup>  | Guillaume Martinent<sup>5</sup>  | Julie Doron<sup>1</sup>  | Marc Jubeau<sup>1</sup> 

<sup>1</sup>Nantes Université, Laboratory Movement – Interactions – Performance (MIP), UR4334, Nantes, France

<sup>2</sup>Université de Montréal, École de kinésiologie et des sciences de l'activité physique (EKSAP), Montréal, Canada

<sup>3</sup>Centre de recherche de l'Institut universitaire de gériatrie de Montréal (CRIUGM), Montréal, Canada

<sup>4</sup>Centre interdisciplinaire de recherche sur le cerveau et l'apprentissage (CIRCA), Montréal, Canada

<sup>5</sup>Université Claude Bernard Lyon 1, Univ Lyon, Laboratory on Vulnerabilities and Innovation in Sport (LVIS), EA 7428, Lyon, France

## Correspondence

Giorgio Varesco, Laboratoire MIP – Nantes Université, 3, rue du Recteur Schmitt Bât F0 – BP 92235, 44322 Nantes, France.  
Email: [giorgio.varesco@univ-nantes.fr](mailto:giorgio.varesco@univ-nantes.fr)

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## Abstract

The fatigue induced by fencing remains scarcely investigated. We aimed to investigate both objective (neuromuscular performance fatigability) and subjective (perceived fatigue, effort, and workload) manifestations of fatigue in elite fencers following a five-bout 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 with the NASA Task Load Index scale. 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 before each bout increased (12% per bout), with similar values observed at the end of all bouts (bout  $\times$  period interaction:  $p<0.001$ ). Perceived effort increased during the bouts (10% per period,  $p<0.001$ ) and during the competition (3% per bout,  $p=0.011$ ). Perceived mental demand increased during the competition (2% per bout,  $p=0.024$ ). These results suggest 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.

## KEYWORDS

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

## 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<sup>1</sup>]. Typically, an international competition of fencing includes preliminary rounds, or poules, and direct elimination bouts. It lasts more than 9 h for

the finalists, with a net match time of about 10% (i.e., 17–48 min in total), with 15 up to 180 min of rest between bouts.<sup>1</sup>

While the specific rules differ across weapons, the international competitions consist generally of four to six bouts of the poule rounds and ~5 direct elimination bouts. The poule bouts last 3 min, where the first athlete scoring 5 points or with the highest score at the end of the time wins. Once the poule rounds are completed,

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fencers are then seeded for the direct elimination bouts based on their performance in the poules. Direct elimination bouts are fenced to 15 touches where the first athlete scoring 15 points or with the highest score at the end of the time wins. For the epee and the foil, the bouts are divided into three periods, each one with a duration of 3 min, with 1 min breaks between periods. In case of a tie at the end of the third period, a 1-min sudden-death bout is used to determine the winner. For the saber, there are two periods divided by a 1-min break, which is allowed when either fencer reaches a score of eight. Bouts and periods are characterized by intense “assaults” followed by a resting time of similar or greater duration [epee: work to rest ratio = 9 s:8 s,<sup>2</sup> foil = 5 s:15 s,<sup>1</sup> saber = 3 s:15 s.<sup>3</sup>].

As other combat sports, fencing practice induces fatigue.<sup>4</sup> 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.<sup>5,6</sup> 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.<sup>6,7</sup> 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.<sup>8</sup> 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 direct elimination phases.<sup>2,9–11</sup> Limited evidence is available on the performance of the neuromuscular system.<sup>4</sup> 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.<sup>10,12</sup> A previous study evaluating countermovement jump (CMJ) height observed no change following a fencing competition.<sup>4</sup> 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.<sup>4</sup> 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.<sup>13</sup> 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,<sup>6</sup> namely the perception of effort.<sup>14–16</sup> 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,”<sup>2,4,11</sup> with stable ratings along a competition.<sup>4</sup> 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 and no fatigability observed during a fencing competition deserves further investigation. One possible explanation could be that fencing, being recognized as a highly technical and tactical discipline,<sup>1,2,17</sup> 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.<sup>4</sup> 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  $5 \pm 0.5$  days/week and for  $5 \pm 1$  h/day. The average time dedicated to technical training was  $3 \pm 1$  h/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 (no. 08042021).

## 2.2 | Study design

This study used a within-subject design with the participants tested on 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 bouts, known as “*Poule*.”<sup>2,11</sup> 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 10–20 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 an isometric dynamometer (ARS dynamometry, SP2, Ltd., Ljubljana, Slovenia), 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 starting 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 (with hands placed on the hips) 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.<sup>18</sup> 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. These tests were chosen based on their external consistency, simplicity of the measure in terms of equipment and execution, as well as known reliability.<sup>19–21</sup>

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 pilot testing, 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 S1.

## 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<sub>TLX</sub>) questionnaire for measuring the perceived workload of each bout.<sup>22,23</sup> The visual analog scale for perceived fatigue was administered immediately before, during the 1-min break between bouts, 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 periods, and the end of every bout of the simulated competition. The NASA<sub>TLX</sub> 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<sub>TLX</sub> also includes an item called "effort," that answers to the question "How hard did you have to work to accomplish your level of performance?"<sup>22</sup> Detailed information on the testing procedures and materials is available in Appendix S1.

## 2.5 | Statistical analysis

Statistical analyses were carried out in R statistical environment (V4.2.3, R Foundation for Statistical Computing, Vienna, Austria).<sup>24</sup> Information on model fitting and assumptions is presented in the Appendix S1. To evaluate the overtime changes of the variables (CMJ, maximal

torque, rate of torque development, voluntary activation, potentiated doublet, NASA<sub>TLX</sub> scores, and visual analog scales), linear mixed-effects models were fitted to the data using the restricted mean likelihood method in the lme4 package.<sup>25</sup> The glmmTMB package<sup>26</sup> was used assuming a beta distribution when data could not be modeled 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<sub>TLX</sub>). *p*-values were extracted from all *F*-tests using Satterthwaite's degrees of freedom method [lmerTest package<sup>27</sup>]. 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 and periods. Besides the time effect, we also evaluated the effect of weapon, sex, and bout's result (victory or defeat) 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  $\alpha=0.05$ .

## 3 | RESULTS

Participants' characteristics at baseline for each weapon 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 periods (detailed information is presented in Appendix S2).

### 3.1 | Fatigability of the neuromuscular system

#### 3.1.1 | Effect of a single bout

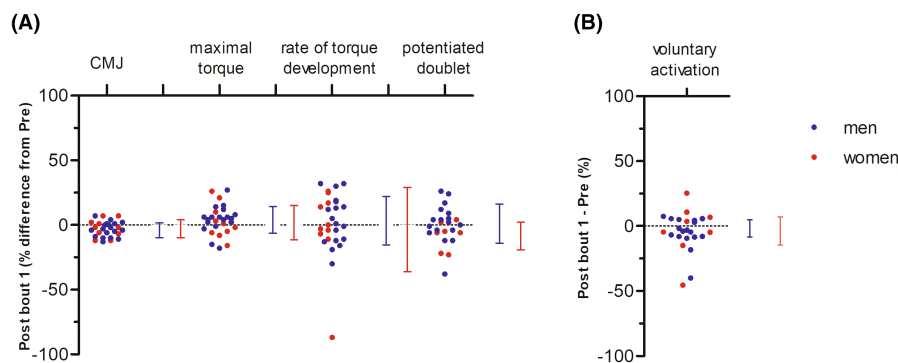
No significant main effects of weapon and bout results were found for the neuromuscular variables (all  $p>0.05$ ). Thus, those effects were removed from the models for the subsequent analyses. CMJ increased from *pre* to *post*-bout, however, this change was within the standard error of

**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 (years)	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 (Nm)	330 ± 64	318 ± 63	302 ± 54	271 ± 62	339 ± 75
Rate of force development (Nm s <sup>-1</sup> )	1222 ± 99	1021 ± 202	1050 ± 288	1103 ± 276	1168 ± 161
Potentiated doublet (Nm)	128 ± 43	104 ± 22	120 ± 24	135 ± 36	162 ± 25
Voluntary activation (%) (median ± IQR) <sup>a</sup>	90 ± 2	93 ± 1	83 ± 9	91 ± 1	92 ± 6

*Note:* Data are presented as mean ± SD unless otherwise specified. The ranking represents the world ranking position of athletes at the moment of the study. Abbreviations: CMJ, countermovement jump; IQR, interquartile range.

<sup>a</sup>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).



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

the measure. Men performed higher jumps heights than women [Intercept (I,  $\beta \pm SE$ ) = 41.4 ± 1 cm,  $t_{(1,29)} = 40.9$ ,  $p < 0.001$ ;  $bout_{(0,1)} = 1 \pm 0.4$  cm,  $t_{(1,27)} = 2.5$ ,  $p = 0.02$ ;  $sex_{(women)} = -10.2 \pm 1.6$  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 to 367 Nm, and the second (saber woman) reported a steep drop in maximal torque values (346–258 Nm). 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 [ $I = 307.7 \pm 16$  Nm,  $t_{(1,26)} = 19.2$ ,  $p < 0.001$ ;  $bout_{(0,1)} = -10.4 \pm 4.7$  Nm,  $t_{(1,25)} = -2.2$ ,  $p = 0.036$ ;  $sex_{(women)} = -57.7 \pm 26.1$  Nm,  $t_{(1,25)} = -2.2$ ,  $p = 0.037$ ]. For the rate of torque development, one outlier was identified (epee woman) showing a steep increase in the rate of torque development values (663–1166 Nm s<sup>-1</sup>). The rate of torque development did not change over time ( $p = 0.08$ ), with greater values for men compared to women [ $I = 1041.8 \pm 54.8$  Nm s<sup>-1</sup>,  $t_{(1,26)} = 19$ ,  $p < 0.001$ ;  $sex_{(women)} = -217.5 \pm 92$  Nm s<sup>-1</sup>,  $t_{(1,26)} = -2.4$ ,  $p = 0.026$ ]. The amplitude

of the potentiated doublet was unchanged after the bout ( $p = 0.87$ ) and was not different across sexes ( $p = 0.17$ ), with  $I = 130.6 \pm 7.2$  Nm ( $t_{(1,23)} = 18$ ;  $p < 0.001$ ). 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 [ $I = 84 \pm 2\%$ ,  $t_{(1,22)} = 44.6$ ,  $p < 0.001$ ;  $bout_{(0,1)} = -5 \pm 2\%$ ,  $t_{(1,14)} = -2.5$ ,  $p = 0.028$ ]. Percentage differences from *pre* to *post* are presented in Figure 1.

### 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

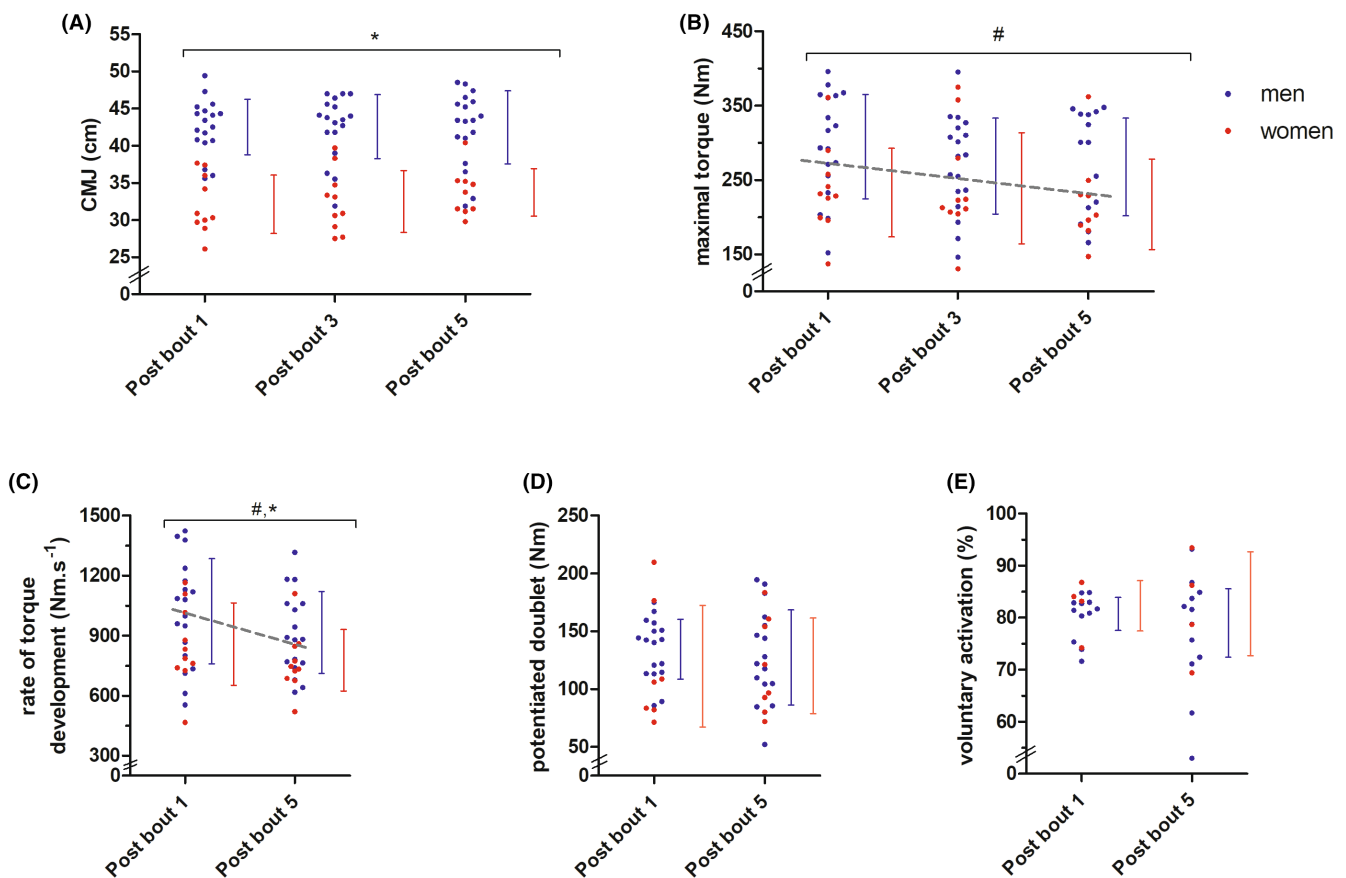
for men than women [ $I=42.5\pm 0.9$  cm,  $t_{(1,25)}=47.4$ ,  $p<0.001$ ;  $\text{sex}_{(\text{women})}=-9.7\pm 1.5$  cm,  $t_{(1,25)}=-6.6$ ,  $p<0.001$ , Figure 2A]. Maximal torque did not show a significant sex main effect ( $p=0.082$ ), but it decreased along the competition [ $I=274.1\pm 12.9$  Nm,  $t_{(1,31)}=21.2$ ,  $p<0.001$ ;  $\text{bout}_{(0,4)}=-4.4\pm 1.8$  Nm,  $t_{(1,52)}=-2.5$ ,  $p=0.017$ , 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 ( $555\text{Nm s}^{-1}$ ) to the end of the competition ( $882\text{Nm s}^{-1}$ ). The rate of torque development was greater for men than women and decreased along the competition [ $I=1033.6\pm 49.8\text{Nm s}^{-1}$ ,  $t_{(1,29)}=20.8$ ,  $p<0.001$ ;  $\text{bout}_{(0,4)}=-24.3\pm 6.0\text{Nm s}^{-1}$ ,  $t_{(1,25)}=-4.0$ ,  $p<0.001$ ;  $\text{se}_{\text{X}(\text{women})}=-176.9\pm 79.9\text{Nm s}^{-1}$ ,  $t_{(1,27)}=-2.2$ ,  $p=0.036$ , 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 Nm) to the end of the competition (52 Nm). 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 ( $p=0.37$ ), [ $I=129.3\pm 7.0\text{Nm s}^{-1}$ ,  $t_{(1,24)}=18.5$ ,  $p<0.001$ , 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 ( $p=0.53$ ) [ $I=79.9\pm 1.5\text{Nm s}^{-1}$ ,  $t_{(1,14)}=53$ ,  $p<0.001$ , Figure 2E].

## 3.2 | Subjective measurements

### 3.2.1 | Perception of fatigue and effort

No main effects of weapon and bout results were found for fatigue ( $p=0.60$  and  $0.25$ ) and effort ( $p=0.12$  and  $0.14$ ). For fatigue, no significant sex effect was found ( $p=0.57$ ). Significant  $\text{bout}\times\text{period}$  interaction was found for fatigue. As the competition progressed, *pre* bout fatigue increased, with



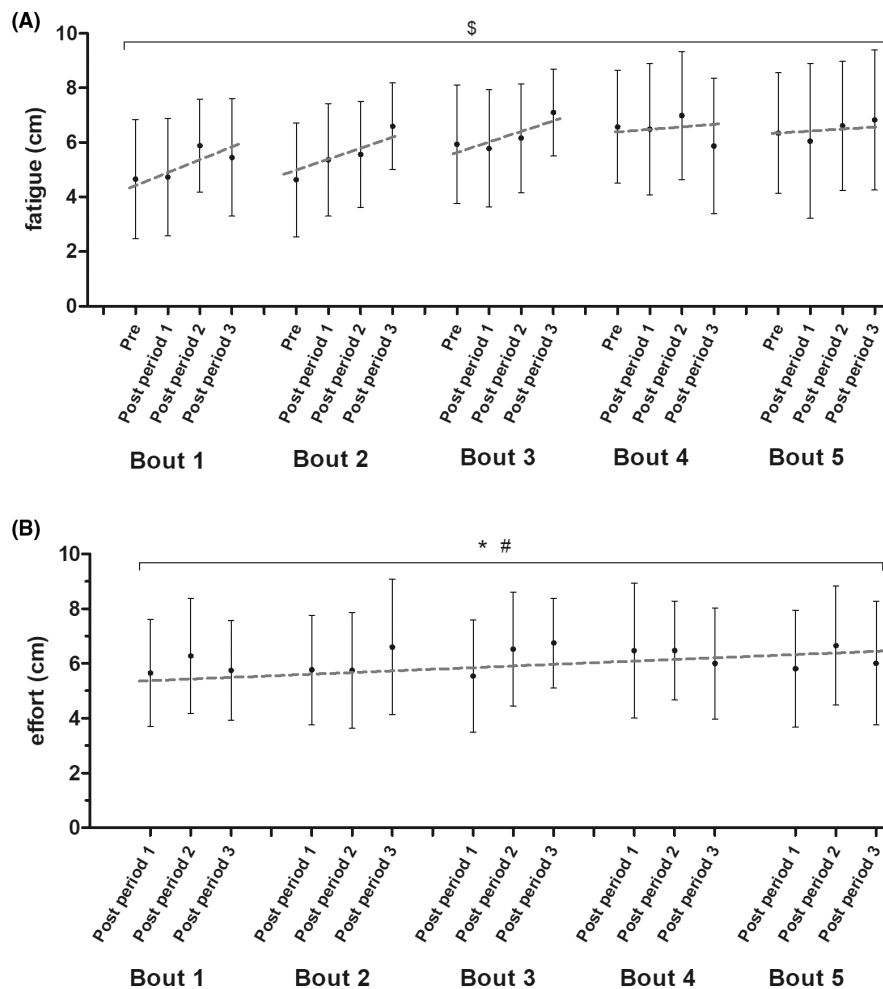
**FIGURE 2** Evolution of the knee extensors' neuromuscular function after the bouts of the simulated competition in men (blue) and women (red). Vertical lines represent mean  $\pm$  SD A–D. The dotted line indicates the estimates from the mixed model (bout effect). (A) Data for countermovement jump (CMJ) after bouts 1, 3, and 5. (B) Data for maximal torque after bouts 1, 3, and 5. (C) Data for the rate of torque development calculated over 200 ms after bouts 1, 3, and 5. (D) Data for potentiated 100 Hz doublet evoked 2 s following the maximal voluntary contraction after bouts 1 and 5. (E) Data for voluntary activation after bouts 1 and 5, vertical lines represent median  $\pm$  IQR. \*Significant sex-related difference ( $p<0.05$ ). #Significant effect of bout ( $p<0.05$ ).

lower differences at *post* between bouts [ $I=4.83\pm 0.35$  cm,  $t_{(1,41)}=12.2$ ,  $p<0.001$ ;  $\text{period}_{(0,3)}=0.7\pm 0.1$  cm,  $t_{(1,422)}=7.05$ ,  $p<0.001$ ,  $\text{bout}_{(0,4)}=0.58\pm 0.07$  cm,  $t_{(1,422)}=8.47$ ,  $p<0.001$ ,  $\text{period}_{(0,3)}\times\text{bout}_{(0,4)}=-0.14\pm 0.04$  cm,  $t_{(1,422)}=-3.33$ ,  $p<0.001$ , **Figure 3A**]. For effort, significant period and bout main effects were found, indicating an increase in effort along the bout and throughout the competition [ $I=5.45\pm 0.31$  cm,  $t_{(1,46)}=17.5$ ,  $p<0.001$ ;  $\text{period}_{(0,2)}=0.54\pm 0.12$  cm,  $t_{(1,300)}=4.42$ ,  $p<0.001$ ,  $\text{bout}_{(0,4)}=0.16\pm 0.06$  cm,  $t_{(1,297)}=2.55$ ,  $p=0.011$ , **Figure 3B**].

### 3.2.2 | Perceived workload

Because mental demand was modeled 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 [ $I=61\pm 3$  A.U.,  $z=20.2$ ,  $p<0.001$ ;  $\text{result}_{(\text{victory})}=7\pm 3$  A.U.,  $z=2.1$ ,  $p=0.03$ ]. Physical demand presented no weapon ( $p=0.21$ ), sex ( $p=0.30$ ), bout ( $p=0.07$ ) or result ( $p=0.20$ ) main effect [ $I=65\pm 3$  A.U.  $z=24$ ,  $p<0.001$ ]. 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<sup>-1</sup>), logit estimates:  $I=0.53\pm 0.21$ ,  $z=2.5$ ,  $p<0.001$ ;  $\text{bout}_{(0,4)}=0.11\pm 0.5$ ,  $z=2.3$ ,  $p=0.024$ ;  $\text{result}_{(\text{victory})}=0.30\pm 0.15$ ,  $z=2.04$ ,  $p=0.042$ ]. For mental demand, estimates were computed using the ggpredict package for R<sup>28</sup> and presented in **Figure 4**. Frustration did not present weapon ( $p=0.45$ ), sex ( $p=0.43$ ) or bout



**FIGURE 3** Evolution of the subjective data of the perceived fatigue and effort collected using visual analog scales of 10 cm. Data are presented as mean  $\pm$  SD. The dotted line indicates the estimates from the mixed model. (A) Evolution of the perceived fatigue during the simulated competition; only the effect of period is presented for clarity. (B) Evolution of perceived effort during the simulated competition; only the bout main effect is presented for clarity. \*Significant effect of period ( $p<0.05$ ). #Significant effect of bout ( $p<0.05$ ). §Significant bout  $\times$  period interaction ( $p<0.05$ ).

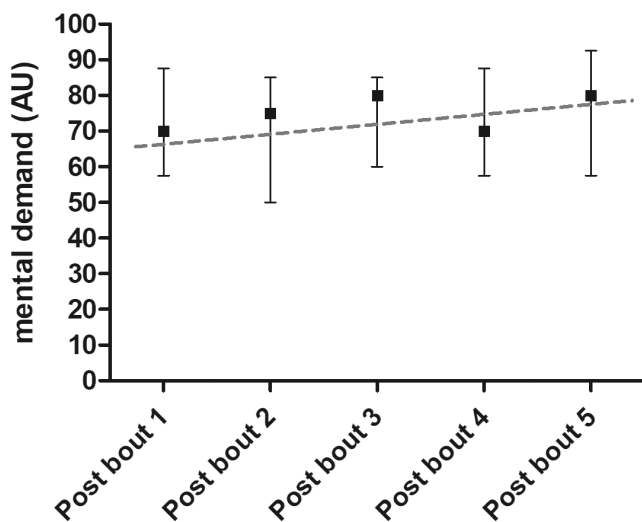


( $p=0.06$ ) main effects but it was scored higher when the bout was lost [ $I=63\pm 4$  A.U.,  $z=15.9$ ,  $p<0.001$ ;  $\text{result}_{(\text{victory})}=-22\pm 4$  A.U.,  $z=-5.8$ ,  $p<0.001$ ]. Perceived performance did not present weapon ( $p=0.65$ ), sex ( $p=0.68$ ) or bout ( $p=0.81$ ) main effects, but was perceived as greater when the bout was won [ $I=38\pm 3$  A.U.,  $z=11.4$ ,  $p<0.001$ ;  $\text{result}_{(\text{victory})}=-24\pm 4$  A.U.,  $z=-6.9$ ,  $p<0.001$ ]. Temporal pressure did not show weapon ( $p=0.08$ ), sex ( $p=0.50$ ), bout ( $p=0.53$ ) or result ( $p=0.31$ ) main effects [ $I=52\pm 4$  A.U.,  $z=14.3$ ,  $p<0.001$ ]. The effect of the bout's result (victory or defeat) is presented in Appendix S3 using the estimated density function for the NASA<sub>TLX</sub> scores. We observed a generalizable high mental and physical demand and considerable effort in the task.

## 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 rate of torque development ability 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



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

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

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 1), 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 S4). 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 low reliability and agreement analyses for maximal torque and voluntary activation presented in Appendix S4 suggest that caution must be taken when interpreting these changes. Regarding the possible increase in CMJ, similar results has been previously documented in fencing.<sup>4</sup> 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.<sup>29</sup>

Following a single bout, fencers perceived high levels of effort, mental, and physical demands. As effort refers to the engagement of physical and cognitive resources to perform in a task,<sup>14-16</sup> a concomitant increase in mental and physical demand could be expected. This was likely due to the rapid and successive recruitment of motor units and motor control demand of the task needed to attack or defend (physical demand) and the continuous attention to the movement of the opponent, as well as the rapid and continuous information processing needed to take accurate decisions (mental demand). The short duration of assaults and recovery time between bouts was likely sufficient to avoid fatigability of the knee extensors in elite fencers.

## 4.2 | Evolution of fatigue during a fencing simulated competition

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.<sup>4</sup> It is also possible that the period of recovery between assaults, periods, and bouts was sufficient to limit the development of neuromuscular fatigue. Indeed, previous studies focusing on energetics, reported limited blood lactate accumulation<sup>4,30,31</sup> and time passed above the anaerobic ventilatory threshold.<sup>30</sup> A more in-depth analysis of the energetic profiling of fencing competition showed a predominance of aerobic and anaerobic alactic processes (e.g., the use of phosphocreatine for the ATP-resynthesis) to support fencing assaults,<sup>31</sup> allowing a rapid recovery kinetic and thus probably limiting the development of neuromuscular impairments. Although the decreased maximal torque of  $\sim 17.8\text{ Nm}$  for the simulated competition might be considered as limited, the decreased rate of torque development was  $\sim 100\text{ Nm s}^{-1}$  ( $\sim 10\%$ ). This loss in rate of torque development could be relevant, considering that recently it has been reported a loss of  $\sim 15\%$  following an intense downhill running session using similar methods.<sup>32</sup> The decrease in the rate of torque development would indicate an impairment in the ability to rapidly develop muscle force along a competition day, and could be a more appropriate measure than maximal torque to detect alteration in neuromuscular function induced by fast contractions.<sup>13</sup>

This is the first study that studied both fatigue and effort in fencing. Fencers perceived about 12% higher level of fatigue for each successive bout. Effort increased by 10% for each period during the bout. Across bouts, we observed a slight general increased in perceived effort (about 3%). Previously, no differences between post-bouts were found during the direct elimination phase of the competition.<sup>4,11</sup> 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<sup>15</sup> and<sup>16</sup>], 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,<sup>4</sup> and 8.<sup>11</sup>]. Importantly, the mental demand increased during the competition, and a

higher mental demand was perceived in case of victory. Taken together, these results suggest that fatigue induced by a fencing competition could have a strong cognitive component, traditionally referred to as cognitive or mental fatigue.<sup>5</sup> As changes in these perceptions are subjective manifestations of cognitive fatigue, future studies should quantify objective manifestations such as changes in cognitive performance—that is, 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. This result could be underpowered due to the low number of participants per weapon. It also suggests 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 S5). Another limitation was the imbalanced number of men and women and across weapons, limiting our analysis when evaluating sex and weapon differences. Finally, we cannot rule out the

possibility that the simulated competition presented a lower intensity compared to a real international competition, leading to an underestimation of the neuromuscular impairments caused by the competition and different perceived fatigue, effort, and workload.

## 5 | PERSPECTIVES

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 resources to the task. 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 (Appendix S3), interventions aiming to manage stress and frustration following a lost bout or a lost *assault*, could also be of great interest to coaches and fencers. The rate of force development was the sole neuromuscular variable impaired by the simulated competition, suggesting that this variable could be of interest to strength and conditioning coaches in monitoring the training of fencers.

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### CONFLICT OF INTEREST STATEMENT

The authors declare that they have no competing interests.

### DATA AVAILABILITY STATEMENT

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

### ORCID

Giorgio Varesco  <https://orcid.org/0000-0001-9385-6972>  
Benjamin Pageaux  <https://orcid.org/0000-0001-9302-5183>

Thomas Cattagni  <https://orcid.org/0000-0002-6650-8339>

[org/0000-0002-6650-8339](https://orcid.org/0000-0002-6650-8339)

Aurélien Sarcher  <https://orcid.org/0000-0002-6408-6291>

Guillaume Martinent  <https://orcid.org/0000-0002-4151-2286>

[org/0000-0002-4151-2286](https://orcid.org/0000-0002-4151-2286)

Julie Doron  <https://orcid.org/0000-0002-3967-709X>

Marc Jubeau  <https://orcid.org/0000-0002-4878-7813>

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## SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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