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Analysis of the effect of fatigue in fencing using reaction time lights

Análise do efeito da fadiga na esgrima usando luzes de tempo de reação

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Abstract – This study aims to investigate the increase in reaction times in fencers and its relationship with physical and mental fatigue. Changes in heart rate (HR) and oxygen saturation (SO_2) were used as indicators of physical fatigue, while variations in reaction time to light-based reactive tasks were employed to assess both physical and mental fatigue, measured after warm-up and post-training. A group of 48 fencers performed a 10-min warm-up followed by a 15-point bout, simulating a regular competition. ANOVA and Friedman tests were conducted to identify statistically significant differences in reaction times for different reactive tasks: Simple Reaction time (SRT), Elective reaction time (ERT), Go-non-Go task (G/NG), and decision making tasks (DM4), including lunge (DML), break (DMB) and march (DMM) tasks, under three distinct conditions based on different fatigue levels: at rest (R), after warm-up (WU), and post training (PT). It was found that most reaction times that were studied were significantly higher in the PT than at R ($SRT1_{PT-R}$ = 70 ms, $ERT2_{pT-R}$ = 58 ms, $G/NG3_{pT-R}$ = 64ms, $DM4_{pT-R}$ = 125 ms, $DML4_{PT-R}$ = 125 ms, $DMM4_{PT-R}$ = 130ms), suggesting a considerable impact of physical activity and fatigue on these exercises, negatively affecting the speed and accuracy of responses. These findings highlight that fatigue plays a critical role in sports like fencing, where the ability to make quick and accurate decisions is essential, and underline the importance of efficiently managing physical and mental fatigue to optimize performance in competitive situations.

Key words: Visual training; Sport vision; Fencing fatigue; Reaction time.

Resumo – *Este estudo tem como objetivo investigar o aumento nos tempos de reação em esgrimistas e sua relação com a fadiga física e mental. Alterações na frequência cardíaca (FC) e na saturação de oxigênio (SO_2) foram utilizadas como indicadores de fadiga física, enquanto variações no tempo de reação a tarefas reativas baseadas em luz foram empregadas para avaliar tanto a fadiga física quanto a mental, medidas após o aquecimento e após o treinamento. Um grupo de 48 esgrimistas realizou um aquecimento de 10 minutos seguido por um combate de 15 pontos, simulando uma competição regular. Foram conduzidos testes ANOVA e Friedman para identificar diferenças estatisticamente significativas nos tempos de reação em diferentes tarefas reativas: tempo de reação simples (SRT), tempo de reação eletiva (ERT), tarefa Go-non-Go (G/NG) e tarefas de tomada de decisão (DM4), incluindo investida (DML), recuo (DMB) e avanço (DMM), em três condições distintas baseadas em diferentes níveis de fadiga: em repouso (R), após o aquecimento (WU) e após o treinamento (PT). Verificou-se que a maioria dos tempos de reação estudados foi significativamente maior no PT em comparação ao R ($SRT1_{PT-R}$ = 70 ms, $ERT2_{PT-R}$ = 58 ms, $G/NG3_{PT-R}$ = 64 ms, $DM4_{PT-R}$ = 125 ms, $DML4_{PT-R}$ = 125 ms, $DMM4_{PT-R}$ = 130 ms), sugerindo um impacto considerável da atividade física e da fadiga nesses exercícios, afetando negativamente a velocidade e a precisão das respostas. Esses achados ressaltam que a fadiga desempenha um papel crítico em esportes como a esgrima, nos quais a capacidade de tomar decisões rápidas e precisas é essencial, e sublinham a importância de gerenciar de forma eficiente a fadiga física e mental para otimizar o desempenho em situações competitivas.*

Palavras-chave: *Treinamento visual; Visão esportiva; Fadiga na esgrima; Tempo de reação.*

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INTRODUCTION

Fencing is a high-intensity sport that demands agility, speed, coordination, and quick decision-making skills. Competing in this discipline requires fencers to react swiftly to their opponents' movements, which can change rapidly during a bout. As a result, fencing is both a physically and mentally demanding sport, with specific characteristics depending on the type of weapon used: épée, foil, and sabre. Each category features distinct rules and action times, affecting the work-to-rest ratio[1-3]. The sport also involves long competition days, with bouts lasting only a few minutes but being interspersed with extended periods of rest, which places additional demands on an athlete's endurance and recovery.

Fencing is primarily an anaerobic sport, relying on both alactic energy systems and, at times, anaerobic glycolysis. These energy pathways contribute to the physical fatigue that athletes experience during competitions, which manifests in increased heart rate and lactate levels[4]. In addition to physical fatigue, fencing also involves considerable mental effort, with fatigue affecting cognitive functions such as decision-making and reaction time[5]. Since the ability to react quickly and accurately is a critical component of success in fencing, both mental and physical fatigue can substantially impair performance, reducing an athlete's ability to generate the explosive force necessary for quick attacks and defenses[1].

Physical fatigue in fencing is typically observed as a decrease in neuromuscular performance and an increase in heart rate. Muscle fatigue has been well documented, showing its negative impact on explosive strength[6]. On the other hand, mental fatigue—driven by the cognitive load required to maintain high performance—becomes more pronounced as the competition progresses. This type of fatigue is particularly impactful in fencing, as even a fraction of a second can determine the success or failure of a move[7]. As the demands of the bout increase, so does the cognitive effort required, suggesting that cognitive fatigue plays a significant role in performance decline[6].

For evaluating physical fatigue, heart rate and oxygen saturation levels have proven to be reliable indicators, offering real-time data on an athlete's recovery and endurance. Meanwhile, changes in reaction times serve as useful proxies for mental fatigue, offering insights into cognitive performance[8]. Reaction time tasks, specifically those involving visual stimuli, have become a popular method to assess and train athletes' cognitive abilities, including their decision-making and reaction times[9]. These tasks, performed with reaction light systems, present random visual stimuli to the athlete, who must respond based on the program's requirements. These systems not only provide a way to measure cognitive abilities but are also valuable training tools that can help improve reaction time, movement efficiency, and overall sensorimotor skills.

Given that fencing requires precise and rapid responses to visual cues, reaction time training is crucial for athletes. From simple reaction times (SRT), which involve executing a quick touch, to elective reaction times (ERT), which require choosing the correct response from multiple options, and "go/no-go" decisions, which assess whether to attack or defend, these cognitive skills are essential for anticipating an opponent's actions and making split-second decisions in a match. The ability to train and measure these reactions in both physical and technical contexts is vital for enhancing overall performance.

Reaction time light systems have proven effective for both training and measuring these cognitive skills, particularly for athletes in recovery or those involved in Paralympic sports like wheelchair fencing. Their portability, ease of use, and ability to provide precise data make them a valuable tool for training, performance assessment, and enhancing motivation among athletes. The versatility of these devices is one of the key reasons for their inclusion in our study.

Given the significant impact of fatigue on fencing performance, this study was designed to evaluate how both physical and mental fatigue affect athletes' reaction times and cognitive performance. By assessing heart rate and oxygen saturation as indicators of physical fatigue, and measuring reaction times across different cognitive tasks as indicators of mental fatigue, we aim to gain a deeper understanding of how fatigue evolves throughout a fencing session. The study examines these variables at three distinct stages of training: resting, post-warm-up, and post-training. The insights gathered will help develop more effective fatigue management strategies, optimize performance, and enhance training routines for fencers. Understanding the interplay between physical and cognitive fatigue is essential for athletes and coaches to better plan recovery strategies and improve performance during both training and competition.

METHOD

The study included 48 fencers (28 men, 20 women; mean age 26.7 ± 11 years) across different competitive levels (12 international, 20 national, 16 regional) and disciplines (25 épée, 14 foil, 9 sabre). Written informed consent was obtained from all participants or their legal guardians, in accordance with the Declaration of Helsinki.

Oxygen saturation (SO_2) and heart rate (HR) were measured with a portable fingertip pulse oximeter (Berrcom, China).

Reactive tasks were evaluated using four Queling Sport lighting devices (Queling, China) synchronized via Bluetooth 5.0 with the ReactionX app on an Android tablet, which also recorded the reaction times. Each device, 9 cm in diameter, was vertically secured with Velcro, and fencers used their own combat weapons. Four exercises were designed to assess reaction time and decision-making under fencing-specific conditions[9].

Simple Reaction Time (SRT), reacting to a known sequence; Elective Reaction Time (ERT), reacting to a randomly activated device; Go/No-Go Reaction Time (G/NG), responding only to specific light colors; and Decision-Making (DM), performing different fencing movements (lunge, march, retreat) based on the light color. Each exercise included two trials, with 30 s of rest between them, and lasted approximately 14 min per participant. Anticipatory (<100 ms) and excessively delayed responses (>1000 ms relative to best time) were excluded.

Measurements of reaction time, heart rate (HR), and oxygen saturation (SO_2) were collected at three key phases: at rest (R), after a 10-min warm-up (WU), and immediately post-training (PT), which consisted of a high-intensity, simulated 15-point bout divided into three 3-min rounds with 1-min rest intervals. All participants completed a familiarization session the day prior to data collection.

Statistical analysis

The normality of the results was tested with the Shapiro-Wilk test. When the data were normal, repeated measures ANOVA was run for the three fatigue levels (R, WU, PT), pairwise Holm-Bonferroni correction was used to identify significant differences, and when normality was not met, the Friedman test was run with Conover contrasts post hoc test to evaluate significant differences between groups. Statistical analyses were performed in JASP for Linux setting the significance level at $\alpha = 0.05$.

RESULTS

The results of the exercises were analyzed based on the athletes' three fatigue phases (at rest, after warm-up, and after training) in Table 1. As the fencers experienced greater physical fatigue, their heart rate increased and their blood oxygen levels decreased, demonstrating that these physiological measurements are reliable indicators of fatigue during fencing activities.

Results on physical fatigue

As expected, there is a direct relationship between heart rate and oxygen consumption ($P < 0.001$).

Table 1. Mean and standard deviation of the physical fatigue variables at the three measured moments.

Condition	At Rest (R) (a)	Post-Warm-Up (WU) (b)	Post-Training (PT) (c)	F	P	η^2 / ω
Heart Rate (bpm)	66.65 ± 11.71 b,c	106.55 ± 9.20 a. c	129.4 ± 10.63 a. b	185.91	< 0.001	0.907
Oxygen Saturation SO_2 (%)	98.2 ± 0.95 b,c	96.4 ± 1.05 a.c	95.25 ± 1.97 a.b	29.70	< 0.001	0.743

Note: The data were analyzed using the Friedman test for SO_2 and repeated measures ANOVA for HR.The difference between groups is also indicated with (a) = Rest, (b) = Post-Warm-Up, and (c) = Post-Training.

Heart rate increased significantly as the fencers became more physically active. At rest, the average heart rate was 66.65 beats per minute (bpm). After the warm-up, it rose sharply to 106.55 bpm, and after completing the full training session, it climbed even higher to 129.4 bpm. Statistical analysis (ANOVA) confirmed that these differences were highly significant ($P < 0.001$), meaning that the changes were not due to chance. Further analysis showed that each stage—rest, warm-up, and training—differed significantly from the others.

Similarly, oxygen saturation levels, which reflect how much oxygen the blood is carrying, decreased as physical activity increased. At rest, the average saturation was 98.2%, very close to the maximum. After the warm-up, it dropped slightly to 96.4%, and after training, it decreased further to 95.25%. A non-parametric test ($P < 0.001$) confirmed that these decreases were statistically significant and strongly associated with increasing fatigue. The biggest drops occurred between rest and the other two phases (both $P < 0.001$), although the decline between warm-up and post-training, while smaller, was still significant ($P = 0.011$).

Results on mental fatigue

Normality was assumed for the results of exercises SRT1, ERT2, G/NG3 and DMB4. However, exercises DML4, DMM4, and DM4 did not follow a normal distribution. Table 2 presents both parametric and non-parametric tests, depending on the distribution of each sample. Nearly all variables (SRT1, ERT2, G/NG3, DM4, DML4, DMM4) showed significant differences across conditions, suggesting that physical activity or fatigue has a substantial impact on these exercises. The effect sizes (η^2) ranged from moderate (η^2 = 0,226) to small (η^2 = 0,068). Exercise DMB4 did not show significant differences across conditions.

Table 2. Results of the four tests based on the fencers' fatigue levels.

TASK	At Rest ® (a)	Post-Warm-Up (WU)(b)	Post-Training (PT)(c)	χ^2/F	P	η^2/ω
SRT1 (*n* = 48)	292 ± 49 c	325 ± 120	362 ± 91 a	3.31	**0.047**	0.149
ERT2 (*n* = 48)	456 ± 61 c	478 ± 64	514 ± 65 a	5.54	**0.008**	0.226
G/NG3 (*n* = 48)	484 ± 98 c	526 ± 74	548 ± 71 a	4.06	**0.026**	0.184
DM4 *(*n* = 48)	1136 ± 277 c	1203 ± 280	1261 ± 253 a	11.31	**0.003**	0.068
DML 4* (*n* = 48)	976± 167 c	1119 ± 1230	1207 ± 220 a	3.93	**0.024**	0.088
DMM 4* (*n* = 48)	1126 ± 234 c	1171± 268	1256 ± 267 a	6.83	**0.002**	0.144
DMB 4* (*n* = 48)	1306 ± 312	1334 ± 295	1321 ± 266	1.85	0.163	0.044

Note: reaction times in ms, "*" Friedman Contrast test, ANOVA in other cases. The difference between groups is also indicated with (a) = Rest, (b) = Post-Warm-Up, and (c) = Post-Training.

SRT (Simple Reaction Time): On average, reaction times were faster when the participants were at rest (70 ms). After training, the reaction times significantly increased, suggesting that the training had an effect. Statistically, this difference was significant ($P < 0.05$), and a more detailed analysis confirmed this effect (p_{Holm} = 0.040).

ERT (Elective Reaction Time: Similarly, the average of the reaction times also showed a significant ($P = 0.008$) increase after training (58 ms at rest), with post hoc analysis that revealed significant differences between resting and post-training conditions (p_{Holm} = 0.007), indicating an increase in fatigue between these conditions.

G/NG (Go/No-Go): The average reaction times for tasks where participants had to quickly react to specific signals also increased after training (64 ms at rest). Again, statistical analysis showed that this increase in reaction time was significant ($P = 0.026$). Post-hoc analysis showed significant differences between resting and post-training conditions (pHolm = 0.039).

DM (Decision-Making): In tasks where participants had to make decisions quickly, there was a noticeable increase in response times (125 ms). This suggests that participants' decision-making ability became slower after training, which was confirmed by a post-training analysis showing that the reaction time significantly increased ($P = 0.004$). Post-hoc analysis confirmed significant differences ($P = 0.003$). Highlighting that training conditions were notably distinct.

DML (Decision-Making Lunge): The time it took participants to make decisions increased from their resting state (125 ms). The analysis confirmed that the increase was significant ($P < 0.001$), between the resting condition and post-training states ($P < 0.001$).

DMM (Decision-Making March): Similarly, this decision-making time also increased after training in 130 ms ($P = 0.040$). Post-hoc analysis confirmed that this increase was significant, though the effect was somewhat less pronounced than in the other tasks (P = 0.019).

DMB: Interestingly, this decision-making task showed no significant changes across the three conditions; no discernible effect of training was observed on participants' balance during decision-making, although average values increased from rest to post-training by 130 ms.

DISCUSSION

Considering heart rate (HR) as an indicator of the intensity of physical activity, it was observed that HR increased significantly across the three evaluated conditions (R, WU, and PT). At rest, heart rate was low (66.65 ± 11.71 bpm), with a notable increase after warm-up (106.55 ± 9.20 bpm) and after training, (129.4 ± 10.63 bpm). This HR was lower than others from different studies in fencing[10], which reported an average HR of 167 bpm and a maximum HR of 191 bpm (approximately 70% of the maximum HR sustained for about 60% of the bout duration). The higher values in this study can be explained by the fact that heart rate was continuously measured during exercise, whereas in our study, HR was measured immediately after the warm-up and simulated bouts. Additionally, our bouts were simulated, while Li and colleagues conducted their measurements during real competition[11].

It has been shown that heart rate during a fencing bout clearly depends on the intensity of the actions[11]. These authors reported that men have lower HRs than women. Moreover, during sabre competitions, HRs tend to be higher, with some ectopic beats observed during the most intense phases of the bout. Another study found that during training sessions for the Italian national team before the 1982 World Championships, it was noted that HR depends on bout intensity, and winners often have lower HRs[3]. Heart rates were observed to be above the anaerobic threshold during 41 ± 34% of the bout duration[12].

The highest oxygen saturation (SO_2) was observed in the resting condition (98.2 ± 0.95%) and decreased slightly after warm-up (96.4 ± 1.05%) and post-training (95.25 ± 1.97%). The difference among the three conditions was small but consistent and significant across the evaluated conditions (R, WU, and PT). This finding has important implications for understanding how physical state impacts SO_2 levels and may be relevant for future research or practical applications in the fencing practice oriented to both competition and physical fitness.

Previous studies show that during fencing competitions, athletes experience a moderate increase on physical demands, involving both aerobic and anaerobic energy sources in a balanced manner[13]. For this reason, activity or fatigue conditions significantly influence heart rate but have a lower effect on blood oxygen saturation. This aligns with our study, as HR was more sensitive to changes in physical activity, whereas oxygen saturation remained relatively stable[14].

Almost all the analyzed variables (SRT1, ERT2, G/NG3, DM4, DML4, DMM4) showed significant differences between the test conditions (R, WU, and PT), suggesting a considerable impact of physical activity and fatigue on these exercises. The results indicate a progressive increase in reaction times as the fencers became more fatigued, Except for the DMB4, the average values across the three DM4 conditions registered significant differences among the three fatigue levels evaluated. However, the effect size was very small, suggesting that fatigue is not a relevant factor for this time of tasks.

Previous research supports these findings about reaction time and fatigue. Ustundağ and colleagues, demonstrated that visual reaction time increases significantly after high-intensity efforts, such as those performed on a cycle ergometer in a study involving 18 high-level fencers[15]. These results highlight the importance of recovery in sports requiring high precision and speed, such as fencing.

In this context, significant differences were primarily observed between resting conditions and post-training, when fatigue levels were highest, while no significant differences were found between resting and post-warm-up conditions. This pattern aligns with a similar study conducted by Devienne and contributors, that measured reaction and movement times in nine fencers who performed isometric efforts at 50% of their capacity[16]. In that study, the applied effort did not produce significant effects on performance, suggesting that the intensity of the effort was insufficient to elicit a relevant neuromuscular response. Furthermore, the characteristics of the exercise (isometric, without dynamic activity) were completely unrelated to fencing plus they had no cognitive engagement. This point makes impossible to compare the results with our study, which involved dynamic activity directly related to actual sports movement.

Another interesting study compared simple reaction time (SRT) records at rest between a group of professional fencers and a group of sedentary individuals. This study found no significant differences between the two groups at rest. However, differences became evident when trials were repeated while the participants performed efforts at varying intensities on a cycle ergometer, with SRT results worsening as the effort intensity increased[17]. In the same study, warm-ups did not influence reaction times in fencing. However, previous studies have demonstrated that both stretching and aerobic warm-ups can reduce reaction and movement times during lunges, highlighting the importance of implementing appropriate warm-up routines to optimize performance. This suggests that the type and intensity of the warm-up may play an essential role in preparing the neuromuscular system, improving speed and precision in fencers[18].

In this study we observed a clear intensification in all reaction times across the three fatigue levels, with more moderate differences between post-warm-up and post-training result. Our findings reveal that the SRT value increases by 24%, or 70 ms, as athletes experience fatigue post-training.

The mean ERT increased by 12,7%, or 58 ms from rest (ms) to post-training times. When comparing these results to those of the SRT exercise, we see more significant differences in ERT. Due to the greater complexity of the ERT task, our findings suggest that the fatigue generated by fencing practice has a greater impact on the cognitive and information-processing aspects of fencers. This may be because fatigue leads to reduced neuromuscular and cognitive performance, which in turn affects athletes selective reaction times. Varesco and contributors[6] indicate that perceived fatigue and effort progressively increase during bouts; therefore, fencers need to allocate more mental resources to maintain performance as they tire.

In the Go/NoGo exercise, reaction times also increased progressively with fatigue by 13,2%, or 64 ms, suggesting a fatigue-driven increase in this variable. In this exercise, mental fatigue impairs resource allocation and error control in response to Go/NoGo stimuli, resulting in longer reaction times and a higher error rate. Response inhibition and execution play crucial roles in any high-speed action. To achieve stability in speed and precision, individuals must utilize appropriate inhibitory control while executing responses[19]. This activates the parasympathetic system of the athlete, leading to neural fatigue and a slowdown in elective visual reaction times.

In the average DM4 exercise, reaction times show a progressive increase across the three conditions by 11%, or 125 milisecons, indicating a decline in reaction times as subjects transition from rest to post-warm-up and finally to the post-training state. Analyzing the individual components of this exercise (DML4, DMM4, and DMB4) reveals a similar pattern, with shorter times at rest and longer times under fatigue conditions, suggesting an accumulative influence of fatigue on reaction times. The results show that the fastest movement in all conditions is the lunge or thrust (DML), followed by the advance (DMM), and finally the retreat (DMB). The effect of fatigue was most steep in the fastest movement (DML by 23.7%, or 231 milisecons), followed by the next slower movement (DMM by 11.5%, or 130 milisecons), while it was almost negligible in the slowest movement (DMB by 11%, or 15 milisecons). Therefore, the impact of fatigue on decision-making is a critical area of research, particularly in high-stakes environments such as contact sports.

Collectively, our results highlight that fatigue level is a critical factor affecting the reaction and movement times, emphasizing the importance of the intensity and the type of effort performed, and its recovery processes for the physical preparation of fencers. Our findings support the idea that fatigue, whether mental or physical, can significantly affect decision-making accuracy, speed, and quality, which can have far-reaching consequences. As in other sports, fatigue in fencing negatively impacts decision-making precision and increases athletes response times, thereby reducing technical quality and complicating judgment in fast-paced, space-constrained situations[20]. Prolonged cognitive tasks can impair the ability to make optimal decisions, influencing cost-benefit evaluations and increasing the perceived effort required for future actions[21].

In elite fencers, the perception of mental demand and fatigue is especially intense during competitions, suggesting that greater mental resources must be allocated to sustain performance as physical fatigue accumulates. This increase in mental load reflects the demand to maintain high performance despite exhaustion, underscoring the importance of both physical and cognitive preparation at the elite level[6].

CONCLUSIONS

The results of this study highlight that both physical and mental fatigue significantly impact the performance of fencers, particularly their visual reaction abilities and decision-making processes. As fatigue levels increased, a progressive rise in reaction times was observed, with this effect being especially pronounced following a bout. In contrast, no statistically significant differences were found between the resting state and the post-warm-up condition, suggesting that acute fatigue induced by combat has a greater influence on performance.

Cognitively, both simple reaction time (SRT) and elective reaction time (ERT) were negatively affected by fatigue, reflecting a decline in processing speed and decision-making accuracy. Additionally, impaired inhibitory control was observed in Go/No-Go tasks, leading to increased response latency and a higher number of errors. Finally, in the decision-making exercise, reaction times progressively increased between the resting, warm-up, and training conditions, with more significant effects on faster movements, such as lunges.

These findings highlight that fatigue compromises both the speed and accuracy of motor and cognitive responses in fencing. Practically speaking, it is crucial for coaches and athletes to recognize the effects of fatigue and implement effective monitoring and recovery strategies during both training and competition. Early management of fatigue, through proper training planning and the incorporation of recovery techniques, could optimize decision-making and enhance overall athletic performance, enabling fencers to maintain high levels of concentration, precision, and agility in competitive situations.

COMPLIANCE WITH ETHICAL STANDARDS

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Data Availability Statement

Research data is only available upon request.

Ethical approval

Ethical approval was obtained from the local Human Research Ethics Committee –Hospital Clínico San Carlos (Madrid, Spain) and the protocol (no. 24/682) was written in accordance with the standards set by the Declaration of Helsinki.

Conflict of interest statement

The authors have no conflict of interests to declare.

Author Contributions

Conceived and designed the experiments: RBA, MSQ, RBV; Performed the experiments: RBA, JBP; Analyzed the data: RBA, MSQ, RBV; Contributed reagents/materials/analysis tools: RGJ, RMNB; Wrote the paper: RBA, MSQ, RBV, JBP.

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