EMG structure, ground reaction forces as anticipatory indicators of the fencing lunge effectiveness

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B Data Collection
C Statistical Analysis
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Abstract

Background and Study Aim: The efficiency of influence of the phenomenon of anticipation on the effectiveness of the most classic technical attack in fencing, which is a straight lunge in épée on the opponent's trunk, is expressed in terms of activating the muscles of the legs and postural indicators recorded as vertical ground reaction forces (GRF) characterized by a delay in relation to EMG signal. The main objective of the research reported in this paper is knowledge about the influence of the phenomenon of anticipation on the effectiveness of a straight lunge in épée on the opponent's trunk.

Material and Methods: Seven of the world's leading athletes, medal-winners of the World Championships and Europe, both in individual and team tournaments, took part in the research. Three research tools applied EMG, ground force reaction platform and the motion capture system (OPTI TRACK).

Results: The research demonstrated a high level of correlation coefficients between the force exerted in the rear leg and EMG of the LAT GAS (caput laterale) muscles ($r = 0.861$) and MED GAS (caput mediale) $r = 0.874$, for the statistical significance level of $p<0.05$. These values indicate a delay of the vertical force to the EMG of about 15 ms. The values of temporal indicators: reaction time (RT) and movement time (MT) indicate the greatest level of correlation with the activation times of the following muscles: PRT TB (premotor reaction time triceps brachii) $r = 0.893$; PRT ECR (-extensor carpi radialis) $r = 0.863$) as well as MRT FZ (movement time Fz) rear ($r = 0.824$) as an indicator of strength. Both phases (premotor RT and motor RT) determine the effectiveness of the fencing lunge, i.e. decrease of the duration of complex response time RT

Conclusions: The phenomenon of anticipation applies to both the premotor time and motor RT intervals. The results of the research also confirmed that the effectiveness of the lunge depends on the speed of activation of the triceps brachii and the volume of EMG generated by the gastrocnemius muscles of the rear leg.

Key words: anticipatory postural adjustment • épée • motor reaction time • premotor reaction time • reaction time • response time

Conflict of interest: Authors have declared that no competing interest exists

Ethical approval: The research has been approved by the Bioethics Committee of the Medical Chamber (Resolution No. 237, 2016 Dec 13)

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Épée – is the heaviest of the three modern fencing weapons (foil, épée, and sabre), each a separate event, épée is the only one in which the entire body is the valid target area. Épée is the heaviest of the three modern fencing weapons.

Ground reaction forces (GRF) – is the force exerted by the ground on body in contact with it.

Anticipatory postural adjustment (APA) – unconscious muscular activities aimed to counterbalance the perturbation caused by primary movement.

Response time (RET) – the interval from the presentation of a stimulus to the completion of a movement; the sum of reaction time and movement time.

Reaction time (RT) – the interval from the presentation of an unexpected stimulus to the initiation of the response.

Movement time (MT) – the interval from the initiation of a movement to its termination.

Premotor reaction time (PRT) – the interval from the stimulus presentation to the initial change in EMG.

Motor reaction time (MRT) – the interval from the first change in EMG to the movement's initiation.

Movement time Fz (rear or forward leg): MRT FZ– the interval from the initiation of a movement to its termination in refer to rear or forward leg muscles activity.

Pre-reaction time Fz (rear or forward leg): PRT FZ – muscles activity in preparation stage of movement [1].

INTRODUCTION

Due to its complexity, the detailed analysis of the motor patterns in fencing needs to take into account at least three groups of factors. This includes analysis of the interdependence of the bioelectric signal of key muscles, ground reaction forces in relation to the leg muscles and the temporal aspects of a technical task. A kind of novelty that was used in the study involved the analysis of the phase that precedes the movement, i.e. the time between the visual stimulus (the stimulus provided by the coach) and the initiation of the technical action by the fencer using EMG (electromyography) and GRF (ground reaction forces) indicators, which is possible as a result of synchronization of EMG and a motion capture system (OPTI TRACK). In this study, the fencing lunge was selected as the most representative and most frequently used technical attack applied in **épée**. The theoretical basis was the well-known reaction time (RT) paradigm [1], which separates RT and movement time (MT), including premotor RT (PRT) and motor RT response time phases (Figure 1).

As a result of the integration of the three EMG research tools, the ground force reaction platforms and the OPTI TRACK system, it was possible to derive time-synchronized indicators describing muscle activity before the initiation of movement and during the execution of a straight lunge on the coach's trunk. It was assumed that the interval between the activation of the stimulus and the initiation of the lunge should be considered as an anticipation of the action. This approach also takes into account the programming of a response understood in the area of information processing study [2], bioelectric activation of muscle plates and the initiation of GRF as an APA (anticipatory postural adjustment) phenomenon [3].

Throughout the tests, and in order to ensure that they corresponded to actual conditions of a fencing practice, EMG electrodes and OPTI TRACK system markers were attached to the coach's body. Similarly, markers were attached to the fencer's weapon at its middle and end parts. The coach took a step forward, and this formed a source of visual stimulation to which the fencers responded by executing a lunge attack on the coach's torso [4-8].

With regard to the lunge, the rear foot initiates the move of the front leg up and forward. A hit should be performed at the moment of the maximum extension of the elbow joint, before the foot of the forward leg touches the ground [9].

The main objective of the research reported in this paper is knowledge about the influence of the phenomenon of anticipation on the effectiveness of a straight lunge in épée on the opponent's trunk.

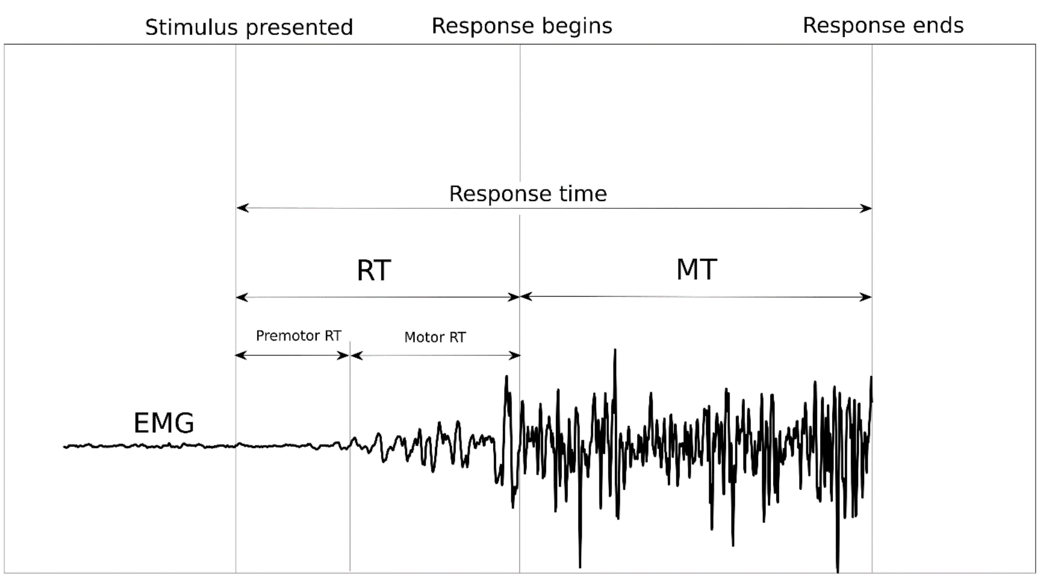

Figure 1. Phases of reaction time (RT) and movement time (MT).

MATERIAL AND METHODS

Participants

Assuming the application nature of the research, seven female of the world's leading athletes, medal-winners of the World Cup and Europe, both in individual and team championships, were invited to participate in the study: age: 23.75 ±7.26 years; body height 175.75 ±7.50 cm; body weight 67.65 ±10.02 kg. Only healthy fencers were qualified for the tests, i.e. ones with a medical certificate confirming their health condition enabling participation in sports competitions (training and sports events). The research group was informed about the goals of the study and the technique applied to implement this goal.

The research has been approved by the Bioethics Committee of the Medical Chamber (Resolution No. 237 of 13 December 2016) regarding the guidelines of the Helsinki Declaration regarding the conduct of clinical trials during humans.

Study design

A visual representation of the lunge is presented in Photo 1 and it is based on research involving an **épée** fencer, vice-world champion in the team competition. We emphasize that visual or even video assessment does not demonstrate the complexity of the technical pattern, which can be adequately verified by the EMG recording involving the activity of the most important muscles participating in a given patterns combined with indicators accounted for in GRF [10].

The authors of this study made the basic assumption that the research should be carried out in conditions that are as close as it was possible to actual fencing practice. On the basis of this assumption, the repeated lunge exercises were performed with the participation of a coach whose fencing outfit had a rectangle with markers, to indicate the location of a precise hit with the tip of a fencing weapon. In addition, individual technical trials were performed at the command given by the coach, as is the case in a typical fencing class with a trainer.

The innovative factor in the research was the use of two ground force reaction platforms (Kistler force plate), from which the athlete started their trials with the back and front limbs:

Photo 1. Lunging attack in épée.

- the assessment of the structure of EMG of lunge involved an assumption regarding a considerable anticipatory activation of the gastrocnemius muscle of the rear leg;
- a general assumption was made that the efficiency of the lunge is determined by the anticipatory processes expressed in terms of the activation of muscle in the legs and postural indicators recorded as vertical forces GRF with a certain delay in relation to EMG;
- an assumption regarding a decrease in the activation of key muscles in the MRT phase affecting a decrease of the MT motor response time is made;
- significant correlations are assumed between the vertical force of the rear leg and the EMG signal values of the gastrocnemius muscles of the back limb in the MT phase of the sensorimotor response.

Research tools

The Motion Capture system (OPTI TRACK, NaturalPoint, Inc., Corvallis, USA) comprising eight motion cameras was used to record the movement patterns executed by fencers and the coach (with a resolution of 832x832 px, 100 fps) and markers were applied to determine specific body positions. On the upper body (left and right), markers were placed according to the Plug-In Gait design [11]: *regio frontalis*, *regio parietalis*, *vertebra cervicale C7*, *acromion*, *humerus lateral epicondyle*, radius styloid process. On the lower body (left and right part) markers were placed according to the CAST technique (calibrated anatomical systems technique): *trochanter major*, *spina iliaca anterior superior* – PSISI; *spina iliaca posterior superior* – ASIS, *epi-condylus lateralis femoris*, *epicondylus medialis femoris*, *malleolus lateralis*, *malleolus medialis*, *calcaneus*, *caput ossis metatarsi* I and V.

Markers were also attached to the blade and guard of the epee and the coach's epee: three markers on each weapon (athlete's and coach's) and 4 markers were located on the coach's torso to define the target field in the shape of a 10x10 cm square.

The 16-channel Noraxon surface electromyography system (sEMG) (DTS type, Noraxon, Scottsdale, USA, 16 bit accuracy at a sampling frequency of 1500 Hz) was applied to record the bioelectric activity of the muscles. In total, the activity of eight muscles was analysed: armored upper limb: *flexor carpi ulnaris* (FCU), *extensor carpi radialis* (ECR), *biceps brachii* (BB), *triceps brachii* (TB) and lower limbs: *rectus femoris* (RF), *biceps femoris* (BF) gastrocnemius – *caput laterale*, *caput mediale* (LAT GAS, MED GAS), [12, 13]. For the purposes of testing bioelectric activity of the muscles, Ag/AgCI electrodes were used located throughout the body according to the procedures specified in the SENIAM project.

Two Kistler force plates (type 9286AA, Kistler, Winterthur, Switzerland, sampling frequency: 1500 Hz) were used to evaluate the reaction forces of the legs. The research equipment was synchronized using TTL signals.

Procedures

After the individual warm-up, the fencers performed 2 attacks with a straight lunge on the coach's body. The fencers' lunging patterns were repeated three times (Figure 2a, -b, -c) with the participation of the coach. The target of the attack was the hitbox marked with the OPTI TRACK markers on the coach's outfit. There are also markers on the blade of the coach's and fencer's **épées**. The individual technical tests were performed at the coach's command in accordance with the principles of a typical fencing lesson with the participation of a coach.

Data analysis

The ground reaction forces recorded by the force plate in the experiment were initially filtered using a fourth order Butterworth low pass filter with a cut-off frequency of 50 Hz. The EMG signals were filtered with a Butterworth bandpass filter with cut-off frequencies of 5–500 Hz and subsequently smoothed by the RMS algorithm with a 50 ms time window. The trajectories of markers on the bodies of the fencers and on the coach's outfit were not subjected to filtration. The signals derived from the platforms and the electromyography were recorded at a sampling rate of 1500 Hz and the trajectories of the markers with the resolution of 100 frames per second.

The response times representing the initiation of the coach's movement and the resulting ground reaction forces (the instant accompanied by the increase in the vertical force generated by the rear leg) were determined using the algorithm designed for identifying abrupt changes in the signal available in MATLAB 2020b (The

Mathworks, Inc.), in the form of the *findchangepts* function. Briefly speaking, this function offers the identification of the points where a numerical signal shifts in terms of its standard deviation beyond a specified threshold. The level of the threshold was determined by trials and confirmed by visual inspection.

The times corresponding to the initiation of the activation of individual muscles were determined using the procedure of finding points where the signal exceeds the threshold being the total of the mean +3SD calculated over the initial 100 ms of the measurement (from the initial fencing position) and the signal additionally asts for at least 100 ms.

In addition to the above times, the maximum force and EMG values were also calculated in the time interval between the initiation of the coach's movement and the instant of the hit on the target (MATLAB max function), which was determined by identifying the instant at which the trajectory of the marker located at the tip of the blade coincided with the marker located on the coach's outfit.

Statistical analysis

The relations between the maximum values of the ground reaction forces and EMG were calculated using the Pearson correlation after the normality of the distribution was checked with the results of the Shapiro-Wilk test. The analysis was performed using the JAMOVI software (jamovi.org). We used the following statistical symbol: SD standard deviation; *p* probability.

RESULTS

Visualization of samples of waveforms with recorded muscle activity and ground reaction forces with marked moments of the coach's movement (coach marker), the initiation of muscle activity above the mean value of + 3SD calculated from 100 ms from the adoption of the adequate fencing position (muscle onset), the beginning of the fencer's movement from the marker on the hand in the direction of movement (automatic Matlab *findchangepts* function) (fencer marker) and instant corresponding to the hit are presented in the figures below.

The legend of abbreviations used in Tables and Figures: **BB** *biceps brachii*; **BF** *biceps femoris*; **ECR** *extensor carpi radialis*; **FCU** *flexor carpi ulnaris*; **LAT GAS** *gastrocnemius caput laterale*; **MED GAS** *gastrocnemius caput mediale*; **RF** *rectus femoris*; **TB** *triceps brachii* (lateral capture).

TB is activated slightly later, and is followed by ECR, BB and FCU. Characteristically, the *extensor* muscles of the arm and forearm indicate the highest level of activity (Figure 2a).

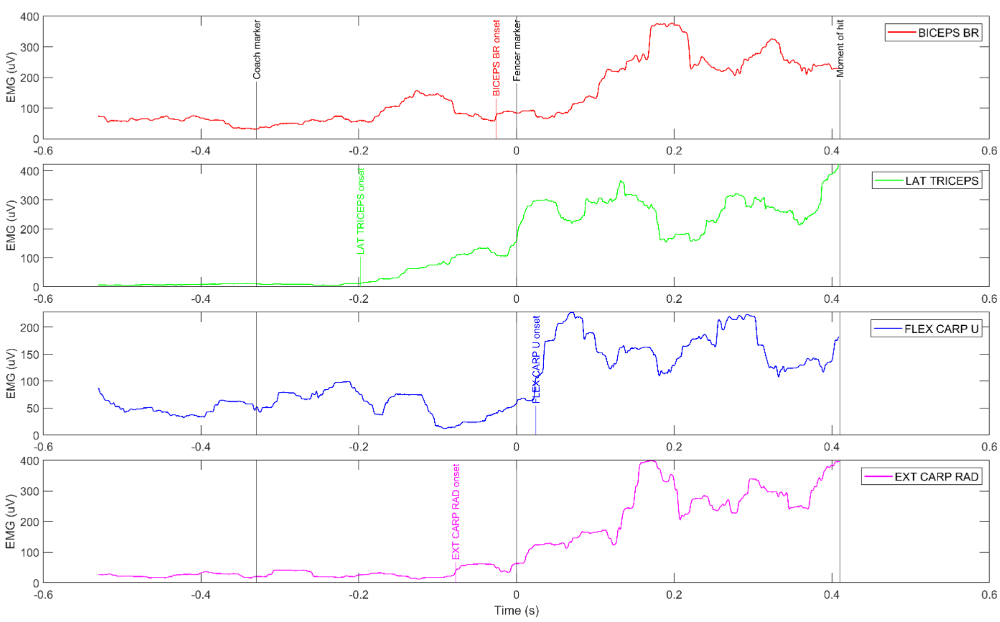

Figure 2a. Course of muscle activation and ground reaction forces with marked instants corresponding to the initiation of the coach's movement (coach marker) – arm muscles (FCU, ECR, BB, TB).

The peak of activation of the BF muscle of the forward leg EMG of around 150 uV corresponds to the synergy with GRF of approx. 400 N (Figure 2b). In the later phase, we can note a sharp decline in the vertical force FZ, because at this point the front limb leaves the platform and it is raised above ground, followed by a significant increase in EMG equal to around 500 uV in the RF muscle in the MT phase.

The muscles in the forward leg are the last ones to be activated, and the first is BF, followed by RF (Figure 2c). This conforms with the predictions foreseen by these authors, as throughout the attack, the rear leg is initiated first and it is lifted above the ground, followed by the activation of BF and then RF during the phase when a move forward is performed using the front leg. The important remark is that the gastrocnemius

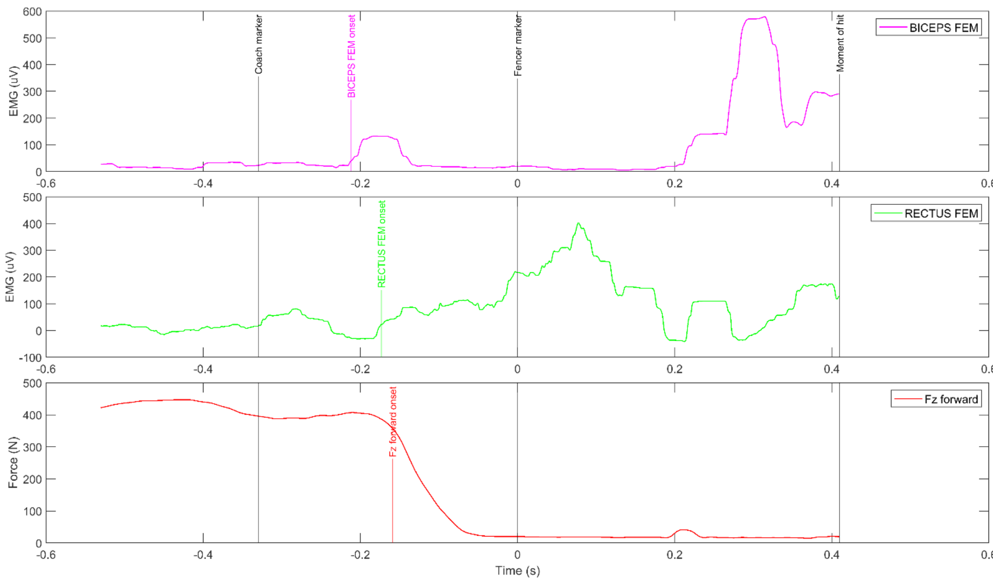

Figure 2b. Course of muscle activation and ground reaction forces with marked instants corresponding to the initiation of the coach's movement (Coach marker) –muscles in forward leg (RF, BF).

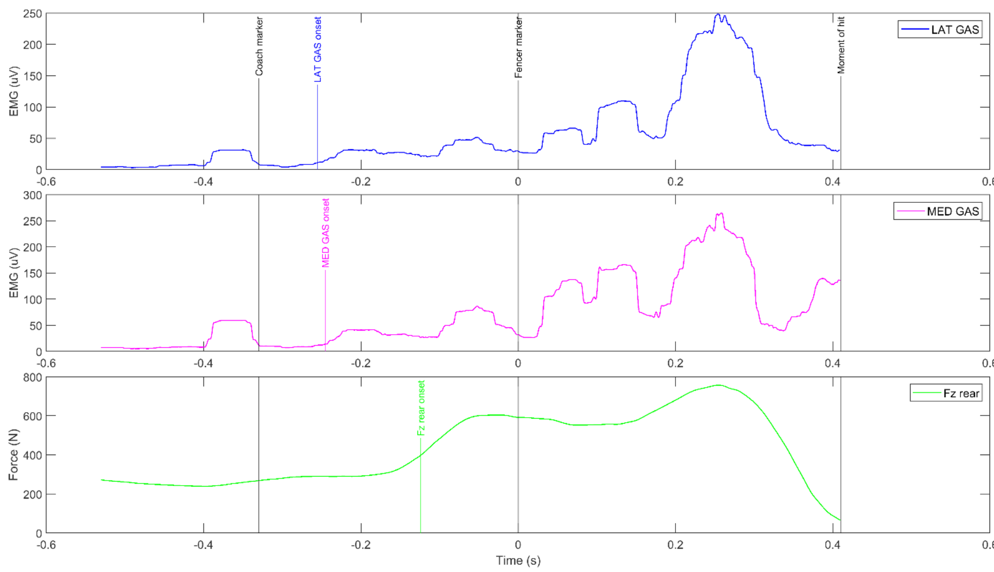

Figure 2c. Course of muscle activation and ground reaction forces with marked instants corresponding to the initiation of the coach's movement (Coach marker) – muscles in rear leg (LAT GAS and MED GAS).

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Two muscles play a key role in the phase of MRT, i.e. the *gastrocnemius* muscles and the *extensor* of the arm. We should assume that in synergy with FZ rear, they form the indicators of anticipatory activity of the muscular system during the lunging attack. The fact that at the time of the hit occurring more than 400 ms from the initiation of the visual stimulus to the start the attack, the main bioelectric activity at the level of more than 400 uV rests on the four muscles of the attacking hand with a smaller ratio equal to around 250 uV BB. At the time of a hit, the indicators of force in both the rear and forward leg virtually fade away.

The waveforms of the vertical force of the rear leg demonstrate high cross-correlations with the EMG waveforms for GAS muscles with small time shifts in relation to each other (in most cases the force delay in relation to the EMG by about 15 ms). Fencer F6 forms an exception in this respect, as the correlations are moderately negative and the value of times are considerable (Table 1).

Table 1. Maximum cross-correlations of courses of force in the forward leg and EMG of GAS muscles (data in brackets denote the corresponding delay/anticipation of exerted force in relation to EMG) – all correlations are statistically significant p<0.05.

Fencer code	LAT GAS (p)	MED GAS (p)
F1	0.743 (0)	0.661 (0.013)
F2	0.861 (0.017)	0.874 (0.025)
F3	0.752 (0.002)	0.673 (0.022)
F4	0.850 (0.022)	0.813 (0.030)
F5	0.854 (0.031)	0.790 (0)
F6	–0.511 (0.473)	–0.524 (0.462)
F7	0.610 (0.013)	0.742 (0.011)

Response time (RET) is understood here as the total of the reaction time (RT) and movement time (MT). As we can see on the basis of the correlation analysis, the temporal values are significantly correlated with the reaction times of the

Table 2. Correlations between response times and movement times and motor response of specific muscles and forces.

Variable	RET	MT	Variable	RET	MT
PRT BB	**0.771***	0.552	**MRT BF**	**0.781***	0.673
MRT BB	–0.572	–0.401	**PRT BF**	–0.093	–0.230
PRT TB	**0.893****	**0.760***	**MRT LAT GAS**	0.614	0.480
MRT TB	–0.071	–0.294	**PRT LAT GAS**	–0.080	–0.120
PRT FCU	0.534	0.262	**MRT MED GAS**	0.633	0.544
MRT FCU	–0.040	0.152	**PRT MED GAS**	–0.141	–0.223
PRT ECR	**0.863***	0.720	**MRT FZ FORWARD**	**0.790***	0.601
MRT ECR	–0.654	–0.651	**PRT FZ FORWARD**	–0.094	–0.140
PRT RF	0.410	0.404	**MRT FZ REAR**	**0.824***	0.623
MRT RF	0.461	0.254	**PRT FZ REAR**	–0.352	–0.344

*p<0.05, **p<0.01

arm muscles (TB and ECR) as well as ones in the BF muscle in the forward leg (Table 2).

It is noteworthy that significant correlations also apply to FZ in the rear leg and FZ in the forward leg in the MRT phase. This fact demonstrates the influence of these muscles on the speed of complex movement still in the premotor phase. Since MT is correlated only with TB, it is legitimate to state a conclusion regarding anticipatory effect of these muscles on the decrease of the sensorimotor response time still in the latency phase.

The MT shows a statistically significant correlation with the maximum value of EMG LAT GAS. A relatively high correlation of RET is with the maximum value of EMG LAT GAS. The found dependencies prove the influence of EMG MAX LAT GAS and the vertical force of the back limb on the time of MT movement (Table 3).

Table 3. Correlations between response and movement time and the maximum values of muscle EMG and force exerted in the vertical back leg over the period of the RET.

Variable	RET	MT
MAX BB	0.390	0.443
MAX TB	0.401	0.470
MAX FCU	0.254	0.341
MAX ECR	0.454	0.472
MAX RF	0.423	0.310
MAX BF	0.570	0.401
MAX LAT GAS	0.741	**0.810***
MAX MED GAS	0.442	0.492
MAX FZ REAR	–0.404	-0.47

*p<0.05

DISCUSSION

When the reports of leading researchers dealing with the structure of the movement pattern of a fencing lunge are taken into account, we can note that due to its common successful outcome, this attack forms the common subject of scientific research. A fencing lunge is considered an offensive action, and forms an attack normally ending in a successful hit of the opponent and a point [14]. During a fencing lunge, movement pattern is mainly executed by the legs, in particular by the rear leg [15], whereas the role of the front leg is to straighten the posture and then execute a hit while considerable force acting through the tibia is exerted [16]. The rear leg is used to generate force and speed of the lunge and is bent at the knee with the foot acting perpendicular to the action. During dynamic extension of the back limb, the forward limb is lifted from the ground and its motor activity includes its displacement in the direction forward.

During a lunge, the energy production of the lower limbs at the beginning is almost exclusively from the rear leg, while the extensors of the forward leg mainly act to contribute to the final phase of braking to stop the movement pattern [17, 18]. The upper limb holding the weapon performs the dominant role as it forms a closed functional chain together with the activity of the rear and forward legs, and the non-dominant upper limb only acts in an auxiliary function.

This study only provided a confirmation of the above motor pattern, as the activation sequence of individual muscles was presented in detail in it. The action is initiated by the gastrocnemius muscles, then the extensor muscles of the arm, then the muscles of the forearm and biceps of the arm, the whole activation is completed by the extensor muscles and the flexors of the front limb (RF and BF). An important innovation of the current work is related to the order of muscle activity in the latency phase, that act as an anticipation following the initial movement of the coach, as well as the movement of the fencer. As it can be seen in Figure 2a, the activation of TB takes place about 200 ms ahead of the remaining arm muscles, whose activation is visible around the baseline – i.e. the initiation of the movement by the fencer forward. Interesting data is provided by the results visible in figure 2b which illustrates the course of the EMG curves of the gastrocnemius muscles in comparison to the GRF curve. Both EMG and GRF occur at a similar intervals already in the RT phase, but we can note that their peaks occur in the MT phase before the final hit. Then the EMG indicators reach 250 uV and the force Fz rear fluctuates around 800 N.

As we can see from Figure 2c, no synergy between EMG and GRF waveforms could be recorded with regard to the forward leg. Already at the moment of RT there are discrepancies and in the MT phase, when the left limb is lifted above the force plate, the FZ forward force declines, whereas RF after approx. 80 ms gains its maximum value at nearly 500uV.

As we can emphasize, and what we consider as a significant merit of the current research, is the fact related to the high correlation coefficient (Table 1) established between the force of the back leg and the gastrocnemius muscle EMG (r = 0.861, $p<0.05$ for LAT GAS and r = 0.874, $p<0.05$ for MED GAS) in the selected fencers. At the same time, the force waveform was delayed by an mean of around 15 ms. This observation provide important inputs since the research needs to take into account the anticipatory activity of EMG before the occurrence of the force curve in the context when we consider the phenomenon of adjustment.

When we perform the analysis of the temporal aspects of a fencing lunge (Table 2), we should note that the six components significantly correlate with the complex motor pattern referred to in this paper as the response time (RET). According to statistical significance, they are, among others PRT TB (0.893, $p<0.01$) PRT ECR (0.863, $p<0.05$) and MRT FZ rear (0.824, $p<0.05$) as strength indicator. Taking into account the fact of marginal interdependencies of the above-mentioned indicators with MT, it can be concluded that they have a significant impact on the initial RET components, i.e. Premotor RT and Motor RT. Therefore, both phases preceding the movement determine efficiency, i.e. shortening the comprehensive Response Time [19, 20].

The entire research procedure demonstrated the considerable influence of the rear leg on the effectiveness of a fencing lunge. This was indicated by the analysis presented above, which demonstrated the relevance of EMG indicators as well as force rear FZ. Therefore, it was justified to investigate the correlation between the EMG of the muscles and the vertical force exerted by the rear leg, and RET and MT. The study only indicated that only EMG MAX LAT GAS affects RET (0.741, $p<0.05$) and MT (0.810, $p<0.05$) [21].

In the summary, the main idea of the work was to investigate the influence of the phenomenon of anticipation on the effectiveness of the most classic technical action in fencing, which is formed by a lunge executed on the trunk in épée. The anticipatory processes take place in the interval between the occurrence of the visual stimulus and the initiation of the attack by the fencer, which forms the first stage of the motor pattern when the task is successfully completed with the trunk hit. The presented research proved that the phenomenon of anticipation concerns both the Premotor Time and Motor RT intervals. This time interval is expressed by the waveform of EMG signal and vertical force. The study results clearly confirmed that the effectiveness of the lunge depends on the time corresponding to the activation of the extensor arm and the volume of EMG generated by the *gastrocnemius* muscles of the rear leg.

CONCLUSIONS

The phenomenon of anticipation is associated with the process of programming sensorimotor responses at the central level and in the premotor phase, where the reaction of ground forces in synergy with EMG also plays an important role. As proven in this study, the decrease of the duration of both phases responsible for reaction times contributes to the reduction of the motor response time MT, and leads to a more effective motor activity.

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