Electromyography, Wavelet Analysis and Muscle Co-Activation as Comprehensive Tools of Movement Pattern Assessment for Injury Prevention in Wheelchair Fencing

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Abstract: The aim of the study was to determine the correct movement patterns of fencing techniques in wheelchair fencers. Through a comprehensive analysis, the key muscles in the kinematic chain exposed to potential injuries were identified. The study participants were 16 wheelchair fencers, divided into two groups representing two categories of disability: Group A (N = 7) comprising fencers with mild paraplegia, having freedom of movement of the trunk and arms; and Group B (N = 9) comprising fencers with a spinal cord injury and partial paresis of the arms. EMG and an accelerometer were used as the main research tools. The EMG electrodes were placed on the muscles of the sword arm as well as on the left and right sides of the abdomen and torso. The EMG signal was transformed using wavelet analysis, and the muscle activation time and co-activation index (CI) were determined. In Group A fencers, first the back and abdominal muscles were activated, while in Group B, it was the deltoid muscle. The wavelet coherence analysis revealed intermuscular synchronization at 8–20 Hz for Group A fencers and at 5–15 Hz for Group B fencers. In Group A fencers, the co-activation index was 50.94 for the right-side back and abdominal muscles, 50.75 for the ECR-FCR, and 47.99 for the TRI-BC pairs of upper limb muscles. In contrast, Group B fencers demonstrated higher CI values (50.54) only for the postural left-side muscle pairs. Many overload injuries of the shoulder girdle, elbow, postural muscles, spine, and neck have been found to be preventable through modification of current training programs dominated by specialist exercises. Modern wheelchair fencing training should involve neuromuscular coordination and psychomotor exercises. This will facilitate the individualization of training depending on the fencer’s degree of disability and training experience.

Keywords: wheelchair fencing; EMG; wavelet analysis; muscle co-activation

1. Introduction

Wheelchair fencing remains one of the most injury-prone Paralympic disciplines. A report following the 2016 Summer Paralympics in Rio de Janeiro concluded that wheelchair fencers ranked second in the number of injuries among 22 disciplines [1]. A diagnostic survey study demonstrated that Paralympians are vulnerable to sports injuries, although for the most part these injuries do not involve long-term recovery [2]. Fencers with disabilities fight with their dominant arm, seated in wheelchairs attached permanently to special platforms [3]. Therefore, their upper limbs are not involved in the movement of the wheelchair as in, for example, rugby, basketball, or tennis for the disabled [4]. Wheelchair fencing is characterized by unique dynamics of the bouts, and fencers’ continuous trunk tilts in the frontal and sagittal planes. The incessant work of the arm and forearm muscles and postural muscles (back and abdominal) create potential and real risks of injuries and overloads of the involved joints and muscles. When comparing disabled and able-bodied
fencers, the former generates about 73% of injuries to the upper limbs, whereas among the latter, about 70% are injuries of the knee and adductor muscles [5]. Based on the report of the International Paralympic Committee published in Human Kinetics Journals [6,7] after the London 2012 Paralympic Games, 15.8% of wheelchair fencers’ injuries were injuries to the shoulder and 32.6% to the elbow. The remaining 40% of injuries, mainly of overload character, occurred in the back, abdomen, neck, and spine. Occasionally, more serious injuries such as fractures and dislocations were also reported [8,9].

These injury percentages provide evidence that shoulder injuries are caused by kinematic chain deficits. It appears that wheelchair fencers are exposed to significant postural stability constraints during combat, which leads to greater upper limb compensation and, over time, to injuries and overloads of the postural muscles. This theory is further supported by the fact that Category B wheelchair fencers (paraplegics) with reduced trunk control were found to have a higher incidence of shoulder and postural muscle injuries compared to Category A wheelchair athletes with greater trunk control. These pilot study results highlight the differences in injury incidence between category A (low level of mobility impairment, e.g., amputees) and category B (paraplegics with significant spinal cord injuries and paresis of the legs) wheelchair fencers. Large-scale epidemiological and biomechanical studies are warranted to gain better understanding of fencing injuries in order to develop effective injury prevention and rehabilitation programs. Specification of prevention methods and precise determination of mechanisms of sports injuries are also necessary. The problem of injuries in sports for the disabled has not yet been subjected to research methodology based on the diagnostic canon’s characteristic of professional sports, including Olympic disciplines, that makes use of new technologies [10].

The aim of this study was to determine the correct movement patterns of wheelchair fencers representing a high international level. The study used surface electromyography to evaluate the EMG signal volume and the timing of activated muscles. The obtained indices provide a model structure of movement patterns during offensive actions in wheelchair fencing. Moreover, the study also implemented EMG signal transforms in the form of wavelet analysis and percentage description of activation time and co-activation of involved muscles expressed by co-activation index (CI).

One of the best tools for a comprehensive analysis of movement and neuromuscular determinants is surface electromyography (sEMG). The decision-making processes in choosing a specific movement reach the skeletal muscles through motor neurons. Bioelectrical muscle tension is defined as the total number of activated motor units expressed in microvolts. This process is illustrated by the EMG signal curve at a given time. EMG signals provide information about the structure and activation sequence of muscles that form a specific movement pattern. The acquired data are used in sports for learning and improving sports techniques and in the physiotherapy of patients with injuries. The advantage of EMG is the possibility to assess the degree and sequence of muscle activation before the execution of a motor task in the anticipation phase of a given movement. This issue should be considered in two regards. First, a precise motor program should activate only those muscles that determine the quality and speed of movement execution in a fully rational and economical manner in accordance with the objective of the motor task. Secondly, in every motor activity the key role is played by mechanisms of postural balance, usually sub-consciously preceding a particular motor task. Through the use of EMG, it is then possible to determine which muscle groups, with how much bioelectrical tension and at what time, maintain balance and stabilize posture before performing a specific sport technique. The activities of the following muscles were examined in the present study: deltoideus middle head (DEL), triceps brachii (TRI), biceps brachii (BC), extensor carpi radialis longus (ECR), flexor carpi radialis (FCR), right latissimus dorsi (LDRT), left latissimus dorsi (LDLT), right external abdominal oblique muscle (EAORT), and left external abdominal oblique muscle (EAOLT).

The above approaches are considered to be the classic methods of EMG signal analysis. In this study, however, a novel approach, i.e., frequency spectrum analysis of the EMG
signal, was proposed as an important complement. The so-called wavelet transform allows for the analysis of non-stationary signals including detailed information about the time-frequency changes in the EMG curve. This phenomenon is used in medicine, for example, to assess disorders of the neuromuscular and cardiovascular systems.

In the present study two groups of antagonist muscles (EDA and LD) were selected and data for both right-side and left-side muscles were analyzed. By monitoring the EMG signal amplitude of the examined muscles, a coherence analysis between muscles was performed for four possible variants of muscle synchronization. This made it possible to analyze anteroposterior and lateral movements.

The results of this study show that in Paralympic wheelchair fencers, muscle activation occurs at low frequency levels, regardless of disability category. Moreover, significantly higher coherence indices were observed in category B fencers at different frequency levels. This may suggest that fencers with more severe neurological deficits (category B) require greater stabilization of trunk muscles in order to maintain stable posture and skillfully perform difficult technical tasks.

The recording of muscle bioelectrical activity makes it possible to demonstrate significant differences in athletes’ performance, even in repetitive motor activities. These differences usually concern the value of the EMG signal, duration of muscle activation, and the simultaneous activity of muscle pairs, i.e., muscle co-activation, occurring when muscles from agonist and antagonist groups simultaneously exhibit co-contraction within a given joint [11,12]. Co-activation involves two groups of muscles contracting at the same time, thereby expressing the percent of movement in which both muscles are simultaneously active. Most commonly, co-activation can be measured from pre-recorded muscle contractions (activity) using surface EMG as the co-activation index calculated as the antagonistic muscle activity divided by the agonistic muscle activity. A decrease in this ratio means that there is more agonist activity or less antagonist activity resisting the movement [13]. The use of the co-activation mechanism is essential in assessing the stability of a given joint and it promotes motor control of particular motor activities [14,15].

The present study used surface electromyography (sEMG) as the main research tool to determine the sequence of activation of particular muscles and co-activation for muscle pairs: TRI–BC, ECR–FCR, LD RT–EAO RT, and LD LT–EAO LT, based on the following assumptions:

- Muscles of the abdomen and the back play a significant role in the muscle activation structure, and they are activated earlier on par with the activation of the sword arm extensor (TRI);
- Longer activation of most muscles in Group B fencers is expected, since these muscles play a stabilizing role, protecting against injuries.

2. Material and Methods

2.1. Participants

The study was conducted at the Polish Paralympic team’s training camp before the 2019 IWAS Wheelchair Fencing World Championships in South Korea. Sixteen members of the Polish Paralympic wheelchair fencing team (disability category A—7 members; disability category B—9 members) participated in the study. The fencers’ mean basic data were as follows: category A fencers, age (years)—33.58 (±6.26), body height (m)—1.74 (±0.08), body mass (kg)—69.01 (±8.92), and training experience (years)—15.28 (±6.31); category B fencers, age (years)—31.33 (±9.68), body height (m)—1.64 (±0.10), body mass (kg)—58.66 (±10.29), and training experience (years)—7.01 (±2.41). The wheelchair fencers under study represented the highest international level and included multiple medal winners of the Paralympic Games.
2.2. Methods and Tools

The research project was approved by the Bioethics Committee of the Opole Medical Chamber (Resolution No. 237 of 13 December 2016) and was in accordance with the Declaration of Helsinki guidelines regarding the conduct of clinical trials on humans.

The study was performed using a 16-channel EMG system (Noraxon, DTS, Desktop Direct Transmission System, Scottsdale, AZ, USA) with a 16-bit sampling accuracy at 1500 Hz. The MyoResearch XP Master Edition for DTS Noraxon system was used for data analysis. To synchronize the EMG system a wireless unit (a 3-axis wireless DTS 3D accelerometer sensor with the nominal output range of \( \pm 6 \) g, sensitivity of \( \pm 0.67 \) V/g, and bandwidth of 5 Hz–1.8 kHz) was used to transmit the EMG signal directly to a PC. The EMG signals were subjected to data rectification.

The sequence of bioelectrical muscle activity was determined by manually selecting the onset and offset of the raw recording of a particular muscle activity while observing the EMG signal waveform [16]. The study protocol followed the SENIAM project guidelines [17]. The series of fencing actions was divided into three attempts in a single set of direct thrusts to a visual stimulus.

Muscle activity time was assessed using the three attempts performed in a single set. The attempts were divided into single sequences. The activity time was calculated as the percentage of the three attempts divided by the time of the entire action. The fencers performed thrusts on the coach’s torso in response to a visual stimulus, which was a quick motion of the coach’s blade from parry quarte to parry sixte. An accelerometer was attached to the knuckle guard of the coach’s weapon to accurately measure the movement timing.

The next measure was complex reaction time (CRT) calculated as the interval between the first significant change in the accelerometer signal and the highest EMG value.

Wavelet coherence was used for the analysis of nonstationary signals. The coherence is computed using the analytic Morlet wavelet. The wavelet coherence of two time series \( x \) and \( y \) is:

\[
\frac{|S(C_x^*(a,b)C_y(a,b))|^2}{S(|C_x(a,b)|^2) \times S(|C_y(a,b)|^2)}
\]

where \( C_x(a,b) \) and \( C_y(a,b) \) denote the continuous wavelet transforms of \( x \) and \( y \) at scales \( a \) and positions \( b \), respectively. The superscript * is the complex conjugate and \( S \) is a smoothing operator in time and scale.

2.3. Co-Activation Index (CI)

To estimate relative co-activation (co-contraction of both muscles) for muscle pairs: TRI–BC, ECR–FCR, LD RT–EDA RT, or LD LT–EDA LT, the co-activation index (CI) was calculated according to the method proposed by Falconer and Winter [18]. Co-activation was calculated based on the following equation:

\[
CI = \frac{2I_{ant}}{I_{total}} \times 100\%
\]

where \( I_{ant} \) is the area of total antagonist muscle activity expressed by the following equation:

\[
I_{ant} = \int_{t_1}^{t_2} EMG_{ANT1}(t)\,dt + \int_{t_2}^{t_3} EMG_{ANT2}(t)\,dt
\]

where \( t_1 \)–\( t_2 \) is the time during which \( EMG_{ANT1} \) is lower than \( EMG_{ANT2} \); \( t_2 \)–\( t_3 \) is the time during which \( EMG_{ANT2} \) is lower than \( EMG_{ANT1} \); and \( I_{total} \) is integral of the sum of \( EMG_{ANT1} \) and \( EMG_{ANT2} \) during task performance. Data were calculated using the equation below:

\[
I_{total} = \int_{t_1}^{t_3} [EMG_{agon} + EMG_{ant}](t)\,dt
\]
3. Results

The sequence of bioelectrical activity of muscles in response to a visual stimulus was determined with the use of EMG. It was demonstrated that fencers in Group A activated first the muscles of the back (LD RT and LD LT) and then the deltoid muscle (DEL RT), the external abdominal oblique muscle (EAO RT), the forearm muscles (ECR RT), and the triceps brachii extensor (TRI RT). At the end of the thrust phase, the flexors (BC RT and FCR RT) were activated.

In fencers from Group B, it was the forearm muscles (ECR RT), abdominal muscles (EDA LT and RT), and muscles of the back (LD LT and RT) that were activated first, followed by the upper limb muscles (BC RT, DEL RT, and TRI RT). At the end of the thrust the flexor carpi radialis muscles (FCR RT) were activated.

The results of a non-parametric test for two independent samples (Wald–Wolfowitz Runs Test) confirmed the above analysis. The shortest activation time was recorded for the LDLT (Group A—0.333 ms; Group B—0.522 ms; \( p = 0.039 \)). However, in intergroup comparisons, with respect to the EMG signal expressed as % of MVC, there were higher MVC values in most of the examined muscles. In this case, the highest statistical significance value was observed for the DELRT (114.63) in category A fencers, and 65.50 in category B fencers (\( p = 0.039 \)). This proves the key significance of the back and upper limb muscles in the structure of offensive actions in wheelchair fencing.

A detailed wavelet coherence analysis revealed intermuscular synchronization at 8–20 Hz in Group A fencers and at 5–15 Hz in Group B fencers. It is significant that coherence increases after the cessation of the most intense activity (offensive action), up to several ms in the range of 60–100 Hz. In addition, previous studies have shown that individuals with high degrees of spinal cord injury displayed higher EMG activity of the trunk muscles while sitting compared to individuals with low degrees of injury. The results of this study revealed that in Paralympic wheelchair fencers, muscle activation occurred at low frequency levels, regardless of disability category. Moreover, significantly higher coherence indices were noted in category B fencers, at different frequency levels. This may indicate that individuals with more severe neurological deficits (disability category B) require greater stabilization of trunk muscles in order to maintain stable posture and skillfully execute difficult technical tasks.

EMG signals were recorded at a sampling rate of 10 KHz. Three frequency bands (2–16, 17–30, and 31–60 Hz) were selected for analysis, and all coherence scores in each specific band from each fencer were averaged to obtain a high average coherence for a given frequency band.

The investigation of muscle co-activation showed that wheelchair fencers displayed a diverse pattern of muscle co-activation indices expressed as a percentage. Considering the actions on the visual stimulus (thrust to the torso in response to the coach’s movement), the fencers in Group A demonstrated higher co-activation in the right-side back and abdominal muscles (50.94) and the upper limb muscle pairs ECR–FCR (50.75), TRI–BC (47.99). In contrast, fencers in Group B reported higher values only for the left-side postural muscle pairs (50.54).

4. Discussion and Conclusions

The study results point to slight differences between wheelchair fencers from groups A and B with regard to the sequence of muscle activations. In Group B fencers, the movement commenced with the deltoid muscle and then the abdominal muscles. The further sequence was the same as in Group A fencers. It should be emphasized that in both groups of wheelchair fencers, the trunk and abdominal muscles performing postural functions were equally significant [19]. In accordance with Anticipatory Postural Adjustments (APAs) [20], these muscles are activated first or in synergy with the arm extensor muscles. The high dynamics of movement results in balance disturbances. In order to maintain a stable posture, the central nervous system triggers an anticipatory mechanism that activates postural muscles. An analogous effect is observed in able-bodied fencers in the form of
anticipatory activation of muscles (from a few to about 150 ms) of the rear leg, in particular, the gastrocnemius muscle, during the fencing lunge [21]. Thanks to the APA phenomenon the fencer can maintain a stable posture in the wheelchair and quickly move the torso towards the target area following the attacking arm. APAs occur in the trunk during tasks such as rapid limb movement and are impaired in individuals with musculoskeletal and neurological dysfunction. To understand APA impairment, it is important to first determine if APAs can be measured reliably and which characteristics of APAs are task-invariant. Characteristics of trunk muscle APAs quantified during a single task may not be representative of an anticipatory postural control strategy that generalizes across tasks. Therefore, APAs must be assessed during multiple tasks with varying biomechanical demands to adequately investigate mechanisms contributing to movement dysfunction [22]. This results in reduced complex reaction time and movement time in response to the opponent’s actions [23,24].

The wavelet analysis also demonstrated the importance of postural muscles in wheelchair fencing training. The specialist training of the trunk and abdominal muscles significantly contributes to improved postural control and balance in wheelchair fencers. Due to the integrity of the motor and sensory neurological system, any neurological deficits can be compensated by the conscious activation of the trunk and abdominal muscles during the preparatory phase, as well as during and after the execution of an offensive technique. Wavelet analysis is a valuable muscle activation assessment tool in the range of lower frequencies, otherwise undetectable by traditional analysis of correlation [25]. The presented method can find application in physiotherapy, as a diagnostic tool, and in the monitoring of training of disabled athletes.

The analysis of muscle activation time—as a percentage of three performed attempts in a set—confirmed the earlier assumptions. The fencers from Group A demonstrated shorter activation times in almost all muscles except for the ECR (58.24) compared to Group B fencers. It can be said that postural muscles (abdominal and back) are activated for a shorter time, which confirms the validity of the sequence of activation of postural muscles according to the previously learned technical patterns. This is related to the activation of antagonist muscles, representing a centrally programmed anticipatory mechanism affecting the stabilization of technical actions. As shown by other authors, higher activity levels of antagonist muscles were noted in elite athletes (karatekas) compared to novice practitioners [26,27]. The general assumption of longer activation of most muscles in Group B fencers in intergroup comparisons is, therefore, confirmed. These muscles play a stabilizing role, protecting against injuries. The desired standard co-activation index of the Paralympic wheelchair fencers under study representing two disability categories was within the approximate range of 48 to 51%.

In conclusion, a comprehensive analysis of the movement patterns of wheelchair fencers enabled the identification of key muscles determining the effectiveness of technical actions. It also demonstrated which of the muscle groups in the kinematic chain are at risk of potential injuries. It is worth mentioning that the continuous increase of training loads combined with pressure on sports performance contribute to more frequent injuries. Disabled athletes are more likely to experience injuries than able-bodied athletes. One explanation for this phenomenon may be the so-called “truncated kinematic chain theory”, according to which, interrupting the kinematic chain by the inactivity of the lower limbs is more likely to result in an injury [28].

Several applications can be suggested to eliminate the risks associated with the incorrect process of teaching movement habits. It should be concluded that many injuries of the shoulder girdle, elbow and postural muscles, spine, and neck due to overloading can be avoided by modifying the current training programs dominated by specialist exercises: individual lessons with a trainer and free-form sparring fights. It is necessary to complement daily fencing training with psychomotor and neuromuscular coordination exercises with elements of stretching. New technologies such as EMG and movement analysis sensors are
essential to prevent technical errors and to individualize the training process depending on the athlete’s degree of disability and training experience.

**Main limitations:** although the presented tests may be a valuable tool for the prevention of injuries, in the future the research protocol should be strengthened with a detailed interview on the occurrence of contusions, overloads and injuries. Furthermore, this study does not reflect any technique (video recording or any other recording technique) that allows the variations detected in the EMG to be correlated with the technique used in order to correct or improve it. In addition, long-term observation of athletes enhanced with the use of optometric systems in the pre- and post-competition period should be implemented to determine the condition of the key muscles in the direction of overload.

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**Data Availability Statement:** The data presented in this study are available on reasonable request from the corresponding author.

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**References**

27. Szczańcowa, A.; Blaszczyszyn, M.; Pawłyta, M. Optical motion capture dataset of selected techniques in beginner and advanced Kyokushin karate athletes. *Sci. Data* 2021, 8, 13. [CrossRef]