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Article

Biomechanical analysis of fencing techniques: Insights from motion capture and analysis

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Abstract: This work explores the biomechanical characteristics of key actions in fencing techniques using motion capture and biomechanical analysis technology, aiming to provide scientific evidence for athlete training and performance. The work combines eight infrared high-speed cameras with the Delsys surface Electromyography system for synchronized analysis, making an innovative contribution to the biomechanical research of fencing techniques. This technological combination allows for more precise tracking of an athlete's three-dimensional movement trajectories and muscle activation, and offers new perspectives and more accurate guidance for training. The results are as follows. (1) During the forward lunge step, the integrated electromyographic activity of the deltoid muscle significantly increases (152.55 μV·s, p = 0.045), indicating a higher demand for arm stability in this movement. There are no significant differences in the activation levels of the biceps brachii and triceps brachii. The activation of the forearm muscles, specifically the extensor carpi radialis longus and extensor carpi radialis brevis, is significantly enhanced, at 81.61 μV·s (p = 0.047) and 98.72 μV·s (p = 0.049), respectively. For the lower limbs, the activation of the tibialis anterior muscle significantly increases (110.34 μV·s, p = 0.000). The activation of the gastrocnemius medialis and gastrocnemius lateralis also significantly enhances, with values of 53.22 μV·s (p = 0.001) and 35.75 μV·s (p = 0.000), respectively. The contribution of the deltoid muscle significantly increases to 31.2%, while the tibialis anterior muscle contribution increases to 26.5%. (2) The work also compares muscle activity, movement characteristics, and biomechanical parameters across athletes of different skill levels (beginner, intermediate, and advanced). The results show that the beginner group has the highest electromyography activity intensity (45.2 ± 5.1 μV), while the advanced group has the lowest (32.5 ± 3.8 μV). The movement trajectory stability is 12.3 ± 2.1 mm/s for the beginner group and 6.5 ± 1.2 mm/s for the advanced group. These results suggest that advanced athletes exhibit higher training effects in muscle activation efficiency and energy economy. These findings provide important theoretical support for optimizing fencing training methods and improving athletic performance.

Keywords: fencing techniques; motion capture; biomechanics; integrated electromyography; muscle contribution rates

1. Introduction

Fencing is a combat sport centered around skill and tactics, and it requires athletes to move quickly and make precise tactical adjustments on a 14-meter-long piste to find the optimal attack timing. Success in fencing depends not only on the athlete's reaction speed and tactical judgment but is also closely related to their biomechanical characteristics. Athletes achieve effective scoring by precisely controlling the trajectory of the sword tip, rapidly traversing complex spaces to strike their opponents. The lunge attack, as one of the core offensive movements in fencing, is frequently used in competitions and directly impacts the athlete's performance [1,2]. The lunge attack can be divided into the static lunge and the lunge performed while moving, with the latter being more commonly used in actual competition. Research has shown that in high-level fencing events, male athletes perform a lunge attack on average every 23.8 s, while female athletes perform it even more frequently, approximately every 20 s [3,4]. Such high-frequency attacking movements require athletes to have strong lower-body strength. In particular, explosive power and quick reaction training are crucial for executing rapid and precise lunges. Studies have also pointed out that horizontal movement speed and sword tip speed are key factors in determining the effectiveness of scoring with a lunge attack.

Sports biomechanics is a discipline that studies the structure and function of human movement and it plays a critical role in the field of sports training. By analyzing the mechanical properties of human movement, it helps to deepen the understanding of the relationship between force and motion in fencing movements [5]. In a fencing competition, athletes need to coordinate the movements of their torso and sword-hand arm precisely, and constantly adjust their relative position to the opponent to create optimal timing for both offense and defense [6]. Meanwhile, the athlete's attacking rhythm, coordination, and precision play an important role in the competition, especially when finding the right fighting position and the best timing for an attack. The fencing technique not only relies on efficient muscle activation but also demands high tactical awareness and body control from the athlete.

The lunge attack is not only a core offensive technique in fencing but also serves as the foundation for defensive and counter-attacking movements. Efficient use of the lunge technique, combined with quick stops, landings, and continuous braking, can provide athletes with a critical tactical advantage [7]. An in-depth analysis of the lunge technique helps to understand how athletes can attack quickly and precisely while maintaining balance and responding to the opponent's defense. Optimizing such techniques improves the athlete's scoring ability and reduces the risk of injury due to improper movements [8,9].

In summary, the biomechanical analysis of fencing techniques aids in understanding the athlete's performance in competitions and provides a scientific basis for optimizing training methods and improving techniques. By systematically studying key biomechanical parameters in fencing movements, more precise technical guidance can be provided to athletes, while also offering important support for injury prevention and training program development. Therefore, this work focuses on analyzing key actions in fencing, and exploring how their biomechanical characteristics affect athlete performance. It intends to provide theoretical support and practical guidance to improve the competitive level of fencing athletes.

2. Related work

Many studies have explored the biomechanical characteristics of fencing techniques. However, there are some limitations in methods and data analysis, especially in the application of muscle activation Artificial Intelligence/Machine Learning (AI/ML) methods, where many gaps remain to be filled. Aresta et al. [10] conducted a systematic review analyzing the role of sports techniques in supporting fencers, including 35 studies. They found that differences in kinematics and dynamics among fencers were closely related to gender and training background. However, most studies have used photometric systems and force platforms to analyze the lunge technique of professional athletes, with only nine studies (25.7%) assessing muscle activation. Furthermore, the application of AI/ML methods accounted for less than 20%, indicating a significant gap in data analysis methods. The review pointed out that the potential contribution of kinematic/dynamic data and physiological measurements had not been fully utilized. It suggested that future research should strengthen the application of related technologies to provide a more comprehensive analysis framework for fencing techniques [10]. Although Aresta et al.'s study laid the foundation for biomechanical analysis of fencing techniques, it remains insufficient in evaluating muscle activation patterns and further applying AI/ML methods. Riyahi et al. [11] compared the upper limb kinematics of elite male and female Iranian national team fencers when executing the lunge technique using kinematic analysis. They found that although male athletes significantly reduced their reaction and movement times, there were no significant differences in other kinematic parameters between male and female athletes. This result suggested that the time differences in the lunge technique reflected differences in training strategies rather than differences in the technique itself [11]. However, their study did not explore the role of the lower limbs in the lunge technique in-depth, particularly the impact of explosive power and speed on technical performance. This presents a potential avenue for future research. Chida et al. [12] explored the effectiveness of two-dimensional video analysis in assessing the lunge technique of fencers. They found that two-dimensional video analysis showed a high correlation with three-dimensional motion analysis when measuring knee joint angles of the front and back legs in the sagittal plane, with correlation coefficients ranging from 0.93 to 0.99. However, there was a significant deviation in the angle measurements of the ankle and hip joints between two-dimensional and three-dimensional analysis, suggesting that three-dimensional motion analysis should be used for these areas. This study supported the use of simplified motion analysis methods in competitive settings. Meanwhile, it highlighted the need for improved precision in analyzing key areas and provided direction for future optimization of video analysis technology [12]. Tona et al. [13] focused on the attack speed of Indonesian fencers. They pointed out that athletes' attack speeds in competitions failed to reach ideal levels due to inadequate training plans, limiting scoring opportunities. The measured average attack speed was 4.37 meters per second, and they recommended specialized speed training to improve the athletes' attack efficiency. Their study revealed the direct impact of training programs on athletes' technical performance but did not explore the relationship between attack speed and lower limb strength, explosive power, and other biomechanical parameters. This provides room for further exploration of this work [13]. Di Martino et al. [14] assessed the impact of fencing training on posture parameters in elite athletes. The findings revealed that although there were no significant anthropometric differences between athletes, 30.8% of participants exhibited abnormal postural tension, especially among epee fencers. This result suggested that long-term asymmetrical training could affect postural stability and it required individualized adjustments to improve posture control. While their study revealed the impact of fencing training on athletes' posture, it did not delve into the specific impact of different technical styles and training methods on posture control. This provides potential for future research [14]. Watanabe et al. [15] conducted an in-depth study on the neuromuscular performance of 19 adolescent fencers, and focused on parameters such as Maximum Voluntary Contraction, Unilateral Vertical Jump, Muscle Thickness, and Motor Unit Firing Rate. They found a strong positive correlation between the front and back legs in fencers with more than three years of fencing experience but no such correlation in athletes with less than three years of experience. This indicated that longer fencing experience led to greater lateralization of neuromuscular components, and dynamic muscle strength lateralization decreased with increased experience. While their study provided important data on neuromuscular performance, it did not explore the relationship between neuromuscular performance and technical movements. This can be further investigated at the technical level in future research [15].

These studies provide rich theoretical foundations for the biomechanical analysis of fencing techniques. Moreover, they also reveal some limitations in current research, such as the assessment of muscle activation patterns, the application of data analysis methods, and the impact of training on athlete performance. This work aims to address these gaps by further exploring muscle activation patterns, the relationship between lower limb strength and speed, and applying more advanced data analysis techniques. It intends to provide scientific evidence for optimizing fencing techniques and athlete training.

3. Theory and methodology

3.1. Theoretical basis

Based on the theoretical basis of sports biomechanics, this work takes the human body as a complex multi-degree-of-freedom motion system. It carefully analyzes the motion path of each joint and the activation state of the muscle to reveal the biomechanical characteristics behind different technical movements. Biomechanics theory provides a framework for this work. This endeavor facilitates a profound comprehension of the mechanical attributes, muscular activity, and joint mobility within human locomotion. This permits a mastery of the dynamic and kinematic sequences of actions.

Electromyographic (EMG) is a kind of methodology that records and analyzes the electrical impulses generated during muscular contractions. It is used to measure the muscle potential during constriction to mirror the activation status of the muscle [16]. The main features of an EMG signal are its magnitude and frequency. The two play a great part in appraising muscle power output, fatigue levels, and coordination. Surface electromyography (sEMG) is a kind of non-invasive means of measurement. It is used to discern the electrical activity of subcutaneous muscles by way of positioning electrodes on the skin's exterior [17]. Needle-pole EMG entails the direct insertion of electrodes into muscle tissue and it is more suitable for the in-depth examination of the activities of particular muscle clusters [18]. EMG has a wide application in evaluating muscle dynamic capabilities in sports analytics and biomechanical investigations. For instance, through the scrutiny of EMG signals during diverse technical maneuvers, this work is able to reveal the patterns of muscle involvement and coordination. It can furnish a scientific underpinning for the refinement of sports training.

Integrated Electrography (IEMG) is a numerical value that is obtained through the integration of the EMG signal. It is an indicator of the cumulative telecommunication signal strength associated with muscle activity [19]. By aggregating the absolute magnitude of the original EMG signal, IEMG can present the comprehensive electrical activity that transpires during muscle contraction. It is frequently harnessed to assess muscle exhaustion, power generation, as well as the degree of neuromuscular regulation [20–22].

3.2. Experimental equipment and data processing

The subsequent apparatus and procedures are employed for the collection of experimental data:

Motion Capture Apparatus: A suite of Vicon systems furnished with 8 infrared high-speed cameras is utilized here. This particular system records the three-dimensional motion paths of fencing athletes' technical maneuvers at a sampling frequency of 200 Hz. To guarantee that the captured data precisely mirrors the movement traits of the body, markers are positioned at crucial regions of the athlete's physique, such as the shoulders, elbows, wrists, hips, knees, and ankles.

EMG Signal Acquisition Setup: The Delsys sEMG system is engaged to log the surface electromyography signals of the principal muscle groups in the athletes' upper and lower extremities. The sampling rate is 1000 Hz. These muscle groups include deltoid, biceps brachii, triceps brachii, extensor carpi radialis, tibialis anterior, gastrocnemius, quadriceps femoris, biceps femoris, and gluteus maximus. By placing electrodes on these muscles, this work can analyze the activation of these muscles in technical movements.

Data processing software: Visual 3D software is adopted for the processing of the motion capture data. Then, it is essential to calculate and the angle change and motion trajectory of each joint through its kinematics analysis module. Meanwhile, this work also uses Matlab software to further process the EMG signal, including filtering, normalization and IEMG calculation.

3.3. Experimental procedure

Ten university students with at least three years of fencing experience (6 males, 4 females), aged between 20 and 24 years, are selected as participants. The participants have an average height of 175.3 ± 5.8 cm and an average weight of 68.4 ± 7.1 kg. All participants provide informed consent prior to the experiment, ensuring both safety and voluntariness throughout the experimental process. **Figure 1** illustrates the experimental procedure.

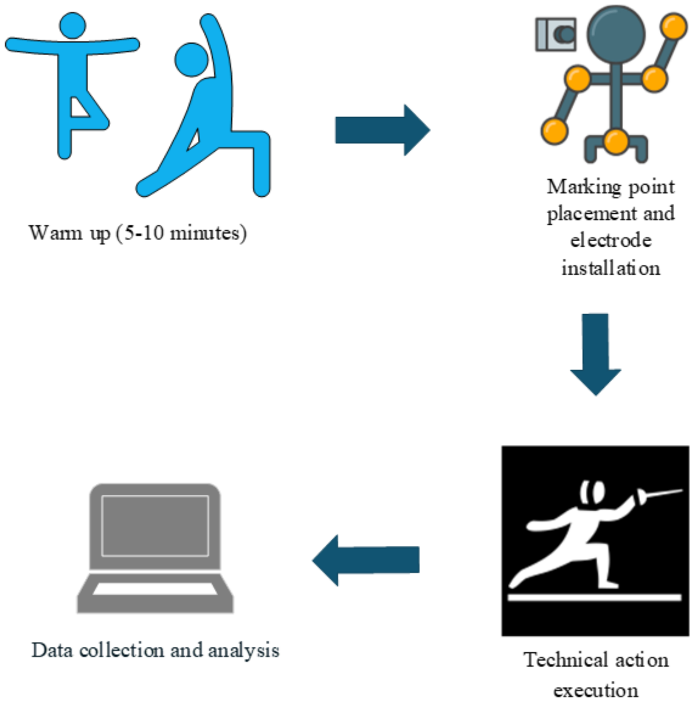


Figure 1. Experimental procedure flowchart.

As shown in **Figure 1**, the experiment is divided into the following stages:

(1) Preparation Phase: Participants warm up with 5–10 min of dynamic stretching to familiarize themselves with the experimental procedures and requirements.

(2) Marker and Electrode Placement: Motion capture markers are attached to specific points on the participants' bodies, and sEMG electrodes are placed on corresponding muscle groups.

(3) Execution of Techniques: Participants perform two fencing techniques, the single lunge and forward lunge, within a standard fencing environment. Each technique is repeated five times to ensure data reliability [23–25].

(4) Data Collection and Analysis: Immediately following the exercises, motion capture and EMG data are collected and analyzed for subsequent biomechanical analysis.

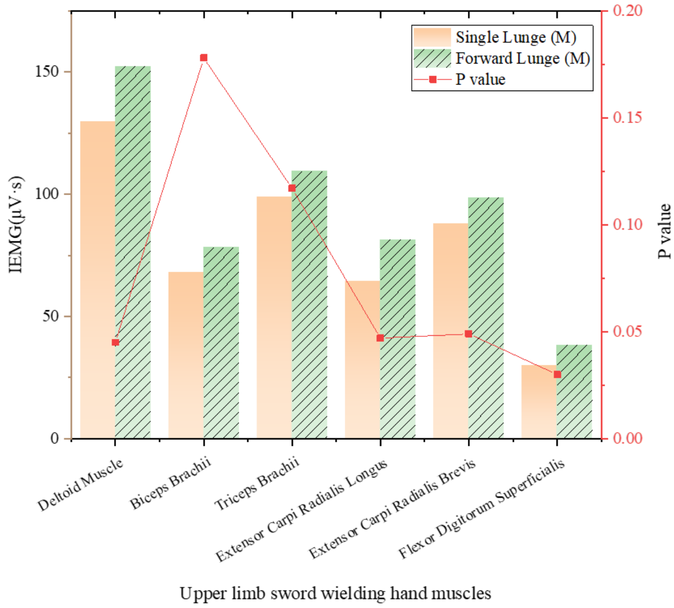
Through this process, the biomechanical characteristics of different fencing techniques are revealed, providing data to support personalized and scientifically informed fencing training.

4. Experimental results and analysis

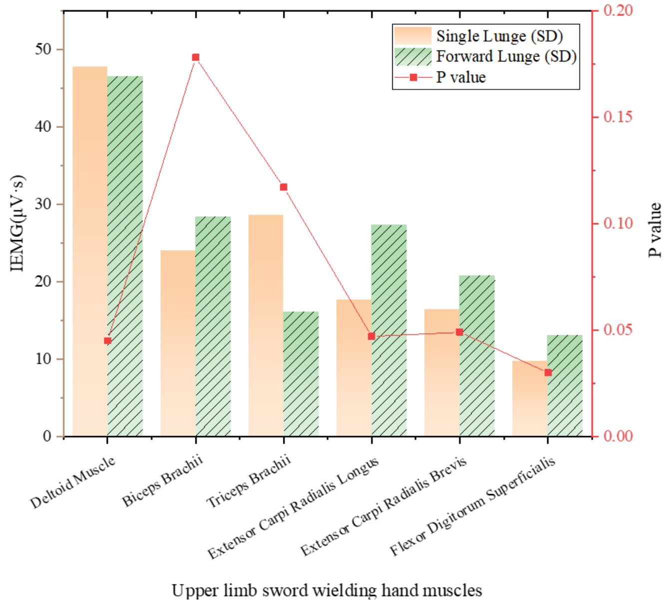
4.1. EMG signal processing and analysis results

4.1.1. IEMG results of the sword-wielding hand muscles

IEMG analysis Is conducted to examine the muscle activity of the sword-wielding hand during the execution of single lunge and forward lunge techniques. **Figure 2** presents a comparison of the IEMG parameters for the sword-wielding hand muscles in these two techniques.



(a)



(b)

Figure 2. Comparison of IEMG parameters for sword-wielding hand muscles in two techniques. **(a)** mean IEMG; **(b)** standard deviation of mean IEMG.

Figure 2 suggests that in the single lunge technique, the deltoid muscle exhibits an IEMG of 129.8 μV·s, which significantly increases to 152.55 μV·s during the forward lunge (p = 0.045). This suggests a higher activation of the deltoid in the forward lunge, contributing to enhanced stability and control in the movement. The biceps brachii shows IEMG values of 68.33 μV·s and 78.39 μV·s for the single lunge and forward lunge, respectively, but without a significant difference (p = 0.178). This indicates relatively consistent involvement and stability in the function of biceps brachii across both techniques. The triceps brachii demonstrates IEMG values of 98.97 μV·s and 109.5 μV·s (p = 0.117), also showing no significant difference, implying stable triceps engagement between the two techniques. In forearm muscles, the extensor carpi radialis longus displays an IEMG of 64.67 μV·s in the single lunge, significantly increasing to 81.61 μV·s in the forward lunge (p = 0.047). It indicates a higher activation demand for this muscle during the forward lunge. The extensor carpi radialis brevis also presents a significant difference, with IEMG values of 88.11 μV·s and 98.72 μV·s for the single lunge and forward lunge, respectively (p = 0.049), highlighting greater activation in the forward lunge. For the flexor digitorum superficialis, the IEMG is 29.89 μV·s in the single lunge and significantly higher at 38.44 μV·s in the forward lunge (p = 0.030). The results show significant differences, which may be related to the demands for sword grip and finger control during the technical movements.

In the single lunge, the standard deviation for the deltoid muscle is 47.74, indicating a certain degree of individual variation, while in the forward lunge, it is 46.58, showing relatively smaller differences. The standard deviations for the biceps brachii and triceps brachii in both technical movements are relatively consistent, measuring 24.05 and 28.65 (single lunge) and 28.45 and 16.15 (forward lunge), respectively. It indicates that participants demonstrate relatively stable performance in these two actions. Regarding the standard deviations for the forearm muscles, the standard deviation for the extensor carpi radialis longus in the single lunge is 17.72, while it increases to 27.36 in the forward lunge, suggesting potential individual differences in forearm muscle engagement. The standard deviations for the extensor carpi radialis brevis in both movements are 16.38 and 20.84, respectively, also reflecting some degree of individual variation. In summary, these results indicate significant differences in the IEMG of upper limb muscles during different fencing techniques, and the standard deviations for each muscle group reflect individual differences among athletes in technical execution. These findings provide important evidence for further optimizing fencing training methods and techniques.

4.1.2. IEMG results of swing leg muscles

Figure 3 presents a comparison of the IEMG parameters of the swing leg muscles during the two technical movements.

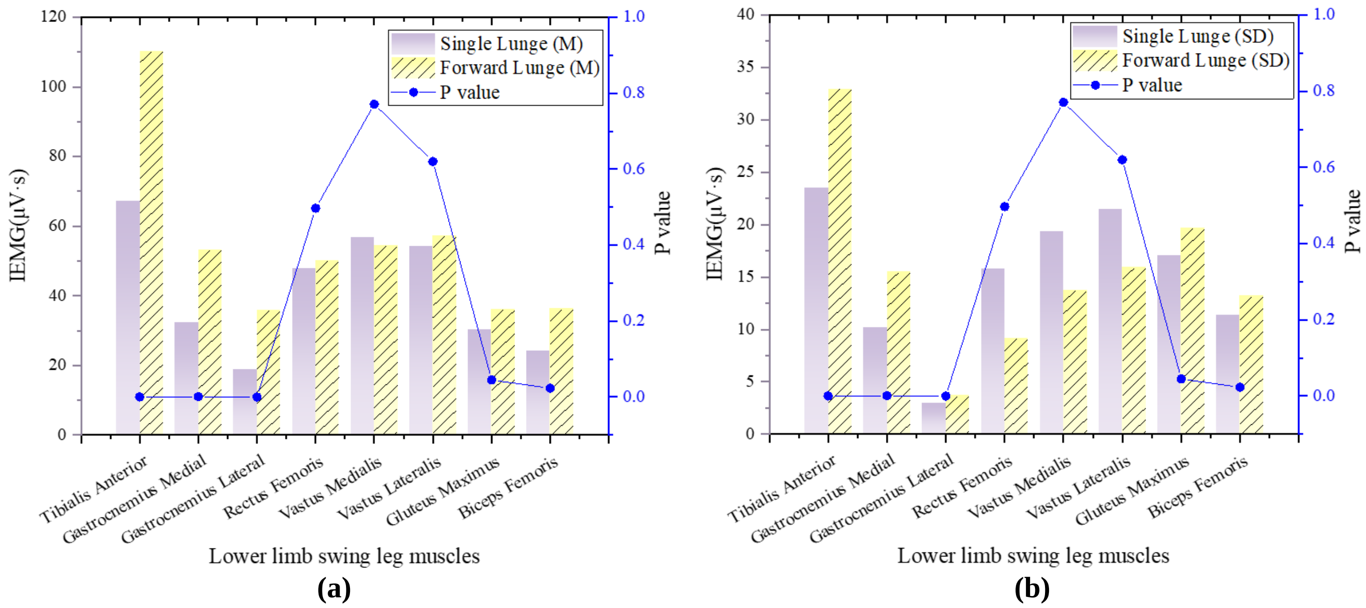


Figure 3. Comparison of IEMG parameters of swing leg muscles in two technical movements. **(a)** mean IEMG; **(b)** standard deviation of mean IEMG.

Based on the data presented in **Figure 3**, the mean IEMG value for the tibialis anterior significantly increases to 110.34 μV·s during the forward lunge ($p = 0.000$), compared to 67.25 μV·s for the single lunge. This indicates a significantly higher demand on the tibialis anterior during the forward lunge technique. The mean values for the gastrocnemius medialis and gastrocnemius lateralis also show significant increases during the forward lunge, reaching 53.22 μV·s ($p = 0.001$) and 35.75 μV·s ($p = 0.000$), respectively. This reflects a clear impact of this technique on the activation of lower limb muscles. In contrast, the rectus femoris, vastus medialis, and vastus lateralis show no significant differences in mean IEMG values between the two movements, with values of 50.12 μV·s ($p = 0.497$), 54.44 μV·s ($p = 0.771$), and 57.18 μV·s ($p = 0.620$). It indicates a relatively stable role for these muscles across the different techniques. Additionally, the mean IEMG values for the gluteus maximus and biceps femoris during the forward lunge are 36.12 μV·s ($p = 0.045$) and 36.22

μV·s (p = 0.023), respectively. It demonstrates an increased demand for activation of these muscles in this technique.

Examining the standard deviations listed in **Figure 3b**, it is observed that the standard deviations for the tibialis anterior, gastrocnemius medialis, and gastrocnemius lateralis increase during the forward lunge, measuring 32.98, 15.49, and 3.67, respectively. This may reflect individual differences among athletes when executing this technical movement. Conversely, the standard deviations for the rectus femoris, vastus medialis, and vastus lateralis are relatively small, indicating consistent activation patterns with minimal individual variation. In summary, the findings highlight that different fencing techniques significantly influence the activation levels of lower limb muscles and individual differences, providing a basis for optimizing fencing training methods.

4.2. Analysis results of muscle contribution rate

4.2.1. Comparison of muscle contribution rates in the sword-wielding hand

Here, the contribution rate of each muscle in single lunge and forward lunge techniques is discussed in depth, aiming at revealing the relative activation degree of different muscles in action. The muscle contribution rate is obtained by calculating the percentage of the IEMG value of each muscle to the total muscle activation of the arm. **Figure 4** shows the comparative results of the muscle contribution rate of the sword-wielding hand.

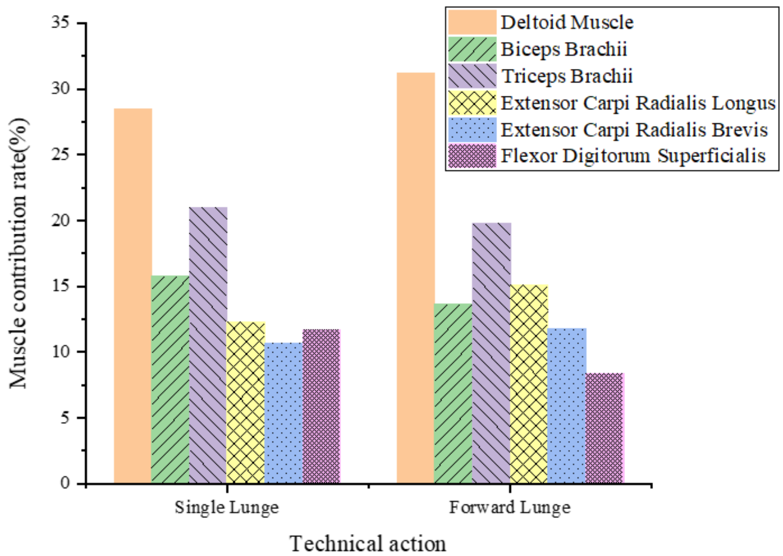


Figure 4. Comparison of muscle contribution rates in the sword-wielding hand.

In the analysis of single lunge and forward lunge, it is found that the contribution rate of deltoid activation increases from 28.5% in a single lunge to 31.2% in a forward lunge. This significant increase implies that the deltoid muscle is more involved in performing forward lunges. The reason is that this particular action requires greater arm stability and power output to prop up the forward extension of the upper limbs as well as the forward shift of the body's center of gravity. In addition, the contribution rate of biceps brachii activation shows a slight decline. It drops from 15.8% in a single lunge to 13.7% in a forward lunge. This suggests that in the forward lunge, in addition to an increased involvement of the upper limbs, there is a heavier reliance on the stability of the shoulder and forearm muscles. Besides, the participation of the elbow flexors diminishes to some extent. In the case of a single lunge, the activation contribution rate of the triceps brachii stands at 21.0%, yet it decreases to 19.8% in the forward lunge. This result suggests that the primary role of the triceps brachii in the forward lunge remains to maintain the extension of the arm, and the alteration in the requirement for power output is relatively minor. The activation contribution rate of the extensor carpi radialis longus witnesses a significant increase, rising from 12.3% in a single lunge to 15.1% in a forward lunge, and that of the extensor carpi radialis brevis ascends from 10.7% to 11.8%. These outcomes demonstrate that the forward lunge technique lays more stress on wrist control. Especially when grasping a sword, the need for wrist strength becomes more pronounced. The activation contribution rate of the flexor digitorum superficialis is 11.7% in a single lunge. However, it decreases to 8.4% in the forward lunge. This occurs because the function of the flexor digitorum superficialis is relatively insignificant in a forward lunge. Besides, there is a need for more strength from other substantial muscle groups in the arm. The purpose is to uphold posture stability and maintain control over the sword.

4.2.2. Comparison of muscle contribution rates in the swinging leg

This section proceeds to conduct a more in-depth examination of the activity levels of the muscles within the swinging legs during both the single lunge and the forward lunge. The objective here is to pinpoint the muscle groups that exhibit the highest levels of activity in these two distinct technical maneuvers. **Figure 5** presents a comparative illustration of the muscle contribution rates pertaining to the swing leg.

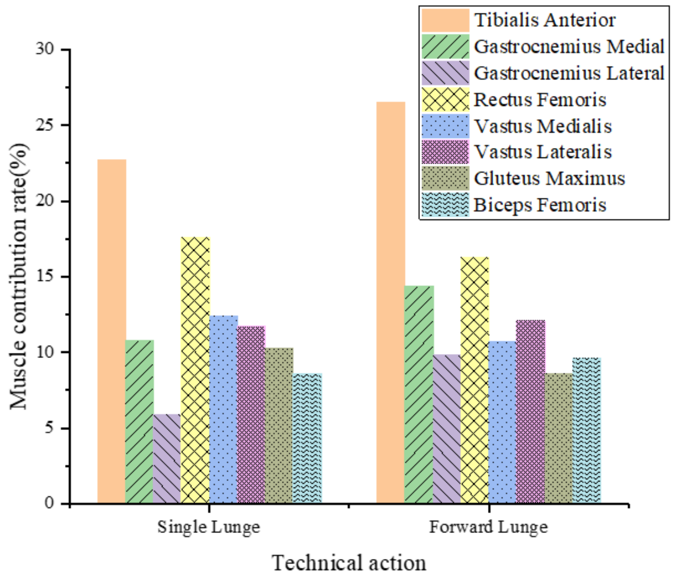


Figure 5. Comparison of muscle contribution rates in the swinging leg.

Within the framework of dissecting the muscle contribution rates of the swinging leg during a single lunge and a forward lunge, it has been ascertained that the contribution rate of the tibialis anterior escalates from 22.7% in a single lunge to 26.5% in a forward lunge. This phenomenon indicates that in the forward lunge, the necessity for ankle joint manipulation and forward propulsive force is more pronounced.

However, the tibialis anterior assumes a more crucial role in buttressing the ankle joint and governing gait. The contribution rates of the medial gastrocnemius and the lateral gastrocnemius also experience respective ascents, from 10.8% to 14.4% and from 5.9% to 9.8%. These augmentations mirror the amplified strength requisites of the calf muscles during the lunge, especially in the course of thrusting the body forward. The contribution rate of the rectus femoris undergoes a marginal diminution, dropping from 17.6% in a single lunge to 16.3% in a forward lunge. Nevertheless, it furnishes stable underpinning in both of these movements.

On the basis of these data, it is feasible to draw the conclusion that diverse fencing techniques exert a substantial influence on the contribution rate of particular muscle clusters. Notably, in the forward lunge, the activation levels of the tibialis anterior, the calf gastrocnemius, and the deltoid muscle are more pronounced. That is particularly conspicuous in terms of control and propulsion. The augmented activation of these muscle groups endows athletes with the requisite strength and stability during the execution of a forward lunge.

4.3. Comparison study of athletes with different skill levels

This experiment aims to compare the differences in EMG activity, movement characteristics, and biomechanical parameters of athletes with different skill levels (beginner, intermediate, advanced) when performing the same fencing technique. The purpose is to provide data support for the development of personalized training programs. **Table 1** presents the comparison results of EMG activity and movement characteristics among athletes of different skill levels.

Table 1. Comparison of EMG activity and movement characteristics among athletes of different skill levels.

Skill Level	EMG Activity Intensity (IEMG, μV)	Movement Path Smoothness (mm/s)	Movement Speed (m/s)	Biomechanical Parameters (Joint Angle Change °/s)
Beginner Group	45.2 ± 5.1	12.3 ± 2.1	1.5 ± 0.3	35.6 ± 4.8
Intermediate Group	38.7 ± 4.2	8.9 ± 1.5	2.1 ± 0.2	28.3 ± 3.7
Advanced Group	32.5 ± 3.8	6.5 ± 1.2	2.8 ± 0.4	22.8 ± 2.9

Table 1 reveals significant differences in EMG activity intensity, movement path smoothness, movement speed, and biomechanical parameters (joint angle change) among athletes of different skill levels. It reflects the impact of skill level on movement characteristics. First, in terms of EMG activity intensity, the beginner group has the highest values (45.2 ± 5.1 μV), followed by the intermediate group (38.7 ± 4.2 μV), and the advanced group has the lowest (32.5 ± 3.8 μV). This indicates that advanced athletes can perform movements in a more efficient manner to avoid unnecessary muscle activation and improve energy utilization. Besides, movement path smoothness improves progressively with skill level. The beginner group shows a smoothness of 12.3 ± 2.1 mm/s, while the advanced group only reaches 6.5 ± 1.2 mm/s. This suggests that advanced athletes possess better movement control abilities, enabling them to execute fencing techniques with a smoother trajectory. In addition, movement speed significantly increases with skill level. The advanced group achieves a speed of 2.8 ± 0.4 m/s, much higher than the beginner group at 1.5 ± 0.3 m/s. This

is closely related to the superior coordination and explosive power of advanced athletes. Finally, regarding joint angle change, the beginner group exhibits the largest variation (35.6 ± 4.8 °/s), while the advanced group shows the smallest (22.8 ± 2.9 °/s). This reflects the higher precision and efficiency of movements in advanced athletes, which reduces unnecessary joint movements. Overall, the improvement in skill level is not only reflected in increased speed and strength but also in the significant advantages in movement precision, energy efficiency, and coordination. This provides an important theoretical basis for developing scientifically structured training programs.

4.4. Analysis of extended biomechanical parameters

In order to gain a more comprehensive understanding of the complexity of fencing techniques, this experiment introduces additional biomechanical parameters to analyze the technical characteristics of athletes from multiple perspectives. These parameters include joint torque, energy expenditure, muscle strength growth rate, and the ratio of movement speed to force. **Table 2** presents the analysis results of fencing techniques with the inclusion of extended biomechanical parameters.

Table 2. Fencing technique analysis with the introduction of extended biomechanical parameters.

Skill Level	**Joint torque (Nm)**	**Energy expenditure (J)**	**Muscle strength growth rate (N/s)**	**The ratio of movement speed to force (N·s/m)**
Beginner Group	25.3 ± 2.7	520.4 ± 40.2	15.8 ± 1.9	3.4 ± 0.5
Intermediate Group	20.7 ± 1.9	460.2 ± 35.8	12.3 ± 1.5	2.8 ± 0.4
Advanced Group	18.4 ± 1.6	380.6 ± 30.7	10.1 ± 1.2	2.2 ± 0.3

First, in terms of joint torque, the beginner group exhibits the highest joint torque (25.3 ± 2.7 Nm), followed by the intermediate group (20.7 ± 1.9 Nm), and the advanced group has the lowest (18.4 ± 1.6 Nm). This suggests that beginner athletes need to apply higher torques to complete the movements, potentially resulting in unnecessary energy waste due to insufficient movement control. In contrast, advanced athletes significantly reduce the torque through more precise joint control. Then, in terms of energy expenditure, the beginner group shows significantly higher energy consumption (520.4 ± 40.2 J) compared to the other groups, while the advanced group has the lowest energy consumption (380.6 ± 30.7 J). This indicates that the higher the skill level is, the greater the energy efficiency of the movements is. Advanced athletes can perform more efficient actions with less energy. Additionally, the muscle strength growth rate data further supports this conclusion. The beginner group has the highest muscle strength growth rate (15.8 ± 1.9 N/s), but its rapid increase might be due to a lack of precise control over force output. In contrast, the advanced group has the lowest growth rate (10.1 ± 1.2 N/s), indicating better muscle coordination and optimized force output control. Finally, the analysis of the ratio of movement speed to force reveals differences in movement efficiency among athletes of different skill levels. The advanced group has the lowest ratio (2.2 ± 0.3 N·s/m), while the beginner group has the highest (3.4 ± 0.5 N·s/m). This suggests that advanced athletes can find a more optimal balance between speed and force output, significantly improving the efficiency of technical movements. In summary, the improvement in skill level is reflected not only in the precision and economy of movements but also in energy utilization efficiency and force output optimization. This provides strong scientific evidence for the technical training of high-level athletes.

4.5. The association between muscle activation patterns and stage characteristics of technical movements

This experiment analyzes the muscle activation patterns of athletes at different skill levels during various stages of fencing movements (preparation, thrust, and recovery) to explore their relationship with the stage-specific characteristics of technical movements. It aims to reveal the details and optimization directions of athletes' technical actions. **Table 3** presents the comparison of muscle activation patterns during the stages of fencing technical movements.

Table 3. Comparison of muscle activation patterns during the stages of fencing technical movements.

Technical Movement Stage	Main Muscle	Beginner Group Activation Intensity (μV)	Advanced Group Activation Intensity (μV)	Activation Sequence (Beginner)	Activation Sequence (Advanced)
Preparation Stage	Quadriceps	22.4 ± 3.2	18.6 ± 2.5	1	2
Thrust Stage	Pectoralis Major	35.7 ± 4.8	28.3 ± 3.9	2	1
Recovery Stage	Hamstrings	19.8 ± 2.7	14.5 ± 2.1	3	3

Table 3 reveals the differences in muscle activation intensity and activation sequence of the main muscles in different stages of fencing technical movements between the beginner and advanced groups. It highlights the impact of skill level on muscle coordination and the characteristics of the technical movement stages. In the preparation stage, the activation intensity of the quadriceps in the beginner group is 22.4 ± 3.2 μV, which is higher than that of the advanced group at 18.6 ± 2.5 μV. This suggests that beginner athletes tend to use their muscles with more tension, lacking an effective energy distribution strategy. Additionally, the beginner group activates the quadriceps first (activation sequence 1), while the advanced group activates it second (sequence 2). This indicates that advanced athletes are better at coordinating their muscles during the preparation phase, reducing unnecessary muscle tension.

During the thrust phase, the pectoralis major shows the highest activation intensity, with the beginner group at 35.7 ± 4.8 μV and the advanced group at 28.3 ± 3.9 μV. Although the beginner group shows higher activation intensity, the advanced group demonstrates greater explosiveness and precision by prioritizing activation of the pectoralis major (sequence 1), while the beginner group places it second (sequence 2). This reflects a higher level of efficiency and coordination in advanced athletes, suggesting that the beginner group still has room for improvement in their technique. Finally, in the recovery stage, the hamstrings are activated with intensities of 19.8 ± 2.7 μV in the beginner group and 14.5 ± 2.1 μV in the advanced group. Both groups activate the hamstrings third (activation sequence 3), indicating a similar muscle activation pattern in this stage. However, the advanced group tends to relax their muscles more, optimizing energy distribution, which reflects a higher level of movement efficiency.

Overall, the analysis shows that the muscle activation intensity is generally higher in the beginner group compared to the advanced group in all stages, indicating weaker muscle control and excessive force application in the former. Advanced athletes enhance movement efficiency and reduce energy consumption through more rational activation sequencing and appropriate intensity distribution. These findings provide scientific evidence for phased training in fencing, particularly emphasizing the importance of a rational muscle activation pattern in improving athletic performance during the preparation and thrust phases.

5. Conclusion

This work provides an in-depth biomechanical analysis of the fencing technique, focusing on key parameters such as joint torque, energy expenditure, muscle strength growth rate, and the ratio of movement speed to force. These findings offer theoretical foundations for optimizing fencing techniques. The results reveal differences in joint load across different athletes, particularly in key muscle groups like the deltoid and tibialis anterior, during the fencing process. This work not only provides a fresh perspective on the biomechanical analysis of fencing techniques but also offers valuable insights for developing training programs and technical optimization. By analyzing the biomechanical data of key muscle groups in fencing athletes, training programs can be designed more precisely to enhance training effectiveness. For example, based on the significant role of the deltoid and tibialis anterior in high-contribution movements, more targeted strength and coordination training programs can be developed in the future. These training programs can improve the strength and flexibility of these muscle groups, thereby optimizing athletes' technical performance.

Future research should further expand the sample size and apply the findings to the development and optimization of practical training programs. Exploring how to integrate biomechanical data with the individual needs of athletes will improve the scientific and effective nature of personalized training. In addition to traditional strength training, new technological innovations offer significant potential for optimizing training methods. For instance, virtual reality training systems can simulate various fencing scenarios, allowing athletes to practice techniques and tactics in a virtual environment. Moreover, combining biofeedback technology to adjust athletes' techniques in real-time can help correct poor posture and improve the efficiency and accuracy of training. Through these emerging technologies, future training programs will not only be personalized but also enhance athletes' overall competitive performance. In conclusion, as training technologies and equipment continue to evolve, future research is expected to further improve the scientific and precise nature of fencing training by integrating modern technological methods. It can lead to the comprehensive improvement of athletes' technical abilities.

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