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# Motion Picture Analysis: A Mechanical Study of Tennis Players during Forehand and Backhand Strokes

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**Abstract**

*Objectives:* The purpose of this article is to utilize video images for the examination of lower limb biomechanics in tennis players while executing forehand and backhand strokes, providing a reference for training. *Methods:* This article provides a brief introduction to forehand and backhand strokes in the sport of tennis. Subsequently, a biomechanical analysis of the lower limbs during forehand and backhand strokes was conducted on ten level 2 tennis players and ten specialized tennis students at XX Sports University. *Findings:* Level 2 athletes who have undergone a long training exhibited higher linear velocity and joint torque in the lower-limb joints during the preparatory and striking phases of forehand and backhand strokes. Additionally, they exhibited more pronounced surface electromyographic signals in the rectus femoris muscle of the lower limbs. *Novelty:* The novelty of this article lies in the use of video imagery, a non-contact and non-intrusive method that does not affect the athletes' movements, to study the biomechanics of their lower limbs.

*Keywords:* Tennis; Forehand and Backhand Strokes; Biomechanics; High-Speed Camera.

## 1. Introduction

Tennis requires a combination of technique and physical fitness, demanding athletes to possess exceptional skills and remarkable physical attributes. Forehand and backhand strokes are crucial techniques in tennis [1] and are also commonly used for scoring points. Biomechanics is a discipline that studies the characteristics of human movement, including the changes in joint angles and limb force during the process. Analyzing the biomechanical features of tennis players' forehand and backhand strokes [2] can lead to more effective training methods and skill guidance for athletes, enabling them to enhance their hitting skills and competitive performance [3]. Using high-speed cameras, Xie [4] captured the hitting process of topspin shots from ten tennis players and processed the images using the APAS motion analysis system. The findings indicated that there was a significant angle and speed in the upper limb joints during the stroke, with the center of gravity positioned on the right side. Furthermore, the flexion of the knee joint resulted in the production of a reactive force by means of pedaling and stretching, which was subsequently transmitted to the racket. Pedro et al. [5] utilized an inertial measurement unit (IMU) to measure the kinematic parameters of the upper limb during a forehand stroke in tennis. The results demonstrated consistency between the IMU measurements and the traditional optical motion capture system.

The study conducted by Gillet et al. [6] assessed the influence of reduced strength in the lower trapezius muscle on the kinematics of the humerus and scapula during a tennis serve, as well as shoulder muscle activity. The findings

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revealed that while lower trapezius muscle weakness did not impact speed or humerus joint kinematics, it significantly impaired scapular kinematics and activation of the shoulder muscles. Wąsik et al. [7] used a motion capture system to accurately assess athletes and their athletic abilities. They found that the wireless motion capture system provided some assistance in training processes and pre-competition evaluations of athletes. Ličen et al. [8] incorporated myofascial training into the training of tennis players with the goal of optimizing rehabilitation and prevention programs, lowering injury rates, and producing beneficial effects on the biomechanical patterns of exercise. Qu et al. [9] used big data to analyze the biomechanical and kinematic indicators in table tennis training. They employed an enhanced decision tree technique to examine the disparities among athletes who have undergone neuromuscular control training and those who have not. The results revealed that non-athletes, following neuromuscular control training, achieved a 10% to 20% enhancement in the standardized rate of their table tennis strokes, reaching 80%. In the aforementioned studies, various methods were employed to analyze the biomechanical changes of athletes during sports. Some utilized high-speed cameras to examine variations in upper limb joint angles, while others used inertial sensors to analyze changes in joint angles during movement.

Additionally, some studies have focused on investigating the biomechanics of athletes by examining muscle changes during exercise. This study combined high-speed cameras and electromyography sensors to investigate the biomechanical changes in the lower limbs of tennis players. By utilizing video images, the researchers observed changes in joint angles and simultaneously captured variations in lower limb muscles using electromyographic signals, thus enabling a more comprehensive collection of data on lower limb movements. The article offers a concise overview of the forehand and backhand strokes in tennis, followed by a biomechanical analysis of lower limb movements during these strokes among ten level 2 tennis athletes and ten specialized tennis students at XX Sports University. The novelty of this article lies in the use of high-speed cameras to capture the joint angles of lower limbs during forehand and backhand strokes by athletes, while simultaneously utilizing electromyography sensors to collect muscle electrical signals from the lower limbs, thus enabling a better analysis of lower limb biomechanics. The structure of this article includes an abstract, an introduction, forehand and backhand strokes in tennis, a case study, a discussion, and a conclusion.

## 2. Forehand and Backhand Strokes in Tennis

Forehand and backhand strokes are fundamental techniques in tennis. The process involves several complex steps, including preparation, backswing, forward swing, stroke, and follow-through [10]. During this process, athletes need to adjust their posture and control the timing and intensity of the stroke to hit the ball deeper, faster, and higher in order to gain an advantage in the game [11]. Therefore, the biomechanical characteristics of both forehand and backhand strokes play a vital role for athletes [12]. Athletes can receive specialized training by focusing on their specific biomechanical features when executing their shots. During the execution of a forehand shot, athletes need to engage the muscles on the side of their palm to swing the racket from back to front in order to hit the ball [13]. The key points include keeping the palm holding the racket parallel to the ground, relaxing the wrist, slightly opening the face of the racket to ensure full contact with the ball, and mobilizing muscles and joints, particularly in the arms, back, and legs, to execute a swinging motion from back to front. During the backhand stroke, athletes need to utilzie the strength of their wrist and arm to swing the racket from the outside to the inside and make contact with the ball. The key points are to keep the inner side of the palm parallel to the ground, relax the wrist, and slightly close the racket to ensure sufficient contact with the ball. Compared to forehand strokes, backhand strokes are relatively slower in speed [14].

Although the key points of the forehand and backhand strokes differ, both require coordinated movements of the arm, wrist, and elbow joints, as well as movements of the lower body [15], to strike the ball with the racket at the correct timing and angle, allowing it to achieve the desired flight trajectory and speed [16]. In this process, the rotation of the upper and lower limb joints, as well as the angle of the racket, are key influencing factors in hitting effectiveness, especially regarding the movement of the lower limbs. The correct and reasonable movement of the lower limbs is an important condition for achieving fast and stable hits [17]. By analyzing the biomechanics of athletes' forehand and backhand strokes, we can gain insight into the joint rotation and muscle exertion characteristics during hitting, which can inform appropriate training [18]. This study conducted a research analysis on the biomechanics of the lower limb in tennis players while performing forehand and backhand strokes, with the aim of providing guidance for their stroke techniques.

## 3. Case Study

The process of analyzing the biomechanics of lower limb movements in tennis players during forehand and backhand strokes is illustrated in Figure 1. Firstly, experimental subjects were selected, followed by setting up a testing area with strategically positioned high-speed cameras. Subsequently, participants wore electromyography sensors. They then performed forehand and backhand strokes while simultaneously recording motion images and electromyographic signals. Finally, mathematical and statistical analysis was conducted on the collected data from both motion images and electromyographic signals.

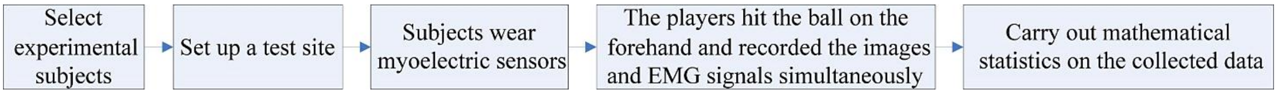


**Figure 1. The flowchart of the study**

### 3.1. Subject for Analysis

Ten Level 2 athletes from XX Sports University and ten students specialized in tennis were selected, and their basic information is presented in Table 1. The sole notable distrinction observed among the two groups of participants was the duration of training, with the Level 2 athletes having a longer training period. All the participants used a right-handed Western grip to hold the racket during testing [19] and adopted an open stance when hitting the ball [20]. Standardized rackets were provided. All the participants wore low-top sports shoes of the same brand to minimize the impact on their joints during testing.

**Table 1. Basic information about the experimental subjects**

| Group | Height/cm | Weight/kg | Age/year | Training time/year | Injury history | Physical damage in the last three months |
|---|---|---|---|---|---|---|
| Level 2 athlete | 175±5 | 75±5 | 20±2 | 6±1 | No | No |
| Specialized tennis student | 174±4 | 74±3 | 20±1 | 2±1* | No | No |

Note: * indicates $P < 0.05$, i.e., the difference was statistically significant.

### 3.2. Experimental Equipment

① A Revealer 10,000-frame X213 high-speed camera with a resolution of 1,280*1,024 pixels, a full-frame capture speed of 13,600 fps, and a maximum capture speed of 1,000,000 fps.

② The wireless surface electromyography testing system PicoBlue and its accompanying sensors [21].

③ A tennis serving machine (SPINSHOP).

④ A Kistler three-dimensional force measurement platform [22] (Model Number: 9281CA), with a sampling frequency of 1,000 Hz.

### 3.3. Experimental Methods

During the execution of forehand and backhand strokes, the kinematic parameters of the subjects, including lower limb joint angles, were recorded using a high-speed camera. The dynamic parameters, such as lower limb joint torque, were obtained based on acting force measurements from a force platform. Additionally, a surface electromyography testing system [23] was used to measure changes in the surface electrical signals of lower limb muscles. Figure 2 is a schematic diagram illustrating the positions of the subjects and cameras during strokes. The subjects were positioned at the midpoint of the baseline, where a three-dimensional force platform was set up. The serving machine delivers balls to various target areas based on the tested striking actions. For forehand strokes, the tennis ball landed on the right side of the subjects, while for backhand strokes, it landed on their left side. During the process of hitting the ball, the subjects also underwent surface electromyography testing. Based on the technical characteristics of forehand and backhand strokes, as well as anatomical knowledge, wireless sensors were attached to the gastrocnemius muscle, vastus lateralis muscle, and rectus femoris muscle for testing surface electromyography [24].

The specific testing procedure is as follows:

①After setting up the test site as described in the previous section and placing surface electromyography sensors on relevant parts of the subject's lower limbs, the subject stood on the force platform.

②During the forehand stroke, the serving machine launched a topspin ball toward the forehand target area at the same angle, speed, and spin rate. The subjects followed the technical key points of the forehand stroke to hit the ball. The serving machine launched a shot every 5 seconds, for a total of five times. High-speed cameras, three-dimensional force platforms, and surface electromyography sensors were used to collect data during this process.

③After completing the forehand hitting test, the subjects rested for 2 minutes before proceeding to the backhand hitting test. The serving machine continued to launch topspin balls toward the backhand target area at the same angle, speed, and spin rate. The subjects followed the technical points of the backhand stroke to hit the balls, with a frequency of one shot every 5 seconds for a total of five shots. During this process, high-speed cameras, a three-dimensional force platform, and surface electromyography sensors were used to record corresponding biomechanical data.

The movements in the three stages of forehand and backhand strokes are demonstrated in Figure 3.

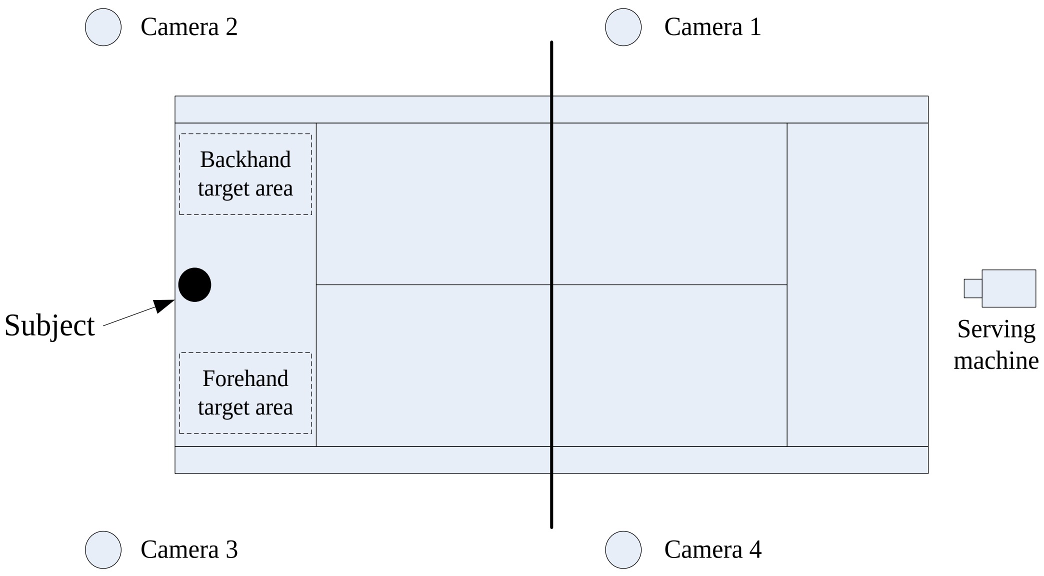


**Figure 2. Schematic diagram of the site layout for forehand and backhand stroke testing**


**Figure 3. Movement demonstrations for three stages of forehand and backhand strokes**

### 3.4. Mathematical Statistics

The collected data was analyzed using SPSS software and presented in the form of $x \pm d$ [25]. Independent t-tests were conducted to compare different groups. When the P value was less than 0.05, there were observed significant statistical disparities among the groups. In addition, when performing statistical analysis on surface electromyography data, the electromyographic signals were standardized to mitigate the influence of individual differences in skin perspiration among athletes. The measurement value of electromyographic signals during maximum isometric muscle contraction at fixed joint angles was considered the reference value 1 (i.e., 100%).

### 3.5. Experimental Results

Regardless of whether it is a forehand stroke or a backhand stroke, the technique can be divided into three stages: the preparation stage, the striking stage, and the follow-through stage. During the preparation stage, the player moves the racket to the appropriate position for hitting the ball. The striking stage involves using the racket to hit the ball away. The follow-through stage is the buffering stage that occurs after the athlete hits the ball. The linear velocities of the lower limb joints during different stages of forehand and backhand strokes are presented in Table 2. Table 2 shows that the hip and knee joint linear velocities of Level 2 athletes were significantly higher than those of specialized students, regardless of whether it was a forehand or backhand stroke, during both the preparation stage and the striking stage.

**Table 2. Linear velocities of the lower limb joints during forehand and backhand strokes (unit: m/s)**

| Stroke | Body side | Lower limb joint | Group | Preparation stage | Striking stage | Follow-through stage |
|---|---|---|---|---|---|---|
| Forehand stroke | Left side | Hip joint | Specialized students | 1.29±0.23 | 1.32±0.26 | 1.28±0.22 |
| | | | Level 2 athletes | 1.39±0.33 | 1.44±0.32 | 1.38±0.31 |
| | | Knee joint | Specialized students | 1.24±0.29 | 1.27±0.31 | 1.23±0.28 |
| | | | Level 2 athletes | 1.30±0.38 | 1.35±0.41 | 1.29±0.33 |
| | Right side | Hip joint | Specialized students | 1.62±0.34 | 1.67±0.43 | 1.63±0.41 |
| | | | Level 2 athletes | 2.11±0.33* | 2.16±0.29* | 2.12±0.28 |
| | | Knee joint | Specialized students | 1.25±0.27 | 1.27±0.29 | 1.26±0.28 |
| | | | Level 2 athletes | 1.79±0.32* | 1.82±0.34* | 1.78±0.33 |
| Backhand stroke | Left side | Hip joint | Specialized students | 1.34±0.33 | 1.36±0.34 | 1.33±0.31 |
| | | | Level 2 athletes | 1.42±0.31 | 1.46±0.36 | 1.41±0.32 |
| | | Knee joint | Specialized students | 1.24±0.31 | 1.28±0.32 | 1.25±0.31 |
| | | | Level 2 athletes | 1.34±0.33 | 1.36±0.35 | 1.35±0.34 |
| | Right side | Hip joint | Specialized students | 1.63±0.34 | 1.65±0.42 | 1.62±0.38 |
| | | | Level 2 athletes | 2.12±0.24* | 2.15±0.26* | 2.13±0.25 |
| | | Knee joint | Specialized students | 1.26±0.28 | 1.28±0.26 | 1.27±0.22 |
| | | | Level 2 athletes | 1.79±0.31* | 1.81±0.32* | 1.80±0.25 |

Note: * Suggests a statistically significant distinction between the two groups.

The joint torque of the lower limbs at different stages during forehand and backhand strokes is shown in Table 3. The positive or negative sign of the torque values only represents the direction of torque, not its magnitude. From Table 3, it can be observed that Level 2 athletes always exhibited significantly higher right lower limb joint torques than specialized students during the preparation and striking stages of forehand and backhand strokes.

**Table 3. Lower limb joint torques of subjects during forehand and backhand strokes (unit: Nm)**

| Stroke | Lower limb joint | Group | Preparation stage | Striking stage | Follow-through stage |
|---|---|---|---|---|---|
| Forehand stroke | Left knee joint | Specialized students | -0.01±0.008 | -0.01±0.014 | -0.00±0.008 |
| | | Level 2 athletes | -0.02±0.001 | -0.02±0.004 | -0.00±0.001 |
| | Left ankle joint | Specialized students | -0.012±0.013 | -0.017±0.013 | -0.010±0.013 |
| | | Level 2 athletes | -0.013±0.003 | -0.018±0.003 | -0.012±0.003 |
| | Right knee joint | Specialized students | 0.01±0.009 | 0.01±0.015 | 0.00±0.009 |
| | | Level 2 athletes | 0.02±0.002* | 0.02±0.005* | 0.00±0.002 |
| | Right ankle joint | Specialized students | -0.029±0.014 | -0.032±0.014 | -0.027±0.014 |
| | | Level 2 athletes | -0.030±0.003* | -0.033±0.003* | -0.028±0.003 |
| Backhand stroke | Left knee joint | Specialized students | -0.01±0.007 | -0.01±0.012 | -0.00±0.007 |
| | | Level 2 athletes | -0.02±0.002 | -0.02±0.005 | -0.00±0.002 |
| | Left ankle joint | Specialized students | -0.012±0.016 | -0.017±0.012 | -0.010±0.016 |
| | | Level 2 athletes | -0.013±0.002 | -0.018±0.002 | -0.011±0.002 |
| | Right knee joint | Specialized students | 0.01±0.010 | 0.01±0.012 | 0.00±0.010 |
| | | Level 2 athletes | 0.02±0.003* | 0.02±0.003* | 0.00±0.003 |
| | Right ankle joint | Specialized students | -0.029±0.011 | -0.032±0.016 | -0.026±0.011 |
| | | Level 2 athletes | -0.030±0.002* | -0.033±0.004* | -0.027±0.002 |

Note: * Suggests a statistically significant distinction between the two groups.

The surface electromyographic signals of the lower limb muscles during different stages of forehand and backhand strokes are presented in Table 4. From Table 4, it can be observed that during the preparation stage, the surface electromyographic signal of the rectus femoris muscle was significantly higher in intermediate-level athletes compared to specialized students. During the striking stage, the surface electromyographic signal of the vastus lateralis muscle was significantly lower in Level 2 athletes than in specialized students, while the surface electromyographic signal of the rectus femoris muscle was significantly higher than that in specialized students.

**Table 4. The surface electromyographic signals of lower limbs during forehand and backhand strokes**

| Stroke | Lower limb muscle | Group | Preparation stage | Striking stage | Follow-through stage |
|---|---|---|---|---|---|
| Forehand stroke | Vastus lateralis muscle | Specialized students | 0.111±0.026 | 0.341±0.113 | 0.201±0.021 |
| | | Level 2 athletes | 0.112±0.045 | 0.231±0.064* | 0.102±0.043 |
| | Rectus femoris muscle | Specialized students | 0.096±0.035 | 0.152±0.061 | 0.094±0.041 |
| | | Level 2 athletes | 0.157±0.023* | 0.221±0.183* | 0.083±0.041 |
| | Gastrocnemius muscle | Specialized students | 0.127±0.076 | 0.272±0.073 | 0.121±0.030 |
| | | Level 2 athletes | 0.177±0.054 | 0.253±0.082 | 0.204±0.093 |
| Backhand stroke | Vastus lateralis muscle | Specialized students | 0.101±0.021 | 0.331±0.111 | 0.191±0.011 |
| | | Level 2 athletes | 0.102±0.055 | 0.221±0.062* | 0.092±0.041 |
| | Rectus femoris muscle | Specialized students | 0.086±0.025 | 0.142±0.063 | 0.084±0.051 |
| | | Level 2 athletes | 0.147±0.013* | 0.211±0.182* | 0.073±0.061 |
| | Gastrocnemius muscle | Specialized students | 0.117±0.077 | 0.262±0.071 | 0.111±0.032 |
| | | Level 2 athletes | 0.167±0.053 | 0.243±0.081 | 0.194±0.091 |

Note: * Suggests a statistically significant distinction between the two groups.

## 4. Discussion

In tennis, forehand and backhand strokes are commonly used for scoring points. During forehand and backhand strokes, there are coordinated movements in the upper and lower bodies. Generally, the more standardized the movements are, the more stable and effective the shots will be, allowing players to fully utilize their abilities. However, human bodies are not machines, and individual differences in physical fitness and habits can lead to deviations from standard shooting techniques. Therefore, continuous practice is necessary to refine one's movements. Furthermore, due to individual physical differences, the standard hitting technique may not be suitable for everyone. By conducting biomechanical analysis of athletes' movements during both forehand and backhand strokes, it is possible to identify their specific characteristics and provide targeted recommendations. The present study utilizes video images recorded by a high-speed camera, along with data from a three-dimensional force platform and surface electromyography sensors, to analyze the lower limb biomechanics of forehand and backhand strokes in specialized tennis students and Level 2 tennis athletes, as demonstrated in the proceeding section.

In the preparation stage, Level 2 athletes exhibited significantly greater linear velocity in their right hip and knee joints compared to specialized students ($p < 0.05$). The torque exerted on the right knee and ankle joints exhibited a statistically significant increase compared to that observed in specialized students ($p < 0.05$). Additionally, the rectus femoris muscle exhibited a significantly greater surface electromyographic signal compared to individuals with specialized training ($p < 0.05$). The reason is as follows. The preparation stage of forehand and backhand strokes required rotation with support from the right side, which involves flexion and extension of the knee joint as well as rotation of the hip joint to drive upper body rotation. Level 2 athletes have longer training times and are more proficient in technical movements, resulting in significantly faster linear velocity of these two joints and greater torque generated by the knee and ankle joints. Therefore, the electromyographic signals from the rectus femoris muscle used for generating force are also more significant.

During the striking stage, the backhand strokes of Level two tennis players exhibited significantly greater linear velocity in the right hip and knee joints compared to specialized students ($p < 0.05$). Additionally, the torque exerted on the right knee and ankle joints was found to be significantly greater in comparison to that observed among students with specialized training ($p < 0.05$). Furthermore, the surface electromyographic signal of the gluteus medius muscle was significantly lower than that of specialized students ($p < 0.05$), while that of the rectus femoris muscle was significantly higher ($p < 0.05$). During the preparation stage, the racket is in an accelerated state. Before hitting the ball during the striking stage, the ball is also in an accelerated state. Level 2 athletes have longer training time, allowing their rectus femoris muscles to provide more force, resulting in greater torque on the knee and ankle joints and enabling them to achieve more acceleration. In the follow-through stage, there was not much difference between Level 2 tennis players and specialized students because it is a buffering stage after hitting the ball where no additional force needs to be applied to maintain acceleration.

The contribution of this study lies in the use of high-speed cameras and electromyography sensors to collect biomechanical data on lower limb movements during forehand and backhand strokes by athletes and comparing the differences between amateur and professional players. This paper provides a valuable reference for training in the technique of forehand and backhand strokes in tennis.

## 5. Conclusion

This article offers a concise introduction to the forehand and backhand stroke techniques employed in the sport of tennis, followed by a biomechanical analysis of the lower limbs of ten second-level tennis athletes and ten specialized tennis students at XX Sports University during forehand and backhand strokes. The results were summarized as follows. After long training, Level 2 athletes showed increased lower limb joint linear velocity and joint torque during the preparatory and striking phases of forehand and backhand strokes. Additionally, there was a more pronounced surface electromyographic signal in the rectus femoris muscle of the lower limbs.

## 6. Declarations

### 6.1. Author Contributions

Conceptualization, Y.Y. and T.G.; methodology, Y.Y.; software, Y.Y.; validation, Y.Y. and T.G.; formal analysis, Y.Y.; data curation, Y.Y.; writing—original draft preparation, Y.Y.; writing—review and editing, Y.Y. and T.G.; supervision, Y.Y.; project administration, Y.Y.; funding acquisition, T.G. All authors have read and agreed to the published version of the manuscript.

### 6.2. Data Availability Statement

The data presented in this study are available in the article.

### 6.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

### 6.4. Institutional Review Board Statement

Not applicable.

### 6.5. Informed Consent Statement

Not applicable.

### 6.6. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## 7. References

[1] Warner, M. B., Wilson, D., Heller, M. O., Wood, D., Worsley, P., Mottram, S., Webborn, N., Veeger, D. J., & Batt, M. (2018). Scapular kinematics in professional wheelchair tennis players. Clinical Biomechanics, 53, 7–13. doi:10.1016/j.clinbiomech.2018.01.022.

[2] Herbaut, A., Chavet, P., Roux, M., Guéguen, N., Gillet, C., Barbier, F., & Simoneau-Buessinger, E. (2016). The influence of shoe drop on the kinematics and kinetics of children tennis players. European Journal of Sport Science, 16(8), 1121–1129. doi:10.1080/17461391.2016.1185163.

[3] Seo, K.-E., Chung, Y.-M., & Kang, Y.-T. (2015). A Comparative Analysis of Horizontal Rotation Movements for Different Ball Course during Two-handed Backhand Drive Stroke in Tennis. Korean Journal of Sport Biomechanics, 25(3), 293–300. doi:10.5103/kjsb.2015.25.3.293.

[4] Xie, X. (2021). Analysis of the movement track of top spinning ball and biomechanics in the process of hitting tennis ball. MCB Molecular and Cellular Biomechanics, 18(3), 147–156. doi:10.32604/mcb.2021.016246.

[5] Pedro, B., Cabral, S., & Veloso, A. P. (2021). Concurrent validity of an inertial measurement system in tennis forehand drive. Journal of Biomechanics, 121, 1–6. doi:10.1016/j.jbiomech.2021.110410.

[6] Gillet, B., Rogowski, I., Monga-Dubreuil, E., & Begon, M. (2019). Lower Trapezius Weakness and Shoulder Complex Biomechanics during the Tennis Serve. Medicine and Science in Sports and Exercise, 51(12), 2531–2539. doi:10.1249/MSS.0000000000002079.

[7] Wąsik, J., Mosler, D., Ortenburger, D., & Góra, T. (2021). Stereophotogrammetry measurement of kinematic target effect as speed accuracy benchmark indicator for kicking performance in martial arts. Acta of Bioengineering and Biomechanics, 23(4), 117–125. doi:10.37190/ABB-01926-2021-06.

[8] Ličen, T., Kalc, M., Vogrin, M., & Bojnec, V. (2022). Injury Prevention in Tennis Players, Linking the Kinetic Chain Approach with Myofascial Lines: A Narrative Review with Practical Implications. Strength and Conditioning Journal, 44(4), 104–114. doi:10.1519/SSC.0000000000000669.

[9] Qu, Q., An, M., Zhang, J., Li, M., Li, K., & Kim, S. (2022). Biomechanics and Neuromuscular Control Training in Table Tennis Training Based on Big Data. Contrast Media and Molecular Imaging, 2022, 3725295. doi:10.1155/2022/3725295.

[10] Kong, P. W., & Yam, J. W. (2022). Shoulder biomechanics of para-table tennis: a case study of a standing class para-athlete with severe leg impairment. BMC Sports Science, Medicine and Rehabilitation, 14(1), 143. doi:10.1186/s13102-022-00536-9.

[11] An, J. (2018). Activation process of brain perception during the serve action of table tennis players. NeuroQuantology, 16(6), 195–199. doi:10.14704/nq.2018.16.6.1614.

[12] Jiang, W., & He, G. (2021). Study on the effect of shoulder training on the mechanics of tennis serve speed through video analysis. MCB Molecular and Cellular Biomechanics, 18(4), 221–229. doi:10.32604/MCB.2021.017050.

[13] Barmaki, S., Khazani, A., & Ziaee, N. (2016). The Responses of Physiological Stress during Table Tennis Competition in Elite Female Players. Annals of Applied Sport Science, 4(2), 17–24. doi:10.18869/acadpub.aassjournal.4.2.17.

[14] Christensen, J., Rasmussen, J., Halkon, B., & Koike, S. (2016). The Development of a Methodology to Determine the Relationship in Grip Size and Pressure to Racket Head Speed in a Tennis Forehand Stroke. Procedia Engineering, 147, 787–792. doi:10.1016/j.proeng.2016.06.317.

[15] Bańkosz, Z., & Winiarski, S. (2020). Using Wearable Inertial Sensors to Estimate Kinematic Parameters and Variability in the Table Tennis Topspin Forehand Stroke. Applied Bionics and Biomechanics, 2020, 1–10. doi:10.1155/2020/8413948.

[16] Syed, F., Myrick, K., Garbalosa, J., & Feinn, R. (2019). A Comparison of Forehand Swing Biomechanics between Male and Female Tennis Players. Medicine & Science in Sports & Exercise, 51(6S), 53–53. doi:10.1249/01.mss.0000560653.37130.35.

[17] Martin, C., Sorel, A., Touzard, P., Bideau, B., Gaborit, R., DeGroot, H., & Kulpa, R. (2020). Can the Open Stance Forehand Increase the Risk of Hip Injuries in Tennis Players? Orthopaedic Journal of Sports Medicine, 8(12), 492–498. doi:10.1177/2325967120966297.

[18] Gülaç, M., Devrilmez, E., Kirazcı, S., & Yüksel, O. (2017). Investigation of the Anticipation Time in Forehand and Backhand Strokes of Badminton Players. Journal of Education and Training Studies, 5(13), 8. doi:10.11114/jets.v5i13.2876.

[19] OConnell, D. G., Brewer, J. F., Man, T. H., Weldon, J. S., & Hinman, M. R. (2016). The Effects of Forced Exhalation and Inhalation, Grunting, and Valsalva Maneuver on Forehand Force in Collegiate Tennis Players. Journal of Strength and Conditioning Research, 30(2), 430–437. doi:10.1519/JSC.0000000000001120.

[20] Sasaki, S., Nagano, Y., & Ichikawa, H. (2018). Loading differences in single-leg landing in the forehand- and backhand-side courts after an overhead stroke in badminton: A novel tri-axial accelerometer research. Journal of Sports Sciences, 36(24), 2794–2801. doi:10.1080/02640414.2018.1474535.

[21] Lucado, A. M., Dale, R. B., Kolber, M. J., & Day, J. M. (2020). Analysis of Range of Motion in Female Recreational Tennis Players with and Without Lateral Elbow Tendinopathy. International Journal of Sports Physical Therapy, 15(4), 526–536. doi:10.26603/ijspt20200526.

[22] Tubez, F., Schwartz, C., Croisier, J. L., Brüls, O., Denoël, V., Paulus, J., & Forthomme, B. (2021). Evolution of the trophy position along the tennis serve player's development. Sports Biomechanics, 20(4), 431–443. doi:10.1080/14763141.2018.1560493.

[23] He, Y., Shao, S., Fekete, G., Yang, X., Cen, X., Song, Y., Sun, D., & Gu, Y. (2022). Lower Limb Muscle Forces in Table Tennis Footwork during Topspin Forehand Stroke Based on the OpenSim Musculoskeletal Model: A Pilot Study. MCB Molecular and Cellular Biomechanics, 19(4), 221–235. doi:10.32604/MCB.2022.027285.

[24] Ferreira, T. R. S., Bastos, F. H., Pasetto, S. C., Torriani-Pasin, C., & Corrêa, U. C. (2016). Self-talk does not affect the transfer and retention in the tennis forehand learning in beginners. Kinesiology, 48(2), 237–243. doi:10.26582/k.48.2.6.

[25] Asahi, T., Taira, T., Ikeda, K., Yamamoto, J., & Sato, S. (2017). Improvement of Table Tennis Dystonia by Stereotactic Ventro-Oral Thalamotomy: A Case Report. World Neurosurgery, 99, 810.e1-810.e4. doi:10.1016/j.wneu.2016.12.117.