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Article

Comparative analysis of biomechanical characteristics of knee flexion and extension muscles in volleyball physical training

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Abstract: This study aimed to analyze the biomechanical characteristics of knee flexion and extension muscles in volleyball physical training from the cellular and molecular biomechanics aspect. Multiple training modes like strength, elasticity, and comprehensive training were chosen to systematically evaluate relevant characteristics of these muscles among volleyball players. Advanced devices such as 3D motion capture systems, ground reaction force platforms, and electromyography equipment were used to gather precise biomechanical data. At the cellular and molecular level, different trainings impact muscle cells differently. For example, strength training might enhance the synthesis of contractile proteins within cells, while elasticity training could influence the elasticity-related molecular structures. With multidimensional data analysis, the effects of various training modes were compared. The comprehensive training group had a kinematic flexion extension angle of 528.27° ± 11.49°, an angular velocity of 135.52° ± 5.97°, and an angular acceleration of 3177.02° ± 116.88°, performing best. This could be due to its comprehensive influence on cellular and molecular processes in muscles, promoting better coordination and force generation. This article offers a theoretical basis for volleyball players to create scientific training plans and gives practical tips for coaches and athletes to optimize programs and prevent injuries. By focusing on cellular and molecular biomechanics, it fills research gaps and helps boost the development of biomechanics in volleyball physical training.

Keywords: knee joint; flexor; extensor muscles; volleyball training; biomechanical adaptations; biomechanical characteristics

1. Introduction

Volleyball is a high-intensity competitive sport that requires athletes to frequently perform movements such as jumping, emergency stops, and turning, which places high demands on the knee joint's flexion and extension muscles. As one of the main weight-bearing joints in human movement, the biomechanical characteristics of the knee joint's flexor and extensor muscle groups directly affect athletes' athletic performance and injury risk [1]. To gain a deeper understanding of the biomechanical performance of the knee flexion and extension muscles of volleyball players under different physical training conditions, this article compared and analyzed the biomechanical characteristics of the knee flexion and extension muscles to help athletes optimize training methods, enhance physical fitness, improve athletic performance, and reduce the risk of catching a cold. This study found that there are problems in current volleyball training, such as a single training method, neglect of joint health, and uneven training load. In volleyball physical training, many training methods rely too much on traditional strength training and lack targeted muscle function training, which prevents athletes from fully exerting their strength in actual competitions. Under high-intensity volleyball training, athletes' knee joints are often injured, especially when the weight-bearing capacity of the knee flexion and extension muscles is not fully considered, which can easily lead to chronic injuries. In volleyball training, there is still a situation where some athletes have an unbalanced load, overly focusing on one aspect of physical fitness while neglecting other elements, resulting in an overall performance imbalance and an increased risk of injury. This study analyzes the biomechanical characteristics of knee flexion and extension muscles to understand the differences in muscle performance under different training modes, to develop more scientific and effective training plans.

Based on the above research background and current situation, this study aims to conduct a systematic and comprehensive comparative analysis of the biomechanical characteristics of knee flexion and extension muscles in volleyball physical training. The impact of different training modes can be comprehensively evaluated by selecting multiple different training modes (such as strength training, elasticity training, and comprehensive training), and systematically evaluating the effects of these modes on the biomechanical characteristics of the knee flexion and extension muscles of volleyball players.

This article introduces advanced data acquisition and analysis techniques, using advanced 3D motion capture systems, ground reaction force platforms, and electromyography (EMG) equipment, combined with multidimensional data analysis methods, to improve the accuracy and reliability of data. A 12-month follow-up study was conducted to observe the long-term effects of different training modes on the biomechanical characteristics of knee flexion and extension muscles and to evaluate the training and injury prevention effects of athletes. By linking biomechanical features with actual training outcomes, it is possible to analyze the correlation between biomechanical features and athletes' actual training and athletic performance, explore the specific impact of training modes on athletic performance, and provide more practical research results. Based on the characteristics of kinematics, dynamics, and electromyography, a multidimensional comprehensive analysis is conducted to comprehensively understand the biomechanical performance of knee flexion and extension muscles under different training modes, and suggestions for optimizing training are proposed from multiple perspectives. This study not only conducted a detailed analysis of existing research but also explored more innovative methods based on this. By integrating advanced biomechanical measurement technologies, such as the latest 3D motion capture system, ground reaction force platform, and electromyography equipment, this study conducted a more comprehensive evaluation of the performance of knee flexion and extension muscles under different training modes. The application of these cutting-edge technologies makes up for the shortcomings of traditional research and provides new insights for the design of more scientific training programs.

2. Related work

In recent years, significant progress has been made in the study of the biomechanical characteristics of knee flexion and extension muscles. The research on knee flexion and extension muscles mainly focuses on knee joint kinematics, dynamics, and electromyography. Research has shown that strength training can effectively improve the range of motion of the knee joint [2], which is crucial for volleyball players' performance in competitions. Many research findings have revealed the potential of strength training in improving knee joint function, but there are also certain limitations. Yang et al. studied the effect of elastic training on the knee joint [3] and found that elastic training can improve the angular velocity and acceleration of the knee joint. Elastic training is of great significance in enhancing athletes' explosive power and reaction speed. Elastic training enhances the dynamic characteristics of the knee joint, which helps athletes complete movements more quickly during competitions.

Knee joint research is crucial in volleyball training. Fatahi et al. conducted a kinematic analysis of the knee joints of adolescent volleyball players during block jumping and found that there are differences and negative correlations between the knee and ankle joints of adolescent volleyball players during block jumping [4]. Messier et al. studied the effects of high-intensity strength training on the knee joint and found that this training did not significantly improve knee joint pressure at 18 months [5]. Chahar et al. studied the isokinetic peak torque of knee flexion and extension muscles during centripetal motion and eccentric contraction at different angular velocities to better understand the different characteristic muscle groups that may cause athlete injuries [6]. Muollo et al. studied the complete characterization of the function of knee extensor muscles in aging and analyzed the effects of different genders and obesity on knee extensor muscles [7]. Alhammoud et al. studied the changes in knee flexion and extension muscles during alpine skiing [8]. Celenk et al. studied the relationship between knee flexion and extension muscles and jumping in young male volleyball players, and concluded that leg strength training can effectively improve jumping height [9]. Many studies lack long-term tracking data to evaluate the effects of different training modes on the knee joint. Kafkas et al. studied the effects of long-term training on male university volleyball players, and the results showed that a two-year volleyball training program can improve the knee extensor and flexor muscle strength of volleyball players [10]. Dela Bela et al. compared the knee extensor and flexor muscles of professional and under-17-year-old female volleyball players at constant speed, and the study showed that different groups of female volleyball players exhibited significantly different knee joint muscle strength at constant speed [11]. Cengizel explored the relationship between speed and isokinetic knee joint strength of female volleyball players at different angular velocities. The study showed that there was no significant relationship between isokinetic knee joint strength applied at different angular velocities and speeds, and there was no significant relationship between speed and isokinetic knee joint strength of female volleyball players [12]. Yılmaz and Kabadayı conducted electromyographic analysis on isokinetic and single-leg jumping tests, and compared the activation of the same muscle in different tests, showing statistically significant differences in all muscles on both sides [13].

Electromyography technology provides in-depth information about the degree of muscle activation and coordination. Lee et al. explored the effects of comprehensive training on the isokinetic strength of the ankle, knee, lumbar spine, and shoulder joints of female professional volleyball players. Research has shown that comprehensive training can improve the isokinetic strength of the ankle, knee, lumbar spine, and shoulder joints of professional female volleyball players [14]. Cabarkapa et al. studied the differences in dynamic and kinematic characteristics between different volleyball serving movements [15]. Peek et al. studied the gender-specific relationship between longitudinal changes in knee extensor and flexor muscle strength associated with maturity and found that significant interactions indicate that the trajectory of knee joint muscle strength maturity differs between adolescent boys and girls, particularly between pre-puberty and adolescence, with boys exhibiting greater mass standardized knee extensor muscle increase than girls. In terms of knee flexors, boys have increased strength, while girls have decreased relative knee flexor strength [16]. Berriel et al. compared the effects of a 4-week complex training on the lower limb muscle strength and maximum isokinetic torque of knee extensor and flexor muscles in volleyball players. The research results showed that after 4 weeks of complex training, volleyball players' jumping performance and knee extensor and flexor muscles were enhanced [17]. Berriel et al. analyzed the relationship between peak torque of knee flexors and extensor muscles in volleyball players and age, as well as the relationship between conventional ratios and age progression. The results showed that volleyball players are easily influenced by age-related muscle performance in their careers [18]. Ghotbi et al. compared the effects of fatigue in five muscle groups on the dynamic balance of volleyball players and found that fatigue in ankle, knee, and hip muscles also reduces dynamic balance [19]. Benelguemar et al. conducted a kinematic analysis of volleyball blocking techniques and their relationship with lower limb explosiveness in elite Algerian team athletes and found a significant relationship between volleyball blocking techniques and lower limb explosiveness [20]. Researchers analyzed the biomechanical characteristics of the knee joints of volleyball players of different ages, genders, and training backgrounds, and explored the effects of training methods, knee muscle strength, and fatigue on athletic performance.

Although existing research has revealed the effectiveness of strength training, elasticity training, and other methods in improving knee joint strength and athletic performance, it also points out common shortcomings in research, such as limited comprehensive evaluation of different training modes. In summary, this article can further explore the impact of comprehensive training methods on the biomechanical characteristics of knee joints based on existing research. This article hopes to promote the development of volleyball physical training in a more scientific and systematic direction by studying the knee flexion and extension muscles, providing a theoretical basis for coaches and athletes, and promoting the scientific development of volleyball.

3. Experimental design

Experimental design is a crucial part of scientific research, especially in the fields of sports science and sports biomechanics. Reasonable experimental design can ensure the rigor of research, the reliability of results, and the effectiveness of conclusions [21]. Reasonable experimental design in volleyball physical training research helps to deepen the understanding of the biomechanical characteristics of knee flexion and extension muscles, providing a scientific basis for optimizing training methods and improving athletic performance.

3.1. Experimental object design

3.1.1. Selection of experimental subjects

Selection criteria: The experimental subjects are divided into male and female athletes, with a gender ratio of 1:1, to analyze the influence of gender on the biomechanical characteristics of knee flexion and extension muscles. The experimental subjects are volleyball players aged between 20 and 35 years old. Individuals between the ages of 20 and 35 typically experience peak physiological and physical activity, providing stable biomechanical data. The experimental subjects need to have no history of serious knee joint or lower limb injuries. All subjects must undergo a physical examination to ensure that there are no health issues such as cardiovascular disease, respiratory system disease, etc., that affect their athletic performance. The experimental subjects need at least 3 years of volleyball experience to ensure basic volleyball skills and physical fitness. The experimental subjects were selected from athletes of different levels, including amateur athletes, semi-professional athletes, and professional athletes, to analyze the influence of training level on the biomechanical characteristics of knee flexion and extension muscles.

Exclusion criteria: Objects with severe cardiovascular disease, respiratory system disease, musculoskeletal system disease, and other conditions that are not suitable for high-intensity exercise can be excluded. Subjects who have recently used drugs that affect muscle function and physical performance can be excluded. Athletes with a history of severe knee or lower limb injuries within the past 6 months can be excluded to avoid interference with experimental results caused by injuries.

Participants can be provided with a detailed explanation of the purpose, methods, potential risks, and benefits of the experiment. It ensures that all participants voluntarily participate and sign an informed consent form.

3.1.2. Experimental grouping

Scientific experimental grouping can control variables, reduce bias, improve the reliability and reproducibility of results, optimize resource utilization, and enhance the scientific validity of conclusions, thereby ensuring the rigor of experimental design and the effectiveness of results.

This experiment was divided into groups based on age group, volleyball level, and training method. The age (years) range is divided into 20–25, 25–30, and 30–35. Volleyball skills are divided into amateur players, semi-professional players, and professional players. The training group is divided into a strength training group, an elasticity training group, comprehensive training group, and routine exercise control group. The control group participated in exercises that included aerobic exercise three times a week, lasting 60 min each time, at a moderate intensity, mainly including jogging, swimming, and cycling. The frequency and duration of these exercises were comparable to the training volume of the experimental group. Strength training usually focuses on strengthening specific muscle groups, while flexibility training emphasizes improving the flexibility and adaptability of muscles and joints. Comprehensive training combines the advantages of strength and flexibility training and aims to improve the overall physical fitness of athletes. However, if the training mode is not properly selected, it will lead to overuse or uneven development of muscles. Some strength training will focus too much on specific muscle groups and ignore the training of antagonistic muscles, which will lead to muscle imbalance and increase the risk of injury. Therefore, when designing a training plan, coaches and athletes need to carefully consider the comprehensive application of various training methods to ensure muscle balance and reduce the risk of injury. This article uses training methods as the main grouping factor. The total number of people in the strength training group is 36, with a male-to-female ratio of 1:1, an age group ratio of 1:1:1, and a volleyball level ratio of 1:1:1. In the strength training group, there are a total of 12 people in the age group of 20–25, with 4 people at different volleyball levels and 2 men and women at the same volleyball level. All group settings are the same. The group names are shown in **Table 1**.

Table 1. Information on different groups.

Type	Amateur volleyball level			Semi-professional volleyball level			Professional volleyball level		
	20–25	25–30	30–35	20–25	25–30	30–35	20–25	25–30	30–35
Strength training group	Stg-A1	Stg-A2	Stg-A3	Stg-S1	Stg-S2	Stg-S3	Stg-P1	Stg-P2	Stg-P3
Elasticity training group	Etg-A1	Etg-A2	Etg-A3	Etg-S1	Etg-S2	Etg-S3	Etg-P1	Etg-P2	Etg-P3
Comprehensive training group	Ctg-A1	Ctg-A2	Ctg-A3	Ctg-S1	Ctg-S2	Ctg-S3	Ctg-P1	Ctg-P2	Ctg-P3
Control group	Cg-A1	Cg-A2	Cg-A3	Cg-S1	Cg-S2	Cg-S3	Cg-P1	Cg-P2	Cg-P3

Different group numbers facilitate comparative analysis of different factors and facilitate subsequent data analysis.

The basic information of the subjects helps to achieve balance in experimental grouping and reduce bias caused by group differences. **Table 2** shows the basic information of the subjects.

Table 2. Basic information of subjects.

Type	Number of people	Height (cm)	Weight (kg)	Dominant Leg
Strength training group	36	181.53 ± 7.67	74.13 ± 6.92	Mostly right leg
Elasticity training group	36	179.08 ± 8.32	72.47 ± 7.15	Mostly right leg
Comprehensive training group	36	180.02 ± 7.58	73.21 ± 6.87	Mostly right leg
Control group	36	180.57 ± 7.89	73.46 ± 6.95	Mostly right leg

Due to gender balance among the participants, females tend to have smaller height and weight compared to males, resulting in a smaller mean and larger standard deviation in the basic information.

3.2. Experimental equipment design

This article uses Vicon's 3D motion capture system to collect the kinematic characteristics of knee flexion and extension muscles, Kistler's ground reaction force platform to collect dynamic characteristics, and Delsys' electromyography equipment to collect electromyographic characteristics.

The 3D motion capture system [22] is used to record the motion trajectory of the knee joint during flexion and extension, accurately capturing the subject's motion data. The 3D motion capture system can provide a 3D view of the dynamic changes in the knee joint, including detailed information such as flexion and extension angles and motion trajectories.

The ground reaction force platform [23] is used to measure the reaction force applied to the ground by the subject during movement and its distribution. The ground reaction force platform can accurately record force data during jumping, running, and other movements, helping to analyze athletes' power output and impact force.

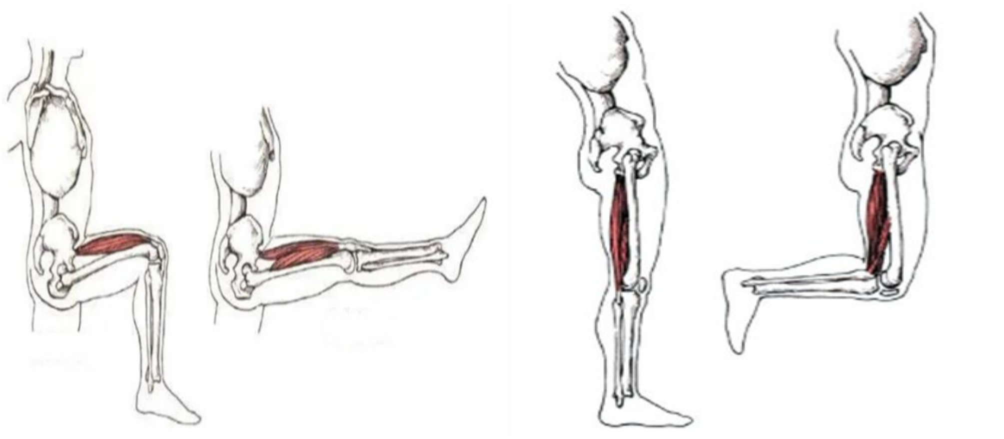
Electromyography equipment [24] is used to record the electromyographic conditions of the flexor and extensor muscles during knee joint flexion and extension. Electromyography can help analyze muscle activation patterns, strength output, and fatigue status.

3.3. Experimental action design

The experimental action design ensures the reproducibility of the experimental process. Scientific experimental motion design can provide accurate and reliable data for evaluating biomechanical characteristics.

Action points: The action should be completed within 10–15 s, maintaining a stable speed and amplitude. The speed of each flexion and extension should be once per second to ensure the stability of the movement and the accuracy of the data, maintain natural breathing, and avoid holding breath.

The specific details of the knee flexion and extension muscles are shown in **Figure 1**.



(a) **(b)**

Figure 1. Knee joint flexor and extensor muscles: **(a)** quadriceps femoris muscle of knee joint; **(b)** biceps femoris muscle of knee joint.

4. Data collection and processing

In experimental research, accurate data collection and processing can ensure the accuracy and completeness of data. Effective data collection can record various indicators of experimental subjects in detail, while precise data processing reveals patterns and trends in the data, enhancing the credibility of research results.

4.1. Data acquisition of 3D motion capture system

Reflective markers can be placed on the knee joint area of the subjects during data collection to ensure stability and accurate positioning of the markers. Before starting the experiment, the motion capture system can be calibrated to ensure accurate angles and positions of each camera. The subjects can perform the knee joint flexion and extension movements designed in the experiment multiple times to ensure the naturalness and consistency of the movements. The system captures real-time position data of marked points, and generates knee joint motion trajectories, angle changes, joint velocities, and accelerations. The captured data can be saved as a motion capture file (.c3d format) for future analysis. The specific collection is shown in **Figure 2**.

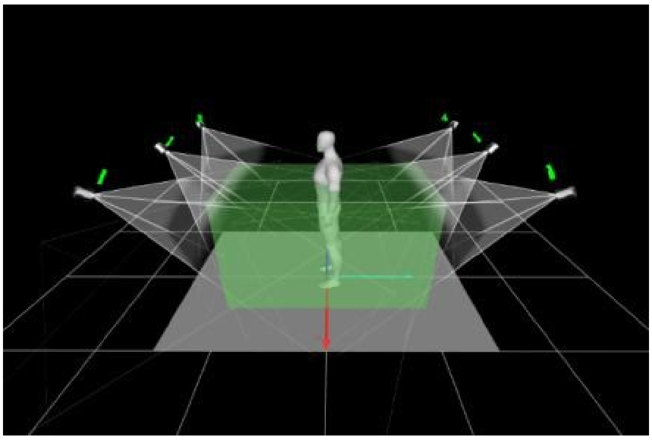


Figure 2. Three-dimensional motion capture data acquisition.

4.2. Data collection of ground reaction force platform

Calibrating the platform before data collection can ensure that its measurement accuracy and sensitivity meet the experimental requirements. It can guide participants on how to perform actions on the platform, ensuring consistent movements. The subject performs a bipedal jump on the platform. The platform records real-time data on the reaction force between the subjects and the platform, generating a force-time curve. The collected data can be saved as a platform-specific format file (.CSV format) for easy analysis and import into the analysis software. The specific collection is shown in **Figure 3**.

Figure 3. Data collection of reaction force.

4.3. EMG equipment data acquisition

During data collection, electrodes are attached to the subject's knee joint flexor and extensor muscles in standard positions to clean the subject's skin and reduce interference, ensuring good electrode contact. The subject performs a predetermined action to activate the target muscle. The device records electromyographic signals and generates muscle activation intensity and signal spectrum data. EMG data can be saved in a file format specific to the EMG device (.emg format) for further analysis. The specific collection is shown in **Figure 4**.

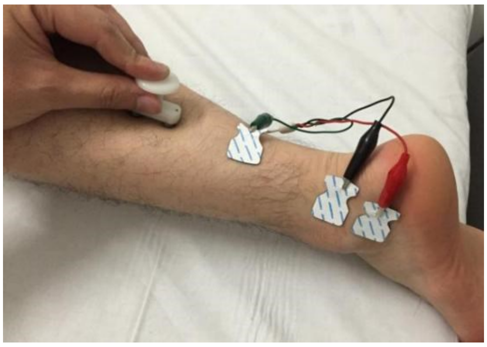


Figure 4. EMG data acquisition.

4.4. Data processing

Data processing is a fundamental step in ensuring the accuracy, reliability, and scientific validity of experimental results. Effective data processing can improve research quality and help researchers make scientifically reasonable conclusions. The collected kinematic feature data, dynamic feature data, and electromyographic feature data can be processed.

It can check and correct errors and missing values in data, and identify outliers by comparing the range and logical consistency of the data. For missing data, interpolation can be used to fill in.

Applying a low-pass filter for noise reduction can eliminate potential noise during the acquisition process, thereby improving the quality and reliability of the data.

Z-score standardization can be used to convert data from different sources to the same scale, to eliminate the impact of different measurement units and ranges.

4.4.1. Kinematic feature processing

Smooth the data collected by the 3D motion capture system [25] both spatially and temporally. Extract motion parameters such as angle, position, and velocity of the knee joint using kinematic analysis software. Calculate key motion parameters during knee joint flexion and extension, including flexion and extension angle, angular velocity, angular acceleration, etc. Extract time series data of joint motion trajectories and conduct further analysis. The angle Equation is shown in Equation (1).

$$\theta = \cos^{-1}\left(\frac{\mathrm{A}\cdot\mathrm{B}}{|\mathrm{A}||\mathrm{B}|}\right) \tag{1}$$

A and B are vectors between two joints, and θ is the angle between the joints. The Equation for angular velocity is shown in Equation (2).

$$\omega_{avg} = \frac{\theta_2-\theta_1}{t_2-t_1} \tag{2}$$

θ_1 and θ_2 are the angles at time t_1 and t_2, respectively.

The Equation for angular acceleration is shown in Equation (3).

$$\alpha_{\mathrm{avg}} = \frac{\omega_2-\omega_1}{t_2-t_1} \tag{3}$$

ω_1 and ω_2 are the angular velocities at times t_1 and t_2, respectively.

4.4.2. Dynamic feature processing

The data collected by the ground reaction force platform [26] can be filtered and processed to calculate the peak, mean, and fluctuation of the ground reaction force. This article analyzes the characteristics of ground reaction force during jumping and landing, calculates the integral of ground reaction force with time, and obtains the total mechanical load of athletes during training.

The data collected by the ground reaction force platform can be used to calculate the vertical ground reaction force and analyze its maximum, minimum, and average values. The reaction force is shown in Equation (4).

$$F_{z,avg} = \frac{1}{N}\sum_{i=1}^{N} F_{z,i} \tag{4}$$

$F_{z,i}$ is the vertical ground reaction force of the ith sampling. N is the total number of samples.

The torque is as shown in Equation (5).

$$M_x = \sum\left(F_{y_i} \cdot z_i - F_{z_i} \cdot y_i\right) \tag{5}$$

z_i and y_i are the vertical height and left-right distance of the measurement point, respectively.

4.4.3. EMG feature processing

EMG data [27] can be filtered and denoised using high-pass filters to remove low-frequency noise and band-pass filters to remove high-frequency noise. It can calculate the amplitude, root mean square value, and time-domain characteristics of electromyographic signals, extract the activation patterns of flexor and extensor muscles, and analyze the collaborative activity of muscles and their changes under different training modes.

The root mean square value of electromyographic signals is used to evaluate muscle activity levels, as shown in Equation (6).

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(EMG_i)^2} \tag{6}$$

EMG_i is the electromyographic signal value of the ith sampling. N is the total number of samples.

The average amplitude of electromyographic signals is used to analyze muscle activity intensity, as shown in Equation (7).

$$MAV = \frac{1}{N}\sum_{i=1}^{N}|x_i| \tag{7}$$

x_i is the electromyographic signal value of the ith sampling point, and N is the total number of sampling points.

The integral value of electromyographic signals within a specific period represents the total muscle activity, as shown in Equation (8).

$$IEMG = \sum_{i=1}^{N}|x_i| \cdot \Delta t \tag{8}$$

x_i is the electromyographic signal value of the ith sampling point, Δt is the time interval, and N is the number of sampling points.

5. Data analysis

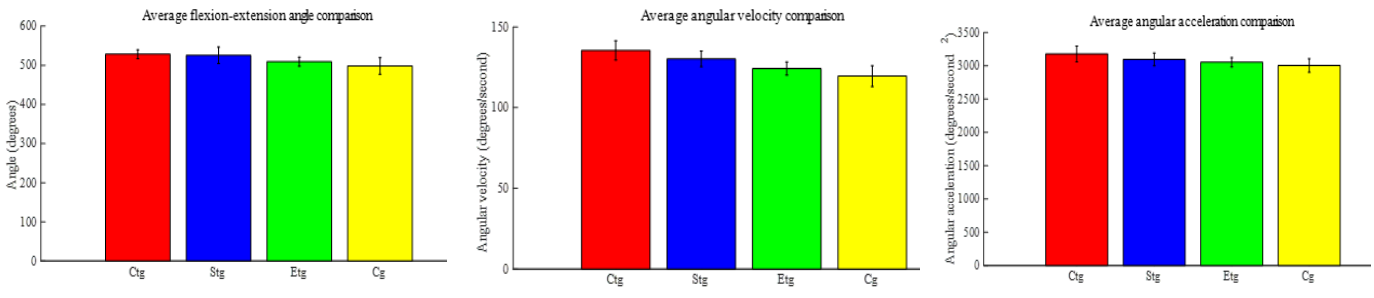
In volleyball physical training, data analysis plays a key role in the comparative analysis of the biomechanical characteristics of knee flexion and extension muscles. By systematically analyzing data such as flexion-extension angle, angular velocity, angular acceleration, ground reaction force, torque, and electromyographic signals, this article can gain a deeper understanding of the specific effects of different training methods on the biomechanical characteristics of the knee joint. Data analysis helps optimize training programs, improve athletes' athletic performance, identify potential injury risks, and develop effective preventive measures. Data analysis ensures the scientific and objective nature of research conclusions, providing empirical evidence and guidance for the physical training of volleyball players. In all data analysis graphs, Ctg represents the comprehensive training group, Stg represents the strength training group, Etg represents the elasticity training group, and Cg represents the control group.

Under different training modes, strength training significantly improves the maximum force output of muscles by increasing the cross-sectional area of muscle fibers, and is suitable for sports that require short-term explosive power, such as jumping and rapid changes of direction in volleyball. Elasticity training mainly improves muscle elasticity and coordination, dynamic balance, and movement efficiency, but because it usually uses light weights and multiple repetitions, the mechanical stimulation provided is not enough to significantly promote the growth of muscle fibers, so it is not as effective as strength training in improving maximum force output. Elasticity training will also change the recruitment pattern of muscles and affect the effectiveness of muscles in high-intensity exercise. Strength training is more effective in improving muscle maximum force output and coping with high-intensity exercise needs, while elasticity training has advantages in improving muscle endurance and flexibility. It is recommended to combine strength training with elasticity training to comprehensively improve muscle function and sports performance.

5.1. Kinematic data analysis

Kinematic data analysis [28] plays a crucial role in research, especially in evaluating athletes' motor performance and physical function. By analyzing kinematic data, motion efficiency, and coordination can be improved, potential motion defects or imbalances can be revealed, and training plans can be adjusted to optimize performance and reduce the risk of sports injuries.

By analyzing the average flexion-extension angle, average angular velocity, and average angular acceleration data of the strength training group, elasticity training group, comprehensive training group, and control group, the average values and their standard deviations of each group were compared to understand the kinematic effects of different volleyball training on the knee joint. The result is shown in **Figure 5**.



(a) **(b)** **(c)**

Figure 5. Kinematic data of different training types: **(a)** Bending and extension angle data for different training types; **(b)** Angular velocity data for different training types; **(c)** Angular acceleration data for different training types.

According to **Figure 5**, the average flexion and extension angle of the comprehensive training group is the highest, followed by the strength training group, the elasticity training group, and the control group the lowest. The kinematic data of the comprehensive training group showed the best performance, with the highest flexion and extension angles, angular velocities, and angular accelerations. Comprehensive training combines the advantages of strength training and elasticity training, which can better improve the overall athletic performance of athletes. The flexion-extension angle, angular velocity, and angular acceleration of the strength training group were higher than those of the elasticity training group and the control group. Strength training has a significant effect on improving athletes' knee joint flexion and extension abilities. The performance of the elasticity training group was slightly lower than that of the strength training group, but still significantly better than the control group. Elasticity training is mainly aimed at training the flexibility and coordination of the knee joint and is inferior to strength training and comprehensive training in terms of kinematics. All indicators of the control group were the lowest.

By analyzing the kinematic data between different genders, the influence of gender on the kinematics of knee flexion and extension muscles in volleyball training is determined. The result is shown in **Figure 6**.

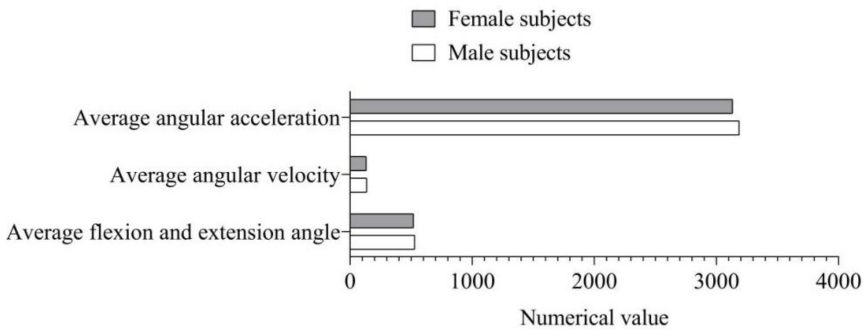


Figure 6. Kinematic data of different genders.

According to **Figure 6**, the average flexion and extension angle for males is 530.17°, while for females it is 520.12°. Men have slightly greater flexion and extension angles than women, which means that their joint range of motion is slightly larger. The average angular velocity for males is 137.52°/s, while for females it is 133.2°/s. Men have slightly higher angular velocities than women, indicating that men move faster. The average angular acceleration for males is 3187.52°/s^2, while for females it is 3133.65°/s^2. The angular acceleration of males is slightly higher than that of females, indicating that males have greater acceleration and exhibit faster speed changes.

By analyzing the kinematic data of different ages, the influence of age on the kinematics of knee flexion and extension muscles in volleyball training is obtained. The result is shown in **Figure 7**.

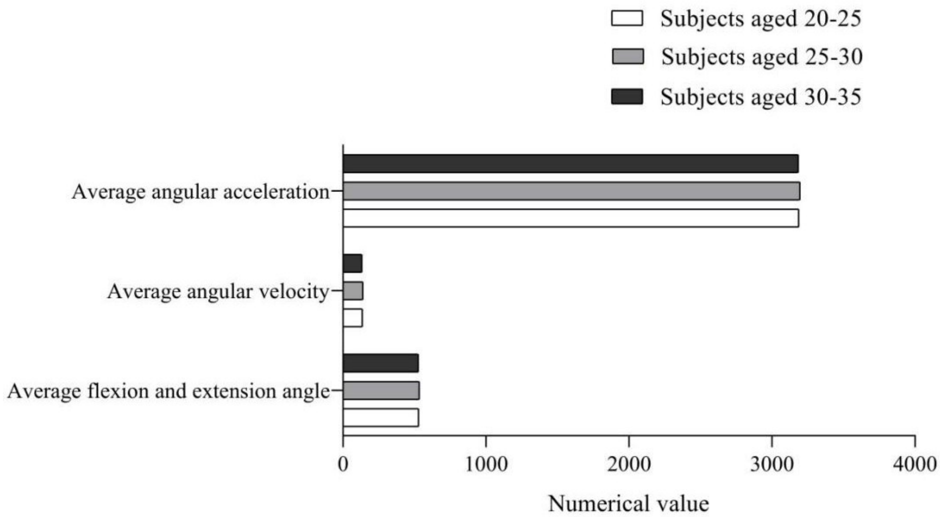


Figure 7. Kinematic data for different ages.

According to the analysis of **Figure 7**, the 25–30 age group has the highest flexion and extension angles, indicating that participants in this age group perform the best in terms of knee joint flexibility and range of motion. The flexion and extension angles of the 30–35 age group are lower than those of the 25–30 age group, indicating that as age increases, joint flexibility and range of motion can slightly decrease. From the perspective of angular velocity analysis, the 25–30 age group has the highest angular velocity, indicating that this group can complete knee flexion and extension movements the fastest. The angular velocity of the 30–35 age group is the smallest, indicating that as age increases, the reaction speed and control ability of the neuromuscular system slightly decreases. From the perspective of angular acceleration, the 25–30 age group has the highest angular acceleration, indicating that this group can generate greater acceleration per unit time during knee flexion and extension movements, demonstrating better explosive power. The angular acceleration of the 20–25 age group and the 30–35 age group is relatively low, but the difference is not significant, indicating that age has a less significant effect on explosive power than on angular velocity.

By analyzing the kinematic data between different volleyball levels, the influence of volleyball level on the kinematics of knee flexion and extension muscles in volleyball training is obtained. The result is shown in **Figure 8**.

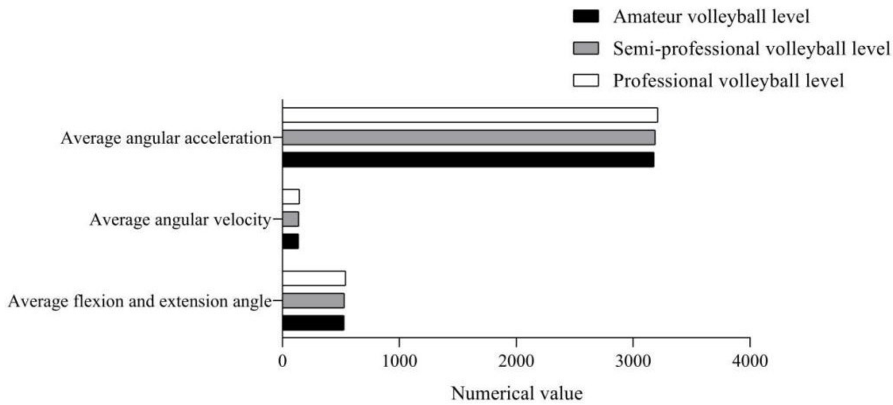


Figure 8. Kinematic data of different volleyball levels.

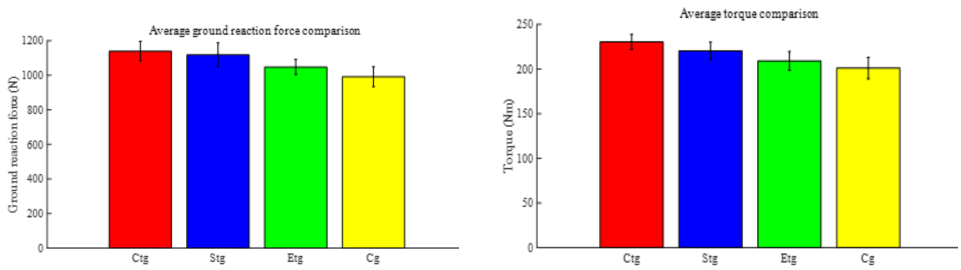
From **Figure 8**, it can be seen that professional athletes have the highest flexion and extension angles, indicating that professional-level athletes perform the best in knee joint flexibility, which may be related to the professional training received. Volleyball players who have received more professional training can achieve greater flexion and extension angles. The angular velocity of professional athletes is 146.22º/s, which is 6.7º/s higher than that of semi-professional athletes and 7.5º/s higher than that of amateur athletes. Professional athletes can complete prescribed movements faster. The angular acceleration of professional athletes is 3211.82º/s^2, which is 22.86º/s^2 higher than that of semi-professional athletes and 32.17º/s^2 higher than that of amateur athletes. Professional athletes have the highest angular acceleration, indicating that they can generate greater acceleration per unit time during knee flexion and extension movements, demonstrating stronger explosive power. The angular acceleration of semi-professional athletes is higher than that of amateur athletes, but the difference between the two is relatively small.

5.2. Dynamics data analysis

Dynamics data analysis [29] focuses on understanding the forces acting on the body during motion and their impact on motion performance. Through dynamic analysis, coaches and researchers can adjust training strategies in a targeted manner to enhance athletes' athletic performance. Dynamics analysis is an important component of sports science research.

By analyzing the average ground reaction force and average torque data of the strength training group, elasticity training group, comprehensive training group, and control group, the average values and standard deviations of each group can be compared to understand the dynamic effects of different volleyball training on the knee joint. The result is shown in **Figure 9**.

According to **Figure 9**, the ground reaction force of the comprehensive training group is the highest, at 1139.40 N, indicating that the comprehensive training type effectively improves the individual's ground reaction force. The ground reaction force of the strength training group was slightly lower than that of the comprehensive training group, but still higher than other groups, indicating that strength training has a better enhancement effect on ground reaction force. The ground reaction force of the elastic training group is 1047.78 N, while the ground reaction force of the control group is 991.34 N. The comprehensive training group produced the highest torque, indicating that the comprehensive training type effectively increased the torque generated by individuals. The torque of the strength training group was 220.45 Nm, which was higher than that of the elasticity training group and the control group, indicating that strength training has a significant effect on enhancing torque. The torque of the elasticity training group was 209.10 Nm, while the torque of the control group was 201.05 Nm. The comprehensive training group performed the best in both ground reaction force and torque indicators, indicating that comprehensive training is most effective in improving reaction force and torque. The strength training group performed second only to the comprehensive training group, indicating a significant effect of strength training on enhancing ground reaction force and torque. The elasticity training group was lower than the strength training group and the comprehensive training group in both indicators, but still higher than the control group, indicating that elasticity training also has a certain effect on improving torque, but it may focus more on improving flexibility. The ground reaction force and torque of the control group were the lowest.



(a) **(b)**

Figure 9. Dynamics data of different training types: **(a)** Ground reaction force data for different training types; **(b)** Torque data for different training types.

The impact of gender on knee flexion and extension muscle dynamics can be analyzed by analyzing dynamic data between different genders. The result is shown in **Figure 10**.

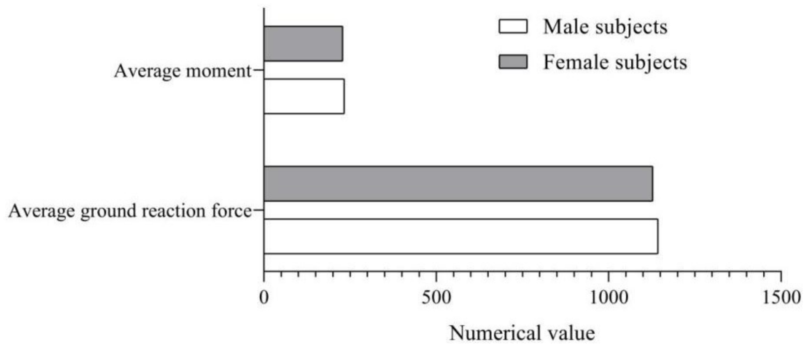


Figure 10. Dynamics data of different genders.

From **Figure 10**, it can be seen that the ground reaction force generated by males is 1143.4 N, which is 15.1 N higher than that generated by females. The torque generated by males is 233.25 Nm, which is 4.09 Nm higher than that generated by females. The difference between ground reaction force and torque indicates that men have stronger forces than women in the experiment, and can generate greater reaction force and torque.

The impact of age on the dynamics of knee flexion and extension muscles can be analyzed by analyzing dynamic data between different ages, as shown in **Figure 11**.

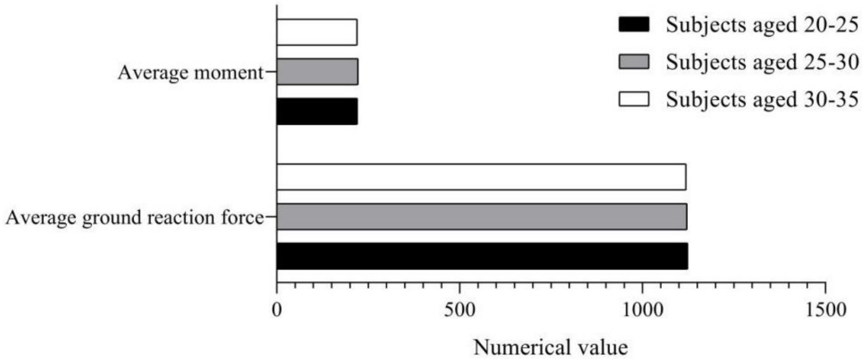


Figure 11. Dynamics data at different ages.

According to **Figure 11**, subjects aged 20–25 have the highest ground reaction force. As age increases, the ground reaction force of subjects aged 25–30 slightly decreases, while the ground reaction force of subjects aged 30–35 continues to decrease. This trend may be related to changes in muscle strength and decreased body coordination caused by aging. The maximum torque was observed in participants aged 25–30, indicating that individuals may be in their optimal state of strength and stamina during this age group. The torque of subjects aged 20–25 and 30–35 is relatively similar, at 220.42 Nm and 220.12 Nm respectively, indicating that young and slightly older adults exhibit similar performance in torque. As age increases, the muscle strength of the body can change, especially between the ages of 20–25 and 30–35, where strength gradually decreases. The age range of 25–30 is when many people's physical strength and coordination reach their peak. Therefore, during this age range, torque reaches its highest value, indicating that this period may be the peak of individual athletic performance.

By analyzing the dynamic data between different levels of volleyball, the influence of volleyball level on the dynamics of knee flexion and extension muscles can be analyzed. The results are shown in **Figure 12**.

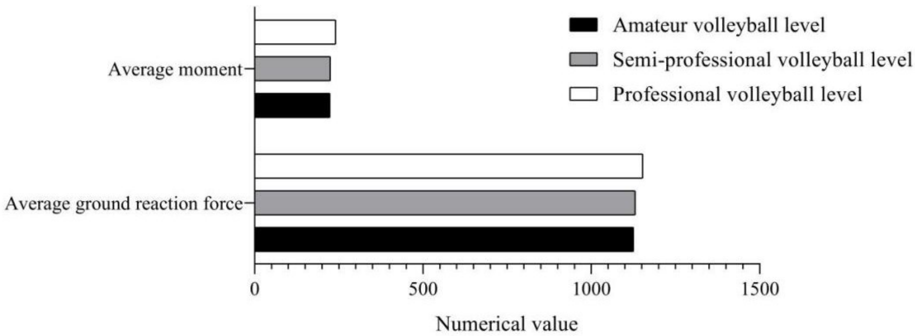


Figure 12. Dynamics data of different volleyball levels.

According to **Figure 12**, the ground reaction force of the occupational group is 1153.23 N, the ground reaction force of the semi-occupational group is 1130.44 N, and the ground reaction force of the amateur group is 1125.63 N. The trend of ground reaction force indicates that as the training level increases, the ground reaction force generated by athletes increases. The torque generated by the occupational group is 241.12 Nm, which is 15.9 Nm higher than the torque generated by the semi-occupational group and 17.4 Nm higher than the torque generated by the amateur group. The torque generated by the occupational group is much greater than that generated by the other two groups. The reason is that athletes in professional groups have received longer professional training and have better physical fitness. The experiment shows that a more professional level of volleyball can generate greater torque in the knee flexion and extension muscles, resulting in better athletic performance.

5.3. EMG data analysis

EMG data analysis [30] is crucial for understanding the activity state of muscles during exercise. EMG data analysis can help coaches optimize training methods, improve exercise efficiency, and effectively prevent muscle injuries. EMG data analysis can also be used to evaluate athletes' muscle function and provide personalized rehabilitation recommendations, which is a key link in sports science and rehabilitation medicine.

By analyzing different types of Root Mean Square (RMS), Mean Absolute Value (MAV), and Integral Electromyography (IEMG) data, the article aims to understand the electromyographic condition of the knee joint. The specific results are shown in **Table 3**.

Table 3. Different types of electromyographic data.

Type	Detailed Type	RMS	MAP	IEMG
Training Type	Strength training group	0.51	0.5	497.75
	Elasticity training group	0.47	0.46	459.14
	Comprehensive training group	0.56	0.54	542.41
	Control group	0.41	0.4	400.35
Gender	Male	0.56	0.52	563.71
	Female	0.42	0.41	428.65
Age	20–25	0.52	0.51	523.48
	25–30	0.57	0.53	551.13
	30–35	0.5	0.49	506.72
Volleyball level	Amateur volleyball level	0.51	0.5	499.79
	Semi-professional volleyball level	0.56	0.51	532.34
	Professional volleyball level	0.59	0.57	561.14

According to **Table 3** analysis, among different training groups, the comprehensive training group has the highest RMS value, reflecting strong muscle strength and activity. The RMS value of the strength training group was 0.51 mV, second only to the comprehensive training group, but significantly higher than the elasticity training group and the control group. The RMS value of the control group was the lowest. The RMS value of the comprehensive training group is the highest, indicating that comprehensive training has the best effect on muscle activation.

The MAV value of the comprehensive training group is 0.54 mV, which is 0.04 mV higher than that of the strength training group, 0.08 mV higher than that of the elasticity training group, and 0.14 mV higher than that of the control group. The comprehensive training group has the highest average amplitude during muscle activity, indicating that the comprehensive training group has a good activation effect on muscles. The IEMG value of the comprehensive training group was 542.41 mV, which was 44.66 mV higher than that of the strength training group, 83.27 mV higher than that of the elasticity training group, and 142.06 mV higher than that of the control group. The comprehensive training group has the highest total muscle activity and the best training effect during the training process.

The RMS, Mean Absolute Value (MAV), and IEMG of males are higher than those of females, indicating significant gender differences in muscle activity levels, with males having higher overall muscle activation and total activity than females.

The RMS, MAV, and IEMG of the 25–30 age group are the highest. The RMS, MAV, and IEMG performance of the 20–25 age group is better, but slightly lower than that of the 25–30 age group. The RMS, MAV, and IEMG of the 30–35 age group are the lowest, indicating that after the age of 25, muscle activity levels decrease as age increases. The 25–30 age group shows the most prominent performance in electromyography, while the 30–35 age group shows relatively lower performance.

The professional volleyball level group performed the best in all indicators, with the highest RMS, MAV, and IEMG. The semi-professional volleyball level group is second, with RMS, MAV, and IEMG slightly lower than the professional level group. The RMS, MAV, and IEMG of the amateur volleyball level group are the lowest. The higher the level of volleyball, the stronger the degree of muscle activity and activation.

5.4. Statistical analysis

To further verify the effects of different training modes on the biomechanical properties of the knee flexor and extensor muscles, this study conducted a detailed statistical analysis. Through independent sample *t*-test and analysis of variance (ANOVA), this paper evaluated whether the differences between the groups were statistically significant. **Table 4** shows the mean and standard deviation of the maximum force output, muscle endurance, muscle flexibility, RMS, MAV, and IEMG of the knee flexor and extensor muscles under different training modes, as well as the corresponding statistically significant results.

Table 4 shows that the maximum force output of the strength training group was 125.4 ± 10.2 N·m, which was significantly higher than 112.3 ± 9.5 N·m of the elastic training group and 105.6 ± 8.3 N·m of the control group ($p < 0.05$). In terms of muscle endurance, the elastic training group was 52.3 ± 6.1 s, which was significantly higher than 40.2 ± 4.9 s of the control group ($p < 0.05$). In terms of muscle flexibility, the elastic training group was 70.1 ± 4.8º, which was significantly higher than the 62.3 ± 4.1º of the control group ($p < 0.05$). Among the electromyographic indicators, the RMS of the comprehensive training group was 0.56 ± 0.06 mV, which was significantly higher than that of the other groups ($p < 0.05$). These results show that different training modes have a significant effect on the biomechanical properties of the knee flexor and extensor muscles, and strength training performs best in improving maximum force output, while elastic training performs outstandingly in improving muscle endurance and flexibility.

Table 4. Statistical analysis of the biomechanical properties of the knee flexor and extensor muscles under different training modes.

Indicator	Stg	Etg	Ctg	Cg	*p*-value (ANOVA)	*p*-value (*t*-test)
Maximum Force Output (Nm)	125.4 ± 10.2	112.3 ± 9.5	120.5 ± 11.0	105.6 ± 8.3	< 0.05	Stg vs Etg: < 0.05< br > Stg vs Cg: < 0.05
Muscle Endurance (s)	45.6 ± 5.4	52.3 ± 6.1	48.9 ± 5.8	40.2 ± 4.9	< 0.05	Etg vs Cg: < 0.05< br > Ctg vs Cg: < 0.05
Muscle Flexibility (º)	65.2 ± 4.3	70.1 ± 4.8	68.5 ± 4.5	62.3 ± 4.1	< 0.05	Etg vs Cg: < 0.05< br > Ctg vs Cg: < 0.05
RMS (mV)	0.51 ± 0.05	0.47 ± 0.04	0.56 ± 0.06	0.41 ± 0.04	< 0.05	Ctg vs Stg: < 0.05 < br > Ctg vs Etg: < 0.05 < br > Ctg vs Cg: < 0.05
MAV (mV)	0.50 ± 0.05	0.46 ± 0.04	0.54 ± 0.05	0.40 ± 0.04	< 0.05	Ctg vs Stg: < 0.05 < br > Ctg vs Etg: < 0.05 < br > Ctg vs Cg: < 0.05
IEMG (μV·s)	497.75 ± 45.67	459.14 ± 42.34	542.41 ± 50.89	400.35 ± 38.21	< 0.05	Ctg vs Stg: < 0.05< br > Ctg vs Etg: < 0.05 < br > Ctg vs Cg: < 0.05

6. Conclusions

This study conducted a comparative analysis of the biomechanical characteristics of knee flexion and extension muscles in volleyball physical training. The results showed that there were significant differences in the biomechanical performance of knee flexion and extension muscles among different training groups, genders, age groups, and volleyball levels. When comparing training types, the kinematic performance of the comprehensive training group is superior to other groups, and the dynamic and electromyographic characteristics are also the best. When compared by gender, males have better biomechanical indicators than females, indicating significant differences in the biomechanical characteristics of knee flexion and extension muscles between genders. When comparing by age, analysis based on different age groups shows that the 25–30 age group has the best athletic performance, indicating that this age group may be the golden period for volleyball players' physiological functions. When compared based on volleyball proficiency, there is a significant difference in the level of professional volleyball participants compared to other participants. This study provides a reference for the biomechanical characteristics analysis of knee flexion and extension muscles in volleyball players during physical training and provides a certain degree of basis for coaches to develop reasonable training methods.

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