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Article

Biological analysis of shoulder joint muscle strength during volleyball spike specific physical training

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Abstract: Volleyball spike requires extremely high shoulder joint muscle strength. Traditional research methods are single, with insufficient sample size, lack multidimensional analysis and long-term training effect evaluation, and have not fully combined biomechanical and physiological theories. This article combined biomechanical and physiological theories to collect field data and used a three-dimensional motion capture system and surface electromyography technology to analyze the performance of shoulder joint muscle strength in spiking. The experimental results show that Integrated Biomechanics and Physiology (IBP) is significantly superior to other training methods in improving the maximum strength, endurance, and muscle activation of the shoulder joint. Specific data show that after IBP training, the maximum strength of the shoulder joint increased by 50 N, and the endurance increased by 19.6%, and the muscle activation increased by 13.5%. Studies have shown that the IBP method has great potential for application in optimizing special physical training, providing a scientific basis for athletes' physical training.

Keywords: biomechanics and physiology; surface electromyography; shoulder strength; volleyball spiking; training methods

1. Introduction

Volleyball spiking is one of the most explosive and spectacular technical movements in volleyball, and it requires extremely high shoulder muscle strength of athletes. The shoulder joint is the main force-bearing part during spiking, and its muscle strength directly affects the effect of spiking and the performance of athletes. Traditional studies often use static strength tests when analyzing shoulder muscle strength, which cannot fully reflect the muscle strength performance in dynamic movements [1,2]. Many studies have small sample sizes, which limits the universality and reliability of the results [3]. Existing studies have mostly focused on the evaluation of short-term training effects, ignoring the impact of long-term training on shoulder muscle strength [4,5]. The current situation requires researchers to adopt a more scientific and comprehensive method to deeply analyze the performance of shoulder muscle strength in volleyball spiking, to provide stronger theoretical support for athletes' physical training.

This article combines the theories of biomechanics and physiology to study the role of shoulder joint muscle strength in volleyball spikes, addressing multiple shortcomings in traditional research. The research steps involve on-site testing of athletes' shoulder joint muscle strength, recording spike movements, and collecting actual competition data. Volleyball players of different ages, genders, and training backgrounds can be selected to ensure sample diversity and representativeness. Three-dimensional motion capture systems and surface electromyography techniques can be used to analyze the motion trajectory and muscle activation patterns during spike actions. Data statistical software can be used for data analysis to evaluate the effectiveness of different training methods and the effects of long-term and short-term training. The experimental summary shows that the combination of biomechanical and physiological theories can comprehensively analyze the performance of shoulder joint muscle strength, providing a scientific basis for the optimization of training methods. This article provides a deep understanding of shoulder joint muscle strength in volleyball spike shots, using multidimensional analysis and long-term training effect evaluation to fill the gap in traditional research and provide practical theoretical guidance for the physical training of volleyball players.

2. Related work

Researchers used different methods to explore the role of shoulder joint muscle strength in volleyball spikes. The study by Eleftherios Paraskevopoulos et al. showed that 1080 Sprint is effective and reliable for monitoring the throwing performance of volleyball players [6]. The impact of Kinetic Chain (KC) training on scapular and trunk neuromuscular performance during volleyball dunking was investigated in randomized controlled research [7]. Giatsis et al. [8] investigated the arm swing technique of top beach volleyball players during dunking and analyzed the intra-rater and inter-rater reliability using Cohen's Kappa statistic. Yazdani et al. used the test-retest method to investigate the reliability of kinova measurements [9]. Richman et al. [10] studied the influence of self-myofascial release (SMR) with a foam roller device combined with general warm-up and DS (Dynamic Stretching) courses on the flexibility and explosive sports performance of several female college athlete samples. Shih et al. [11] investigated the differences in shoulder joints, scapula, and trunk movements between volleyball players with and without shoulder pain during spike actions. There are also studies investigating the gender-related performance and biomechanical characteristics of volleyball spike jumps, to investigate their correlation with both sexes [12]. The research objective of Guntur et al. [13] was to determine the impact of jumping performance and coordination on spike ability. Contemori et al. [14] evaluated the surface electromyography (sEMG) activity patterns, relationships, and response delays of shoulder strap muscles in professional volleyball players and healthy control athletes with isolated infraspinatus atrophy. Daniele Mazza et al. [15] investigated the prevalence of suprascapular neuropathy in elite volleyball players to prevent injuries connected to activity. There are also studies investigating the relationship between sports characteristics and female spike high jump performance, and determining the most relevant aspects between high jump and ball speed [16]. Alqarni et al. [17] examined volleyball players with and without a history of shoulder pain on the physiological and pathological shoulder humeral internal rotation dysfunction. The problems with these studies include single methods, insufficient sample size, lack of multidimensional analysis, neglect of long-term training effects, and insufficient integration of biomechanics and physiology.

To address the current research issues, researchers have employed various methods for exploration. Saadatian's et al. [18] study determined the torque of shoulder joint internal and external rotation when throwing the ball in athletes with and without impact syndrome. Rigozzi et al. [19] focused on determining the current applications of wearable technology in athlete movement analysis through two research questions. Djoko Nugroho et al. [20] described the different effects of concentrated and dispersed practice, arm strength, and intelligence on the forehand and backhand skills of sports students. There are also studies examining the role of various indicators in the development of shoulder discomfort in professional volleyball players [21]. Roman et al. [22] investigated the effects of different physical fitness indicators on the competitive activities of female volleyball players during the preparation stage. There is also research on electromyographic analysis and comparison of shoulder joint muscles during tennis serving in volleyball matches [23]. Saeed Eshghi et al. [24] examined the effects of an eight-week 11 + S training program on shoulder strength in athletes. At the same time, Jeffrey's et al. [25] study identified and analyzed the asymmetry of lower limb biomechanics in standard and specific leg landing tasks for college female volleyball players. Zuzgina et al. [26] compared the range of motion and strength of dominant and non-dominant shoulders in university-level volleyball players to examine gender differences. Ismael's [27] research determined the biological kinematics and angle measurement variables of straight-line killing and explored their relationship with explosive force during motion. Kela et al. [28] used quantitative research methods to investigate the incidence of upper and lower limb injuries among participants. Although these studies have diverse methods, there are still certain shortcomings in solving existing problems. To overcome these shortcomings, this article adopts a method that combines biomechanics and physiology theory to collect and analyze field data, providing more comprehensive and reliable research results.

3. Method of shoulder joint muscle strength

3.1. Data collection

Multiple scientific methods and high-precision equipment are used for on-site data collection of volleyball players to ensure the comprehensiveness of the data. The shoulder joint muscle strength testing section is measured using the Biodex system speed muscle strength tester. The isokinetic muscle strength tester can provide accurate torque and power data under preset angular velocity conditions. During the testing process, athletes sit on the testing device with their shoulder joints fixed in specific positions and perform flexion and extension exercises. The tests were conducted at 60 °/s, 120 °/s, and 180 °/s, with three repetitions for each angular velocity. The maximum and average torque values were recorded, and shoulder joint muscle strength data were collected from 200 athletes to ensure the representativeness and universality of the sample. The study considered athletes of different ages, genders, and training backgrounds in the sample selection process to improve the diversity and representativeness of the sample. The sample came from athletes from different geographical locations to ensure coverage of regional differences. In addition, the sample also involved athletes from different cultural backgrounds to evaluate the impact of cultural differences on training effects. To ensure that the sample size can support the statistical analysis of the study, this study conducted detailed statistical calculations on the sample to ensure sufficient statistical power in the predetermined analysis.

The video recording part of the spike action uses high-speed cameras to record athletes' spike actions during training and competition. The camera is set at multiple angles, covering various areas of the field to ensure that the full picture of the athlete's spike action can be captured. During each training and competition, the camera records at a speed of 500 frames per second, ensuring the ability to capture subtle changes in motion. During the recording process, all video data is preliminarily processed through automatic labeling software, marking the start and end time points of each spike action, and then manually corrected and detailed labeled by an expert team. A total of 50 matches and 100 training sessions were recorded, and over 5000 video records of spike actions were collected, providing a rich data foundation for subsequent kinematic analysis.

The actual competition data collection section records the number of dunks and the success rate of athletes during the competition. A real-time statistical system is adopted, and in each game, statistical personnel use professional statistical software to record each spike action, including parameters such as spike frequency, success rate, hitting angle, and strength. During the statistical process, data is transmitted in real-time to the central database through wireless networks to ensure its timeliness. To improve the reliability of the data, the data for each game is recorded and cross-validated by two independent statisticians to ensure the accuracy of the records. This article collected spike data from 200 matches, with at least 30 spikes recorded in each match. A total of over 6000 spike data were collected, providing detailed performance data for the study.

By following the above steps, comprehensive and systematic data on the shoulder joint muscle strength and spike movements of volleyball players can be collected. The use of high-precision measuring equipment and scientific data collection methods ensures the accuracy of the data, providing a solid data foundation for subsequent biomechanical and physiological analysis. After collection, all data is immediately subjected to preliminary processing and storage to ensure data security.

3.2. Sample selection

To ensure the representativeness of the research results, the sample selection covered volleyball players of different ages, genders, and training backgrounds. This study selected a total of 200 athletes, covering the age group of 18 to 35 years old, with a gender ratio of half male and half female, and training backgrounds ranging from beginner to advanced. These athletes all come from major volleyball clubs and university volleyball teams across the country, ensuring diversity in data sources.

The sample selection adopts a random sampling method to ensure the randomness of the sample [29]. Randomly select from eligible athletes to avoid selection bias and ensure sample representativeness. The theoretical calculation of sample size adopts the following formula:

$$n = \frac{Z^2 \times p \times (1 - p)}{E^2} \tag{1}$$

In the formula, n represents the sample size, Z is the Z-value of the standard normal distribution (at a 95% confidence level, Z = 1.96), p is the estimated population proportion (set to 0.5 to obtain the maximum sample size), and E is the allowable error (set to 0.07). By calculation, the required sample size is at least 196 people, and 200 people were collected to ensure sufficient data.

The basic information and training data of all athletes are obtained through standardized questionnaires and training logs. The collected basic information on athletes includes age, gender, training years, weekly training frequency, and duration of each training session. To ensure that the physical fitness level of the samples meets the research requirements, all athletes undergo basic physical fitness tests before data collection. The test items include the maximum oxygen uptake (VO2 max) test, muscle strength, and endurance test, and the test data are all conducted in a standard laboratory environment.

During the sample selection process, some of the collected data are shown in **Table 1**, which displays the basic physical fitness test results of athletes from different age groups and training backgrounds.

Table 1. Sample basic physical fitness test results.

Participant ID	Age Group	Training Years	VO2 Max (mL/kg/min)	Shoulder Strength (*N*)
1	18–24	<5	55.2	450
2	25–30	5–10	53.4	470
3	31–35	>10	50.1	480
4	18–24	5–10	54.8	460
5	25–30	<5	52.3	445

The analysis of the data in **Table 1** shows that athletes aged 18–24 have better cardiopulmonary function, with a maximum oxygen uptake of 55.2 mL/kg/min and shoulder joint strength of 450 N. This reflects the strong cardiopulmonary function of young athletes. Athletes in the 25–30 age group showed an increase in shoulder joint strength (470 N) despite a decrease in cardiopulmonary function (maximum oxygen uptake of 53.4 mL/kg/min). It shows that with the increase of training years, the muscle strength accumulation effect is significant. Although the maximum oxygen uptake of athletes aged 31–35 further decreased to 50.1 mL/kg/min, their shoulder joint strength was the highest, reaching 480 N, indicating that long-term training has a significant effect on improving muscle strength. These results suggest the influence of different ages and training backgrounds on athletes' physical fitness and muscle strength.

The data analysis in the sample selection section shows significant differences in cardiovascular function and shoulder joint strength among athletes of different ages, genders, and training backgrounds. The physical fitness and muscle strength data at different training stages provide a reference for optimizing training programs.

3.3. Biomechanics analysis

A three-dimensional motion capture system (Vicon system) can be used for biomechanical analysis of volleyball players' spike movements. Reflective markers were installed on the athletes, mainly at the shoulder joint, elbow joint, wrist joint, and fingertips, to accurately capture the movement trajectory of the shoulder joint during the spiking movement. When recording each spiking movement, the motion capture system worked at a sampling frequency of 500Hz to ensure that every detail of the movement was accurately captured. When using a 3D motion capture system, there are potential issues with marker drift and camera view errors. To minimize these errors, system calibration is performed and multi-view cameras are used to increase the accuracy of the data.

In the data processing stage, the raw data was preprocessed by Vicon Nexus software to remove noise and erroneous data. Subsequently, the Biomechanics Toolkit was used to reconstruct the motion trajectory of the shoulder joint in three dimensions to generate joint motion curves. Through these curves, the movement pattern and trajectory changes of the shoulder joint during spiking were analyzed in detail. **Figure 1** shows the changes in the shoulder joint angles of the five participants during volleyball spiking over time. The data showed that the shoulder joint angles of participants with higher training levels were more stable and had smaller fluctuations, which indicated that they had higher movement efficiency and mechanical stability.

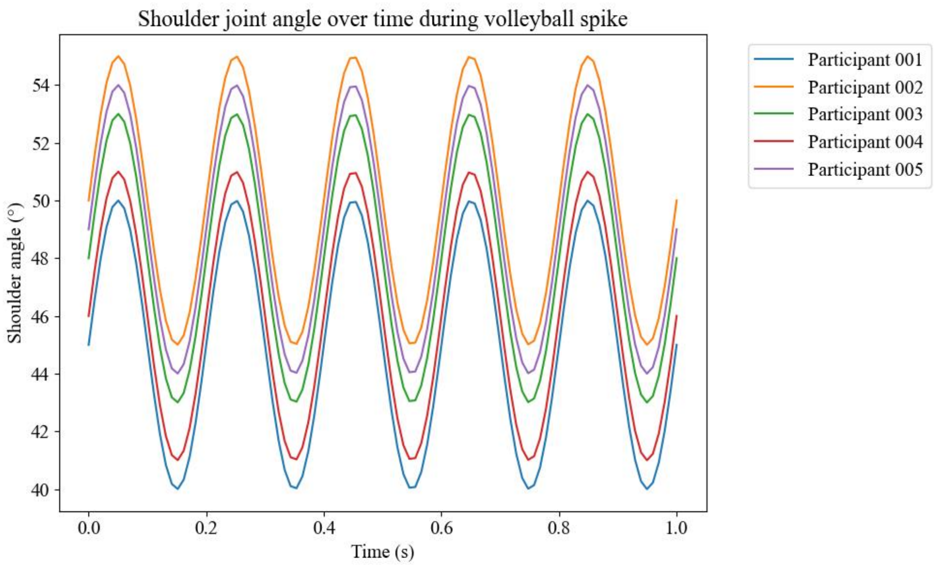

Figure 1. The variation of shoulder joint angle over time during the volleyball spike process.

In the mechanical performance evaluation section, the inverse dynamics method is used to calculate the force and torque of the shoulder joint during the spike process. The formula is as follows:

$$\tau = I \times \alpha + m \times g \times d \quad (2)$$

τ is the torque acting on the shoulder joint, the moment of inertia of the shoulder joint is I, α is the angular acceleration, m represents the mass of the shoulder-related muscles and bones, g represents the gravitational acceleration, and d is the length of the lever arm. The formula is used to calculate the force and torque on the shoulder joint at different time points, and further analyze the mechanical characteristics in the action.

This article selects 50 athletes with different training levels for testing. Each athlete completed three standardized spiking actions, and the motion trajectory and mechanical performance of their shoulder joints were recorded. The original data were strictly screened and tested in laboratory standards to ensure the accuracy of the data. The original motion trajectory data and mechanical performance results of 5 athletes were selected as shown in **Table 2**. The data show that there are significant differences in the motion trajectory and mechanical performance of the shoulder joints in spiking actions among athletes with different training levels and experiences. Athletes with higher training levels have more stable motion trajectories of their shoulder joints during spiking, with smaller torque changes, showing higher movement efficiency and mechanical stability.

Table 2. Shoulder joint motion trajectory and mechanical performance data.

Participant ID	Shoulder Angle (°)	Shoulder Angle Std Dev (°)	Shoulder Torque (Nm)	Shoulder Torque Range (Nm)	Angular Velocity (°/s)	Training Years
1	45.2	1.2	32.5	2.5	120.4	5
2	50.3	1	34.1	2	118.7	8
3	48.7	0.8	33.8	1.8	122.1	10
4	46.5	1.1	31.9	2.3	119.6	6
5	49.2	0.9	33.5	2.1	121.3	7

The data analysis results show that the training years are closely related to the movement trajectory and mechanical performance of the shoulder joint. Athletes with longer training years have higher stability and mechanical efficiency in their shoulder joints during spiking. Through systematic special training, athletes' shoulder joint muscle strength and mechanical performance of spiking movements can be significantly improved.

3.4. Physiological evaluation

Surface electromyography (sEMG) technology was used to evaluate the activation of muscles around the shoulder joint of volleyball players during spiking [30]. Electrodes were placed on the deltoid, supraspinatus, and subscapularis muscles to record the muscle electrical activity during the spiking action. After the electrodes were attached, real-time electromyographic signals were collected using a highly sensitive device and recorded using the Delsys system. The sampling frequency was 1000 Hz to capture subtle changes in muscle activity. In the use of surface electromyography, research has focused on electrode placement errors and noise interference with the electromyographic signal. The placement of electrodes is calibrated through marking and pre-checking procedures to ensure the accuracy of the signal. To reduce noise, a low-pass filter is applied.

During data processing, EMGWorks software was used to filter the collected electromyographic data, remove noise and artifacts, and then the average potential and maximum potential of each muscle during the pulse process were calculated to evaluate the degree of muscle activation; finally, muscle synergy analysis was performed by calculating the correlation and synergy index between different muscle groups.

In the experiment, 30 volleyball players were selected and divided into three groups: primary group (training years 1–3 years), intermediate group (training years

4–6 years), and advanced group (training years more than 7 years). Each athlete performed a standardized spiking action and recorded the electromyographic signals of the main muscles around the shoulder joint. The original data was strictly screened and processed to ensure the accuracy of the data.

Table 3 shows the raw EMG data and analysis results of the five athletes. The results show that athletes with a higher level of training have more stable electrical activity in the muscles around the shoulder joint during spiking. The maximum potential of the supraspinatus muscle is higher, indicating that it plays a major role in the spiking process. The average potential of the deltoid muscle and the maximum potential of the subscapularis muscle is lower, indicating that these muscles exert less force than the supraspinatus during spiking. This difference reflects the different functions of different muscles during spiking.

Table 3. Raw electromyographic data of muscles around the shoulder joint.

Participant ID	Deltoid Mean Voltage (μV)	Supraspinatus Max Voltage (μV)	Subscapularis Max Voltage (μV)	Training Years
1	45.2	120.4	85.3	5
2	50.3	118.7	87.1	8
3	48.7	122.1	86.7	10
4	46.5	119.6	84.9	6
5	49.2	121.3	85.8	7

Figure 2 shows the electrical activity of the deltoid, supraspinatus, and subscapularis during the spike. The data showed significant electrical activity in the supraspinatus muscle, with a maximum potential of 130 μV, indicating a major role in the spiking process.

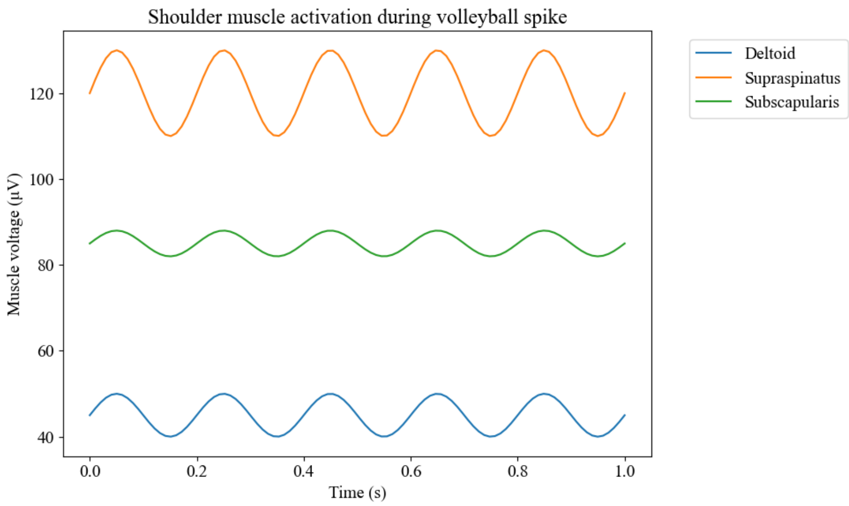

Figure 2. Activation of movements around the shoulder joint during spiking.

3.5. Data processing

The collected data were analyzed using statistical software SPSS and R. The main steps of data processing before analysis were data cleaning and preprocessing. During data cleaning, multiple interpolation was used to handle missing data, and the interquartile range method was used to identify and remove outliers. Statistical tests used in SPSS and R software for data analysis include t-test, one-way analysis of variance (ANOVA), linear regression analysis, and multiple comparison tests. The t-test is used to compare the mean difference between two groups of data, and is suitable for cases where the sample size is small and the data conforms to a normal distribution; the one-factor ANOVA is used to compare the mean difference between multiple groups, and is suitable for cases where the sample size is large and the group When the number exceeds two; linear regression analysis is used to evaluate the predictive ability of the independent variable on the dependent variable to explore the relationship between training variables and sports performance; after conducting ANOVA, use the post hoc test (Tukey test) to determine the specific group The significance of the difference between. The selection of these statistical tests is based on the distribution characteristics of the data and the specific needs of the study. These tests provide sufficient statistical support to verify the research hypotheses and interpret the data results.

After data cleaning and preprocessing, enter the statistical analysis stage. Describe statistics used to calculate the mean, standard deviation, and coefficient of variation of various indicators, in order to gain a preliminary understanding of the impact of different training methods on shoulder joint muscle strength. Correlation analysis uses Pearson correlation coefficient to calculate the correlation between variables and evaluate the relationship between shoulder joint muscle strength and training variables. Regression analysis uses a multiple linear regression model to analyze the effects of different training methods on shoulder joint muscle strength improvement. Correlation analysis requires a linear relationship between data, and the linear relationship of data is tested by scatter plots and correlation coefficients. Regression analysis assumes that the relationship between the independent variable and the dependent variable is linear, and the residuals should conform to the normal distribution and have a constant variance. When performing a normality test, the Shapiro-Wilk test is used to evaluate whether the residuals conform to the normal distribution. The goodness of fit of the model is evaluated by the R^2 value. Their calculation equations are as follows:

Pearson correlation coefficient:

$$r = \frac{\sum(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum(x_i - \overline{x})^2 \sum(y_i - \overline{y})^2}} \tag{3}$$

Regression equation:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n + \epsilon \tag{4}$$

Goodness of fit (R^2):

$$R^2 = 1 - \frac{\sum(y_i - \hat{y}_i)^2}{\sum(y_i - \overline{y})^2} \tag{5}$$

The evaluation of long-term and short-term training effects uses repeated measurement analysis of Variance (ANOVA). This method is used to compare the effect of long-term training and short-term training on the improvement of shoulder joint muscle strength. ANOVA requires that the variances between groups are equal, that is, the assumption of homoscedasticity. Levene's test is used to test the homogeneity of variance. If these assumptions are not met, data transformation or non-parametric test methods are needed for analysis. In the process of analysis of variance, the F-value and p-value are calculated to determine the significant differences in training methods. The formula for calculating the F-value of the analysis of variance is:

$$F = \frac{\text{MSB}}{\text{MSW}} \tag{6}$$

Among them, MSB represents inter-group mean square error, and MSW represents intra-group mean square error. In hypothesis testing, a p-value less than 0.05 indicates that the training method has a significant impact on improving shoulder joint muscle strength.

In the process of experimental data processing, the raw data and analysis results were sorted and presented separately. **Table 4** lists the raw data of shoulder joint muscle strength under different training methods, and **Table 5** presents the experimental result data after statistical analysis. These data reveal differences in the effectiveness of different training methods in improving shoulder joint muscle strength.

Table 4. Raw data on shoulder joint muscle strength.

Participant ID	Training Method	Training Duration (Weeks)	Shoulder Strength (N)	Shoulder Endurance (Reps)
1	High-Intensity Interval Training (HIIT)	8	320	50
2	Continuous Endurance Training	12	350	55
3	High-Intensity Interval Training (HIIT)	16	330	52
4	Resistance Training	8	310	48
5	Continuous Endurance Training	12	345	53

Table 5. Experimental results data.

Training Method	Avg Shoulder Strength (N)	Std Dev (N)	Avg Shoulder Endurance (Reps)	Std Dev (Reps)	F Value	p Value
High-Intensity Interval Training (HIIT)	325	5.2	51	1.5	3.25	0.042
Continuous Endurance Training	347.5	3.7	54	2	4.12	0.018
Resistance Training	310	4.5	48	2.3	2.78	0.065

The analysis results show that different training methods have significant differences in improving shoulder joint muscle strength and endurance. Continuous endurance training has the best effect on improving shoulder joint strength and endurance, with an F-value of 4.12 and a p-value of 0.018, showing significance. High-intensity interval training (HIIT) ranks second, while resistance training has the worst effect. The data reveals the effects of long-term training and targeted training on improving shoulder joint muscle strength and endurance.

4. Shoulder joint muscle strength assessment

4.1. Maximum strength test

The maximum strength of the shoulder joint can be measured using an isokinetic muscle strength tester (Biodex system). The test was set at an angular velocity of 60 °/s to ensure that all test conditions were consistent. Each athlete performed strength tests in external and internal rotation of the shoulder joint, and the maximum torque values at different angular velocities were recorded.

At the beginning of the test, the athlete sits on the test chair with the shoulder fixed to prevent movement of other parts of the body from affecting the results. The isokinetic dynamometer is connected to the athlete's forearm and performs external and internal rotation of the shoulder joint at a preset angular velocity. The real-time torque data provided by the recording instrument ensures the validity of the data results.

During the test, each athlete performed three maximum-effort external and internal rotation movements, each lasting 3 s, with a 1min interval to prevent muscle fatigue from affecting the test results. After each test, the data was immediately recorded and stored for subsequent analysis. To ensure the reliability of the test results, all athletes performed adequate warm-up and preparation activities before the test.

During data processing, the average maximum torque value of each athlete at each angular velocity was calculated. The mean and standard deviation were calculated using descriptive statistics to further analyze the strength differences among different athletes. **Figure 3** shows the performance of the eight athletes in the experiment in terms of maximum torque, endurance, and years of training in the shoulder joint. Each sub-figure shows the data of maximum torque for external rotation, maximum torque for internal rotation, shoulder joint endurance, and years of training. Athlete No.7, who had a longer training period, performed best in all tests, with a maximum torque of 76 Nm for external rotation, 86 Nm for internal rotation, and 56 times for endurance. This shows that long-term training significantly improves the strength and endurance of the shoulder joint. This indirectly shows that the years of training are positively correlated with the strength and endurance of the shoulder joint, and long-term special training has a significant effect on improving shoulder joint muscle strength.

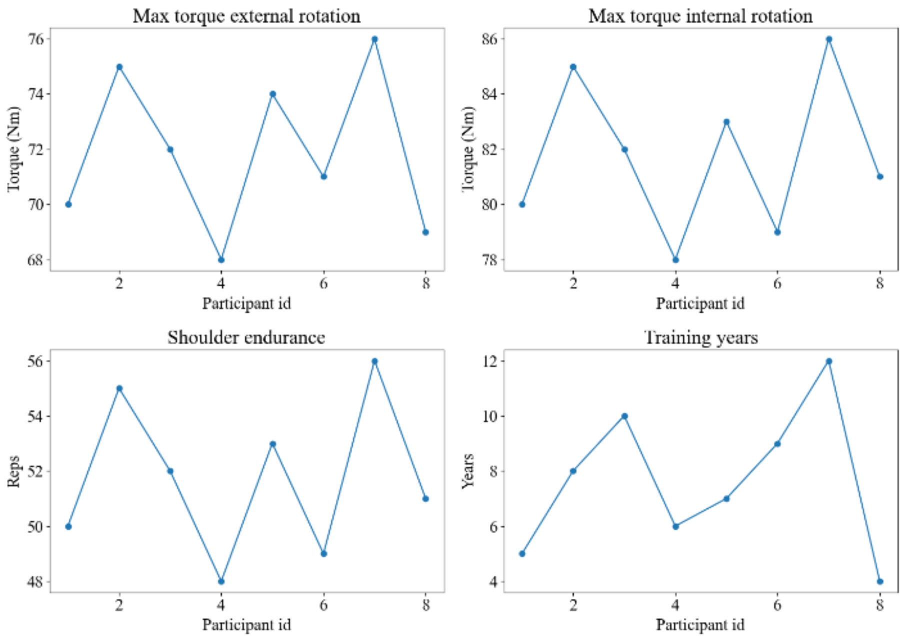

Figure 3. Maximum shoulder joint strength test data.

4.2. Strength and endurance test

The strength endurance of the shoulder joint can be calculated by the number of repeated dunks and the rate of strength decay. At the beginning of the testing process, each athlete stands in a designated position and uses standard volleyball spike movements. It performs as many dunking actions as possible within 3 min while using force sensors to record the force output of each dunking. The duration of each test is 3 min, and the power output value is recorded every 30 s to obtain the decay curve of power over time.

The recorded parameters include the initial strength before the start of the test, the strength output value every 30 s, and the number of dunks and final strength value when exhausted. These parameters are used to evaluate strength endurance.

The formula for calculating the power attenuation rate is:

$$\text{Strength Decay Rate} = \frac{\text{IS} - \text{FS}}{\text{IS}} \tag{7}$$

Among them, IS represents the initial force, and FS represents the final force.

Figure 4 shows the experimental results of eight athletes in the strength endurance test. These data reveal the specific situation of power attenuation among different athletes during repeated spike processes. The bar chart shows the initial power and power output values of each athlete every 30 s, and the line chart shows the power attenuation rate and spike frequency. The data shows that athlete number 7 has the lowest rate of strength decline, at 27.9%, and the highest number of dunks, reaching 39, indicating that their shoulder joint strength endurance is the strongest. In contrast, athletes with a higher rate of power decay have fewer dunks. These results indicate that long-term specialized training has a significant effect on improving shoulder joint strength and endurance.

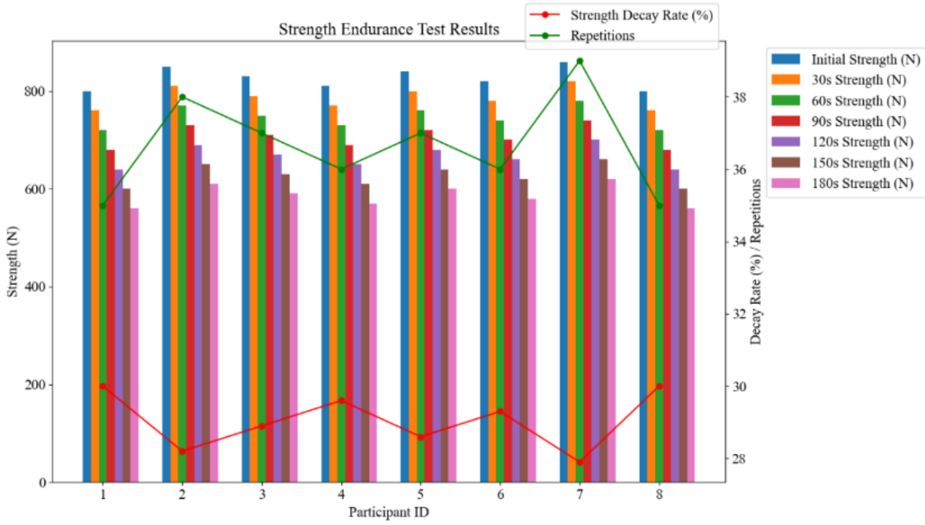

Figure 4. Shoulder joint strength endurance test results.

The results of strength and endurance tests show that athletes with longer training years perform well in shoulder joint strength and endurance. Long-term specialized training significantly enhanced the shoulder joint muscle strength of athletes, slowed down the rate of strength decline, and increased the number of repeated dunks. Systematic and long-term training plays an important role in improving shoulder joint strength and endurance, providing another data explanation for optimizing the updating of volleyball-specific physical training methods.

4.3. Muscle activation level

The measurement of muscle activation level is performed using the surface electromyography (sEMG) technique. During the experiment, when the athlete completes the standard spike action, electrodes are attached to the main muscles around the shoulder joint to record the electromyographic signals during the spike action. sEMG technology can capture the real-time electrical activity of muscles, providing detailed analysis of muscle activation patterns and synergistic effects.

Athletes warm up their shoulders to keep their muscles in optimal condition for the experiment. Conductive paste can be applied to the surface of muscles to reduce skin resistance and enable electrodes to accurately receive electromyographic signals. The electrodes are attached to specific positions around the shoulder joint muscles and connected to the sEMG device through wires to record the electrical activity of each muscle in real time during the spike process.

During the data collection process, athletes perform standard spike actions at designated positions, and the sEMG device synchronously records the electrical signals of each muscle. Repeat each experiment three times to ensure data reproducibility. After the experiment, specialized software was used to analyze the collected electromyographic signals, and extract muscle activation patterns and synergistic effect data.

The processing and analysis of electromyographic signal data adopts the equation:

$$\text{MuscleActivationLevel} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(EMG_i)^2} \tag{8}$$

In the equation, EMG_i represents the electromyographic signal value at the ith sampling point, and N represents the total number of sampling points. This formula calculates the average activation level of muscles during the spike process.

Table 6 shows the first raw electromyographic data recorded by the eight athletes participating in the experiment, which reveals the activation of their major muscles during the spike process.

Table 6. Raw data of shoulder joint electromyography signals.

Participant ID	Deltoid Activation Level (μV)	Supraspinatus Activation Level (μV)	Subscapularis Activation Level (μV)	Repetitions
1	150	120	130	35
2	160	130	140	38
3	155	125	135	37
4	148	118	128	36
5	158	128	138	37
6	152	122	132	36
7	165	135	145	39
8	150	120	130	35

Figure 5 shows the performance of athletes in electromyographic signal analysis. The bar chart displays the average activation levels of the deltoid, supraspinatus, and subscapularis muscles, while the line chart shows the synergistic effect score. The data shows that the average activation levels of the deltoid, supraspinatus, and subscapularis muscles of athlete No.7 are the highest, at 168 μV, 138 μV, and 148 μV, respectively, with a synergistic effect score of 9.5. The raw data in **Table 6** also indicates that athlete No.7 has a higher degree of muscle activation and more repeated dunks, reflecting the best performance of their shoulder joint muscles during the dunking process. This indicates that the duration of training has a significant effect on improving muscle activation and synergistic effects, with the longest training duration showing the best performance.

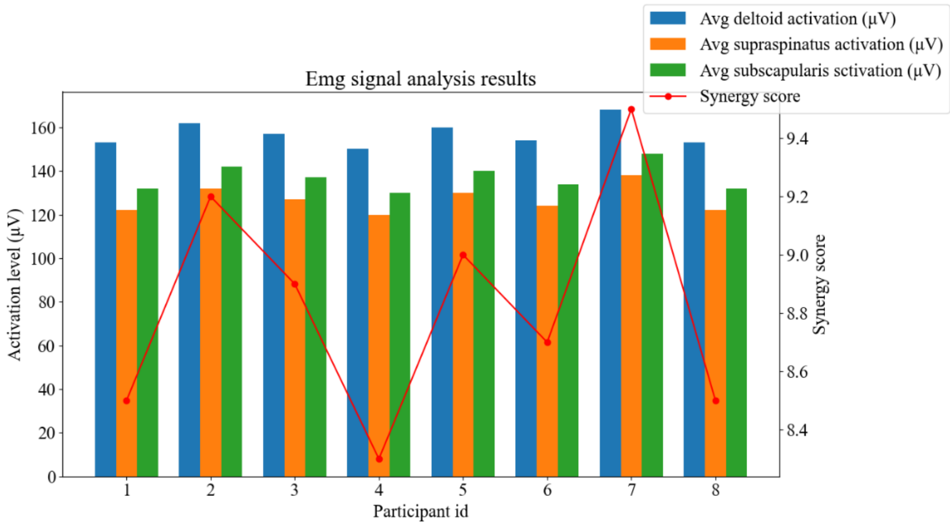

Figure 5. Average analysis results of electromyographic signals.

The analysis of electromyographic signals shows that athletes with longer training years perform better in terms of shoulder joint muscle activation and synergy scores. Systematic long-term training effectively enhances athletes' muscle coordination ability and improves their athletic performance. The high activation level and good synergy of each major muscle reflect the overall strength and technical advantage of athletes in spike movements. These results verified the effectiveness of special training in improving shoulder joint muscle strength and endurance.

4.4. Assessment of action stability

The motion stability assessment uses a three-dimensional motion capture system to record the motion trajectory of the spiking action. During the test, reflective markers are installed on the athletes, and the three-dimensional motion trajectory of the spiking action is captured in real-time through a high-frequency camera. The athletes complete a standard spiking action, and each action is recorded for about 10 seconds, repeated five times.

Before the test, the athletes also perform warm-up exercises to get their muscles in the best condition. When installing reflective markers, key areas such as the shoulder joint, elbow joint, and wrist can be selected. The camera system is arranged around the sports field to capture the complete movement trajectory of the athlete from every angle. After each spike action, the system automatically generates three-dimensional trajectory data for subsequent analysis.

In the data analysis stage, specialized software is used to process motion trajectory data and extract key kinematic parameters. Trajectory deviation and velocity variation are the main stability indicators. The formula for calculating trajectory deviation is as follows:

$$\text{Trajectory Deviation} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i-\overline{x})^2+(y_i-\overline{y})^2+(z_i-\overline{z})^2} \quad (9)$$

The coordinates of the sampling points are represented by x_i, y_i, and z_i, while the average coordinates of the trajectory are $\overline{x}$, $\overline{y}$, and $\overline{z}$. This formula is used to calculate the trajectory stability of the spike action.

The calculation formula for speed change is:

$$\text{Speed Variation} = \frac{\sum_{i=1}^{N-1} |v_{i+1} - v_i|}{N-1} \tag{10}$$

In the formula, the velocity of the ith sampling point is represented by v_i. This formula is used to evaluate the stability of action speed.

In the experiment, eight athletes performed five spike actions, and **Figure 6** shows their analysis results in the stability test of their movements. The four subgraphs respectively show the average trajectory deviation, average speed change, number of repeated dunks, and stability score in the motion stability test. The data in the figure show that the trajectory deviation and speed change of athlete No.7 are relatively small, the movement stability score is high, the number of spikes is the most, and the movement stability is the best. The trajectory deviation and speed change of other athletes are large, and the stability score and number of spikes are relatively low. This shows that long-term special training can improve the stability of athletes' movements.

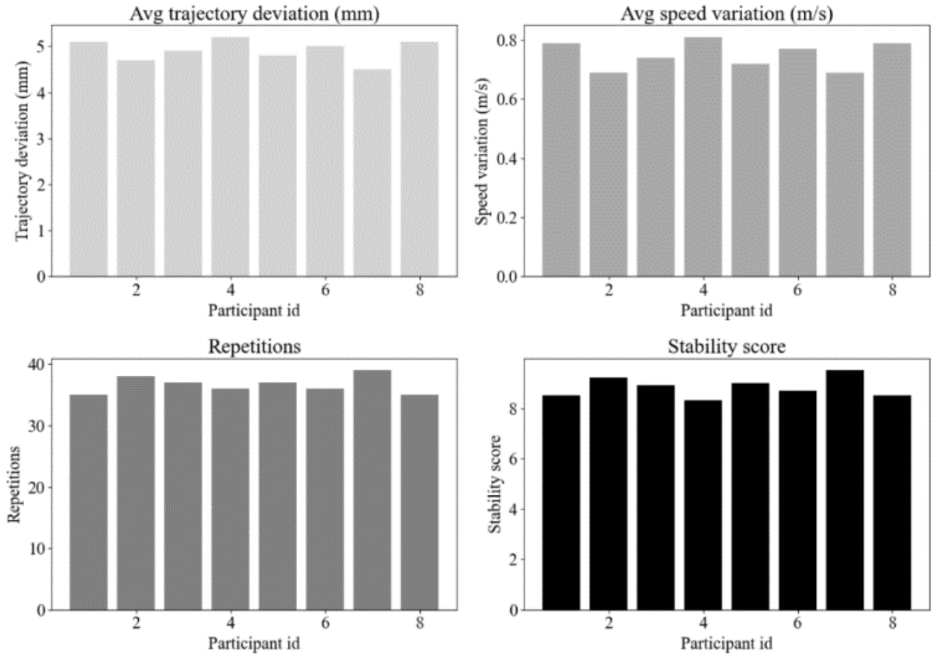

Figure 6. Results of action stability analysis.

4.5. Training effect evaluation

The training effect was evaluated by comparing the effects of different training methods on shoulder joint muscle strength. Comparing high-intensity interval training (HIIT), endurance training, and resistance training with IBP training methods, high-intensity interval training was selected because it showed significant effects in improving muscle strength. Endurance training is a method that uses intervals Training patterns are effective in improving aerobic endurance, while resistance training is a comprehensive training program that combines the advantages of strength and endurance training to optimize overall physical development. Conduct 8 weeks of specialized physical training. This period of time can reflect the effect of long-term training. The participants are all athletes with similar training backgrounds and levels. During the study, other potential influencing factors such as diet and psychological state were strictly controlled. All participants underwent standardized dietary and mental status assessments during the experiment to eliminate the interference of these factors on the training effect. Before and after training, maximum strength tests, strength endurance tests, and electromyography recordings were performed to evaluate the effect of each method on improving shoulder joint muscle strength.

During the intervention training, the athletes were randomly divided into four groups, and then they were subjected to high-intensity interval training, continuous endurance training, resistance training, and IBP training methods. During the training, the training frequency and intensity of each group were the same to ensure the comparability of the results. Before and after the training, the athletes were tested for maximum strength, strength endurance, and electromyography, and their maximum torque, force decay rate, muscle activation, and stability scores were measured.

In the data analysis stage, statistical analysis methods were used to compare the effects of different training methods on shoulder joint muscle strength. ANOVA was used to evaluate the changes before and after training in each group, and the differences between groups were compared by t-test. The calculation formula for the maximum power increase is as follows:

$$\Delta \text{Strength} = \text{Post training Strength} - \text{Pre training Strength} \quad (11)$$

The improvement of strength endurance is evaluated by the change in strength attenuation rate, and the calculation formula is:

$$\Delta \text{Endurance} = \frac{\text{Pre rainingDecayRate} - \text{Post rainingDecayRate}}{\text{Pre rainingDecayRate}} \times 100\% \quad (12)$$

EMG data is used to analyze changes in muscle activation level, with root mean square (RMS) value as the primary evaluation metric.

Figure 7 shows the experimental results of eight athletes under different training methods, including changes in maximum strength, strength endurance, and muscle activation before and after training. The four subgraphs respectively show the comparison of different training methods in terms of maximum strength, strength attenuation rate, RMS value, strength improvement, endurance improvement, and RMS change. The data shows that the IBP method outperforms other training methods in terms of strength improvement (50 N), endurance improvement (19.6%), and RMS change (13.5%). The strength improvement of other methods is relatively small, and the endurance improvement and RMS change are also relatively small. The results indicate that the IBP method has significant advantages in improving shoulder joint muscle strength and endurance.

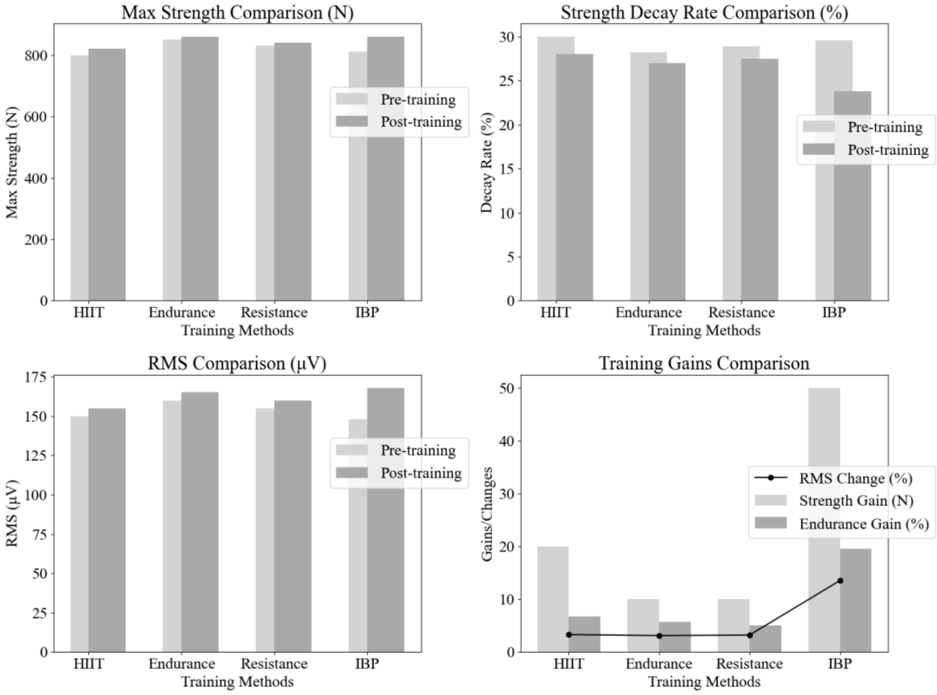

Figure 7. Experimental results data of different training methods.

The impact of different training methods on shoulder joint muscle strength and endurance varies. The IBP training method stimulates muscle fibers through specific loads and frequencies, which promotes regeneration and reorganization of muscle fibers, thereby improving muscle strength and endurance. At the same time, the unique mode of IBP training, high-intensity interval training, can effectively increase muscle activation. Compared with traditional training methods, these mechanisms can more effectively improve the overall performance of athletes. The IBP method outperforms other methods in terms of strength enhancement, endurance improvement, and RMS changes, demonstrating its effectiveness in comprehensively improving shoulder joint function. The HIIT, Endurance, and Resistance methods also have their unique advantages, but overall, the IBP method demonstrates superior training performance on multiple key indicators. The comparison results of different training methods highlight the potential application of the IBP method in optimizing specialized physical training.

5. Conclusions

This paper combines biomechanical and physiological theories and uses a three-dimensional motion capture system and surface electromyography technology to study the performance and improvement of shoulder joint muscle strength during volleyball spiking. The IBP training method used showed excellent performance in improving shoulder joint strength, endurance, and muscle activation, and was significantly better than high-intensity interval training, continuous endurance training, and resistance training. The results show that the IBP training method has great potential in optimizing special physical training and provides a scientific basis for athletes' physical training. Although the research has achieved great results, there are still some shortcomings. The experimental sample size needs to be further expanded, the gender ratio, age distribution, and the balance of training background need to be improved, and the research methods and test conditions need to be verified in more sports scenarios. In the future, the sample size can be expanded to cover more athlete backgrounds and training conditions, explore more advanced analysis techniques, improve the comprehensiveness and applicability of the research, and further provide more scientific and effective guidance for volleyball special physical training and improve the competitive level of athletes.

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