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Article

A biomechanical study of the jumping muscles of gymnasts for specific abilities

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Abstract: This biomechanical study investigates the muscle group-specific abilities of gymnasts during the jump take-off, focusing on the hip, knee, and ankle joints. Using 3D kinematic and kinetic analysis, the study explores the role of these joints in jump height, reaction time, and stability. Key findings show that centrifugal contraction of the hip extensor muscles enhances jump stability, while the knee joint's transition from centrifugal to centripetal contraction is critical for responding to ground reaction forces and generating vertical velocity. The ankle joint's power output during centripetal contraction is crucial for vertical acceleration. Moreover, the synchronization between these joints significantly influences the overall efficiency of the jump, highlighting the importance of joint coordination in maximizing performance. The ability of the knee to rapidly switch from a flexion to extension phase also plays a vital role in controlling the impact forces and optimizing take-off velocity. This research provides important insights into the biomechanics of gymnastics jumping and informs targeted plyometric training to optimize jump performance.

Keywords: gymnastics; jumping muscles; biomechanics; special training

1. Research purpose and significance

1.1. Research purpose

The jumping movement in gymnastics requires athletes to achieve vacating in a short period of time through powerful jumping and complete a series of difficult movements in the air, so the jumping technique is crucial to the performance of gymnasts [1]. This study aims to use biomechanical analysis theory to explore the mechanical characteristics of lower limb muscle groups during the jumping process of gymnasts. Specifically, by analysing the angle changes, moment characteristics and muscle contraction modes of the hip, knee and ankle joints during the jumping phase, the dynamics of different joints during the jumping action are revealed .The study aims to clarify the synergistic working mode of the lower limb joints during the jumping process, so as to provide a scientific basis for further optimising the special training of gymnastics, and to improve the athletes' explosive power and stability in the air.

1.2. Research significance

In order to scientifically optimise the special training of gymnasts and improve their jumping ability, this paper studies the mechanical characteristics of lower limb muscles of gymnasts in the process of jumping based on the theory of biomechanical analysis. By analysing the angle changes, moment characteristics and muscle contraction of the hip, knee and ankle joints during the jumping process, this study aims to clarify the kinetic roles of the joints in the jumping action, and to reveal the relationship between the joint strength and the jumping performance. The results of the study will help to provide scientific guidance for lower limb strength training of gymnasts, especially in terms of hip, knee and ankle joint coordination and muscle explosiveness, and to optimise the design and implementation of specialised training in order to improve the overall performance of athletes. In addition, this study provides a practical basis for the subsequent application of biomechanical analyses in gymnastics training

1.3. Review of domestic and international studies and entry point of this study

In recent years, there has been a significant increase in research in the field of sports biomechanics on gymnastics, jumping and other explosive sports, with particular attention paid to the kinetic and kinematic characteristics of the lower limb joints during the jumping process. Hay and Nohara [2] thoroughly analysed the biomechanical characteristics of sprinters during the jumping phase, and suggested that the rapid transition from the end of the run-up to the jumping phase is crucial for the enhancement of the height in the air, and pointed out that the moment output of the joints of the lower limbs and the change of joint angles are the key factors.

Subsequently, Lees et al. [3] conducted a fine-grained biomechanical study of the jumping manoeuvre of long jumpers and found that knee joint stiffness and its rapid centrifugal-centripetal contraction transition were critical for shortening the ground contact time and increasing the height of the lift-off. These studies revealed the profound effects of lower limb joint stiffness and moment output on athletic performance, establishing the importance of the knee and ankle joints in explosive movements. In domestic research, Wei [4] explored the kinetic characteristics of long jumpers during the jumping phase through systematic biomechanical analysis, and pointed out that the centrifugal contraction capacity of the hip and knee joints plays a key role in buffering the ground impact and stabilising the jumping action in the early stage of the jump.

Zhang [5] further conducted an isokinetic force measurement study on the strength ratios of the knee muscle groups of our sprinters and long jumpers, and concluded that the strength ratio of the knee flexors to the extensors needs to be more than 85% in explosive sports to improve the stability and explosive power of the lower limbs during the centrifugal-centripetal transition. The domestic study provided a theoretical basis for specialised strength training, emphasising strategies to improve hip and knee strength ratios and explosive power.

Although there are systematic studies on the biomechanical properties of jumping and vaulting movements at home and abroad, the vaulting movements of gymnasts are significantly different, especially in the process of vaulting, the ground contact time is very short, and the athletes need to complete the transition from run-up to vaulting and generate high vertical lift-off in a split second, so as to complete a series of difficult manoeuvres in the lift-off. Therefore, it is still necessary to explore how the hip, knee and ankle joints work together to generate the optimal moment to achieve a stable centrifugal- centripetal contraction transition in a very short period of time for gymnasts' jump [6]. In addition, the strength characteristics of jumping muscle groups and the role of lower limb joints in dynamic stabilisation also need to be studied.

2. Research objects and methods

2.1. Research objects

The subjects of this study are seven excellent male gymnasts (N = 7) selected from a national gymnastics team, who all have rich training experience and have performed well in domestic events. The average age, height and weight of all the athletes met the basic standards of national gymnasts, and their jumping movements were stable and technically mature to ensure the accuracy and representativeness of the experimental results. However, the relatively small sample size ($N = 7$) is a limitation of this study. This small sample may restrict the generalizability of the results to a broader population of gymnasts, as individual variations in biomechanics or skill levels might not be fully captured. Future research should aim to include a larger and more diverse sample to enhance the robustness and applicability of the findings. Furthermore, a power analysis should be conducted to determine whether the current sample size is adequate for detecting statistically significant effects. Incorporating such an analysis would provide stronger justification for the sample size and help ensure the reliability of the conclusions drawn. Before the experiment, all participants signed an informed consent form to clarify the experimental process and related requirements.

2.2. Experimental methods

The experiment adopts the multi-equipment synchronous testing method, recording the athlete's assisted jumping process synchronously with a high-speed video camera and a three-dimensional force measuring table to capture the kinematics and dynamics data at the moment of jumping [7].

Equipment arrangement and setting

(1) High-speed camera: using JVC9800 high-speed camera, shooting from the side of the side of the run-up and jump in a fixed position, the height of the camera is set to 1.10 m, the main optical axis is perpendicular to the plane of the human body's movement, and the shooting distance is 14.50 m. The sampling frequency of the camera was 100 frames/second, and the shutter speed was set to 1/250 s to ensure the clarity and smoothness of the picture.

(2) Three-dimensional force measuring table: Kistler9281B three-dimensional force measuring table is used, the surface of which is covered with a plastic mat of 2.0 cm thickness, which is consistent with the surface of the running track. The sampling frequency of the force measuring table is 500 Hz, which is used to record the ground reaction force (including horizontal and vertical force) data in real time when the athlete jumps. The force platform is synchronised with the camera and is connected via a light emitting diode trigger to synchronise data acquisition [8]. To address the different sampling rates of the high-speed camera (100 Hz) and the force platform (500

Hz), a temporal alignment process was employed. A common synchronization trigger was used to mark the starting point in both datasets. Force platform data were subsequently down sampled to match the 100 Hz rate of the camera using a low-pass filter to preserve signal integrity, ensuring precise temporal alignment for accurate biomechanical analysis.

The JVC9800 high-speed camera and Kistler9281B three-dimensional force measuring platform were selected for their high-frequency sampling capabilities and precise motion capture performance, enabling accurate recording of rapid jumping movements and ground reaction forces. This ensured the reliability of the collected data.

The experimental procedure was as follows:

Before the experiment, each athlete underwent a comprehensive warm-up routine, which included dynamic stretches and gymnastics-specific drills to ensure they were in optimal condition for jumping and to reduce the risk of injury. The warm-up consisted of 5 min of jogging, knee and ankle mobility exercises, and a series of bounce drills to activate muscles and enhance joint flexibility. The athletes were required to complete the jumping manoeuvre at the specified running distance and speed. In order to ensure the accuracy of the data, each athlete had to make several attempts to ensure that the soles of the feet were completely on the force platform to be considered as valid data, and each athlete recorded one successful jump as a sample for analysis. Athletes were warmed up sufficiently before the experiment to ensure that they could achieve the best jumping condition during the test jumps. To prevent fatigue and ensure consistent performance, athletes were given a standard rest period of 2–3 min between each jump attempt. During this period, athletes were encouraged to hydrate and perform light dynamic stretches if needed. Fatigue effects were monitored by tracking jump performance metrics (e.g., height, ground contact time) across attempts and visually assessing any signs of reduced effort or technique degradation. No significant fatigue-related variations were observed during the experimental trials.

2.3. Data analysis in the data processing stage

The collected data were finely analysed in this study by professional kinematics and dynamics software to ensure the scientificity and reliability of the results. The specific data processing process is as follows:

2.3.1. Kinematic data processing

The motion images captured by the high-speed camera were analysed using Simi Motion human motion analysis software. Simi Motion human motion analysis software was chosen for its exceptional accuracy in parsing and handling large volumes of dynamic data. Compared to other software, Simi Motion allows faster and more precise analysis of multi-point trajectories while providing effective noise reduction and time normalization for consistent results.

Firstly, the video captured by the camera was imported through the software, and the coordinates of the athletes' joint points, including hip, knee and ankle positions, were calibrated based on Dempster's [9] human model parameters. To ensure accuracy, all joint coordinates were triple-spline smoothed during parsing to eliminate high-frequency noise in the image data. To minimize the influence of environmental factors on the data, room temperature and lighting were controlled during the experiment. All equipment was calibrated before each test to ensure consistency and scientific rigor. The output of kinematic data processing includes the angle, velocity and acceleration changes of the hip, knee and ankle joints throughout the jumping process, which lays the foundation for analysing the motion characteristics of each joint.

2.3.2. Dynamics data processing

The three-dimensional ground reaction force (GRF) data recorded by the force measuring platform was imported into the data processing software through A/D conversion. The support reaction force data were accurately recorded at an acquisition frequency of 500 Hz to ensure that the ground reaction force characteristics at the jumping moment were captured. Through inverse dynamics calculation, the muscle moments of the hip, knee and ankle joints were further calculated by taking the support reaction force as a known quantity and combining it with the joint movement trajectories. This moment data reveals the characteristics of different joint muscle groups in resisting ground impact and generating explosive force during the jump.

2.3.3. Calculation of joint moments

The calculation of joint moments is based on the simplification of the athlete's lower limb into three rigid link models: thigh, calf and foot. Assuming that the joints are smooth hinge connections, the moment equations of the hip, knee and ankle joints are derived through the inverse dynamics method. In the calculations, the muscle moment characteristics generated by the centrifugal-centripetal contraction transition of each joint are taken into account to analyse the moment changes of each joint muscle group under different contraction modes. The resulting joint moment data were used to further investigate the muscle force characteristics of the hip, knee and ankle during the centrifugal (landing cushion) and centripetal (jumping push-off) phases.

2.3.4. Data standardisation

To eliminate the effect of individual differences on the results, all data were standardised. The time data were standardised to 100% of the whole jumping process, with a standardised time resolution of 1%, to ensure that the details of the jump were captured in detail; the ground reaction force and joint moment were standardised to body weight (N/kg) and body weight × distance (N-m/kg), respectively, to facilitate the comparison of the data between different athletes, and to ensure that the results were generalisable.

2.3.5. Statistical analysis and image generation

All standardised data were statistically analysed in SPSS 23.0 software to calculate the mean and standard deviation in order to analyse the significant differences in the characteristics of each joint. In addition, Excel was used to generate the curves of joint angle, velocity, moment and other variables over time, which provided visual support for the biomechanical characteristics of the lower limb joints during the jumping process. These curve diagrams make the dynamic performance of each joint in the centrifugal and centripetal phases more intuitive, help to clarify the functional division of each key joint, and provide a scientific basis for the optimisation of gymnastics-specific training.

3. Results and recommendations

3.1. Data analysis of hip, knee and ankle joint angle changes

The hip, knee and ankle joint angle changes of the athletes during the jumping process were recorded by a high-speed camera and reflective marking points, and the experimental process is shown in **Figure 1**. Hip, knee and ankle joint angle change data are shown in **Table 1**; the angle change curve is shown in **Figure 2**.

Figure 1. Measurement of joint angle changes-human figure schema.

Table 1. Data on hip, knee and ankle joint angle changes.

Phase	Hip angle (°)	Knee angle (°)	Ankle angle (°)
Time of contact	20.5 ± 1.2	135.8 ± 5.6	78.2 ± 3.3
Peak cushioning	45.3 ± 2.1	144.1 ± 6.4	83.5 ± 3.1
Moment of maximum extension	85.7 ± 2.3	180.0 ± 0	110.2 ± 2.8
Moment of ground release	75.5 ± 1.9	170.3 ± 3.1	90.1 ± 2.5

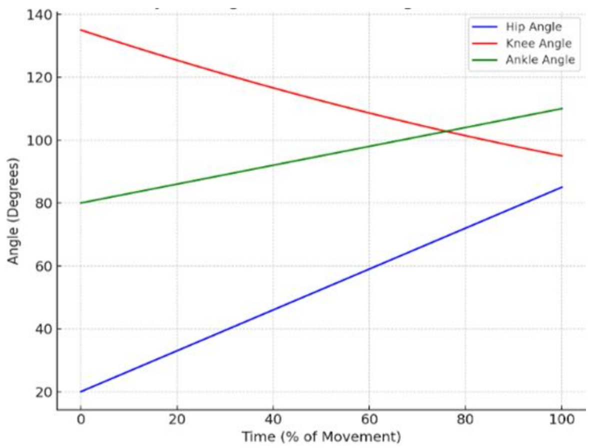

Figure 2. Hip, knee, and ankle joint angle change curves.

The analyses showed that:

Hip joint: the hip joint angle continued to increase during the jump, which was mainly characterised by centrifugal contraction of the hip extensor muscle groups to resist the ground reaction force and help to complete the vacating [10]. In addition to extension moments, the hip joint plays a critical role in maintaining lateral stability through abduction and adduction movements. During the takeoff phase, controlled hip abduction helps to stabilize the pelvis and counteract any lateral forces that could disrupt balance. These actions are particularly important for achieving an optimal takeoff trajectory and minimizing asymmetrical loading on the lower limbs. Future studies could incorporate three-dimensional motion capture to further quantify the role of hip abduction/adduction in jump stability.

Knee joint: the knee flexion angle was larger during the cushioning period, and it was quickly converted to extension, reaching the maximum flexion value of 144.1° to increase the height of vacating, which indicated that the active contraction of the knee joint at the moment of contact played an effective cushioning role under the impact of the ground reaction force [11]. The reported standard deviation of 0° for the knee angle at maximum extension (180.0 ± 0°) is notably small. This value has been verified against the original dataset and reflects the high technical precision and uniformity among the gymnasts in this phase of the jump. All participants demonstrated an identical knee extension angle, as captured by high-speed cameras and motion analysis software. This consistency is likely due to the athletes' advanced training level and the biomechanical requirement of achieving full extension during the jumping phase. If measurement or rounding errors are suspected, further calibration and re-analysis of the data may be conducted in future studies.

Ankle joint: The ankle joint undergoes the process from dorsiflexion to dorsal extension, which demonstrates the strong pushing ability of the muscles of the posterior group of the calf.

3.2. Analysis of joint moment changes under rigid link model

An inverse dynamics method was used to analyse the role of different joints in the jumping process in terms of the changes in hip, knee and ankle joint moments.

The formula for calculating the ankle joint moment Ma is as follows: $M_a = I_{c3} \cdot \ddot{\theta}_3 - F_{ay} \cdot L_{c3} \cdot \sin\theta_3 + F_{ax} \cdot L_{c3} \cdot \cos\theta_3 - GRF_x \cdot (L_3 - L_{c3}) \cdot \cos\theta_3 + GRF_y \cdot (L_3 - L_{c3}) \cdot \sin\theta_3$.

The knee moment Mk is calculated as follows: $M_k = I_{c2} \cdot \ddot{\theta}_2 + M_a - F_{ky} \cdot L_{c2} \cdot \sin\theta_2 - F_{ax} \cdot (L_2 - L_{c2}) \cdot \sin\theta_2 + F_{kx} \cdot L_{c2} \cdot \cos\theta_2 + F_{ax} \cdot (L_2 - L_{c2}) \cdot \cos\theta_2$.

The hip joint moment Mh is calculated as follows: $M_h = I_{c1} \cdot \ddot{\theta}_1 + M_k - F_{hy} \cdot L_{c1} \cdot \sin\theta_1 - F_{ky} \cdot (L_1 - L_{c1}) \cdot \sin\theta_1 + F_{hx} \cdot L_{c1} \cdot \cos\theta_1 + F_{kx} \cdot (L_1 - L_{c1}) \cdot \cos\theta_1$.

To clarify the joint moment calculation formulas, the following nomenclature defines all variables and their respective units:

M_a, M_k, M_h: Joint moments for ankle, knee, and hip, respectively (N·m/kg).

I_{c1}, I_{c2}, I_{c3}: Moments of inertia for the hip, knee, and ankle segments, respectively (kg·m^2).

$\ddot{\theta}_1$, $\ddot{\theta}_2$, $\ddot{\theta}_3$: Angular accelerations of the hip, knee, and ankle joints, respectively (rad/s^2).

F_{hx}, F_{hy}, F_{kx}, F_{ky}, F_{ax}, F_{ay}: Components of force (horizontal and vertical) acting at the hip, knee, and ankle joints, respectively (N).

L_1, L_2, L_3: Lengths of the hip, knee, and ankle segments, respectively (m).

L_{c1}, L_{c2}, L_{c3}: Distances from the joint centers to the segment centers of mass for the hip, knee, and ankle, respectively (m).

GRF_x, GRF_y: Ground reaction force components in horizontal and vertical directions, respectively (N).

The calculated data are shown in **Table 2**, and the moment variation graph drawn by analysing and plotting the data is shown in **Figure 3**:

Table 2. Hip, knee and ankle moment change curves.

Phase	Hip moment (N·m/kg)	Knee moment (N·m/kg)	Ankle moment (N·m/kg)
Instant of contact	2.35 ± 0.15	4.12 ± 0.27	1.89 ± 0.14
Peak cushioning	3.87 ± 0.21	7.75 ± 0.45	3.02 ± 0.19
Instant of maximum extension	1.95 ± 0.13	6.42 ± 0.31	2.88 ± 0.16
Off-ground moment	1.21 ± 0.10	5.11 ± 0.26	2.35 ± 0.15

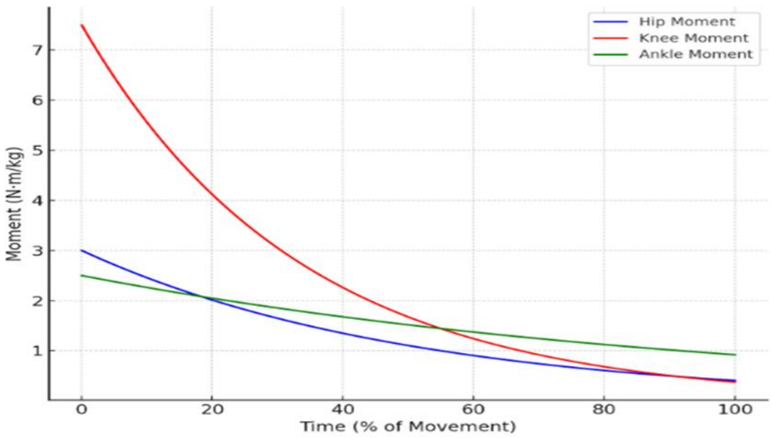

Figure 3. The moment variation graph.

The analyses showed that:

The hip joint produces a large extensor moment at the beginning of the jump and this strong centrifugal contraction helps to support the jumping action. The knee joint produces a significant flexor moment after landing, followed by a rapid shift to centripetal contraction to support the athlete's lift-off. The ankle joint primarily reflects extensor moments, revealing the important push-off role of the ankle joint in the jumping manoeuvre. The knee joint moment peaked at 7.75 N-m/kg during the cushioning phase, indicating that the knee joint played a key role in force transmission and cushioning in support and stirrup extension, whereas the ankle joint moment gradually increased during the push-off phase of the jump, which was important for the realisation of the vacated height.

3.3. Analysis of muscle contraction data

The contraction patterns of the target muscles (quadriceps and hamstrings) were recorded by electromyography (EMG) as shown in **Figure 4** below. During the transition phase between centrifugal and centripetal contraction, the peaks of the electrical activity signals of the muscles reflected the contraction strength of the muscles at different stages, and the breakdown of the data is shown in **Table 3** below.

Table 3. Breakdown of muscle contraction data.

Joint of joint	Joint Initial centrifugal contraction(ms)	Centripetal contraction transition time(ms)	Peak centripetal contraction (mV)
Hip extensor group	15 ± 2	60 ± 5	0.82 ± 0.05
Knee extensor group	18 ± 3	52 ± 4	1.25 ± 0.08
Ankle extensor group	20 ± 2	47 ± 3	1.02 ± 0.06

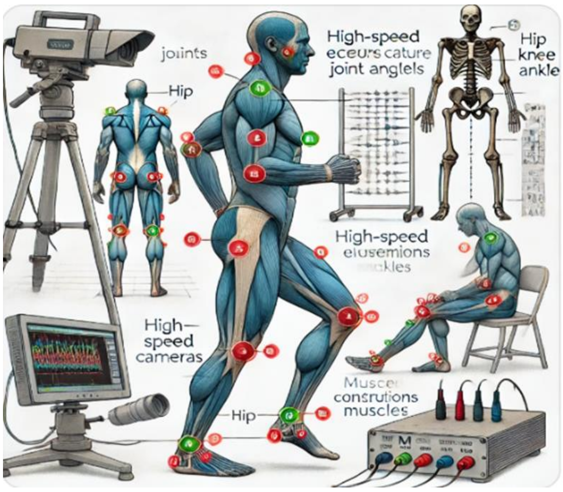

Figure 4. Schematic diagram of the muscle contraction test process.

Throughout a gymnast's jump, the hip, knee, and ankle joints exhibit unique moment and angle change characteristics, respectively. In order to understand the function of each joint in depth, the following is a step-by-step explanation of the functional roles of each joint from the four phases of contact, cushioning, extension, and leaving the ground:

1) Contact phase Hip: The hip joint angle is relatively small at the moment of contact (about 20.5°), when an initial centrifugal contraction is generated to slow down the impact. The hip joint moment is approximately 2.35 N-m/kg and provides stability for the initial movement to support the body and control the centre of gravity.

Knee: The knee joint is at a greater angle at this point (approximately 135.8°), demonstrating some flexion in favour of initial cushioning. The knee joint has a moment of 4.12 N-m/kg, which begins to respond to the ground reaction force and acts as an impact absorber.

Ankle: Ankle angle of 78.2° produces a slight dorsiflexion moment (1.89 N-m/kg) that sets the stage for subsequent bracing and pushing off the ground.

2) Cushioning phase

Hip joint: the hip joint enters the strengthening phase of centrifugal contraction, the angle increases to 45.3°, the centrifugal moment increases to 3.87 N-m/kg, the main function is to cushion the ground reaction force and maintain the stability of the lower limb.

Knee: the knee angle further flexes to 144.1°, with a peak moment of 7.75 N-m/kg. This centrifugal contraction with maximum moment effectively resists the ground impact force and prepares for the upcoming centripetal contraction [12].

Ankle: The ankle gradually transitions from dorsiflexion to dorsal extension at an angle of 83.5° with a moment of 3.02 N-m/kg, which helps to create a supportive thrust.

3) Extension phase

Hip joint: the hip joint angle continues to increase to 85.7°, centrifugal contraction turns to centripetal contraction, and the moment decreases to 1.95 N-m/kg, providing upward power support.

Knee joint: the knee joint quickly returns from maximum flexion to extension, generating a centripetal moment of 6.42 N-m/kg, pushing the centre of gravity upwards in preparation for vacating.

Ankle Joint: The ankle joint is fully dorsiflexed at an angle of 110.2°, and the extensor muscles generate a moment of 2.88 N-m/kg, providing a strong push-off action off the ground [13].

4) Ground release phase

Hip: Hip angle is slightly reduced to 75.5°, moment is reduced to 1.21 N-m/kg, centripetal contraction is completed, transferring kinetic energy to the upper body [14].

Knee joint: the knee joint is slightly flexed to 170.3°, the moment is reduced to 5.11 N-m/kg, providing the final vertical thrust for the ground release process.

Ankle joint: the ankle thrust is maximised with a ground clearance angle of approximately 90.1° and the moment is maintained at 2.35 N-m/kg to provide the final acceleration for the lift-off phase.

4. Research results and recommendations

4.1. Research results

This study showed that the centrifugal and centripetal contraction capacity of the lower limb joints of gymnasts directly affects the height and stability of the vacated air during the jump. The centrifugal contraction of the hip joint provides the necessary impact resistance in the support phase to ensure the homeostasis and cushioning effect of the lower limb; the knee joint plays a central role in the centrifugal-centripetal transition phase, rapidly converting the support to the stirrup-extension force; and the ankle joint ensures the adequate output of the vertical acceleration through the powerful push-off moment.

These joint characteristics determine the gymnast's ability to achieve an efficient lift-off in a very short period of time. Similarly to the studies in the long jump, the performance of the gymnast's knee flexor moments against ground impact is particularly important, and this characteristic plays a central role in strengthening jump support and ground clearance speed. Gymnastics-specific strength training should be enhanced in the future to improve athletes' jumping efficiency and performance [15].

4.2. Research recommendations

Based on the above biomechanical analyses, this study provides the following scientific recommendations for the special training of gymnasts in jumping.

4.2.1. Strengthen the centrifugal contraction training of hip extensors

Improving the eccentric contraction ability of the hip extensors at the moment of landing is crucial for resisting ground reaction forces and maintaining lower limb stability. To achieve this, incorporate exercises like weighted squats combined with jump training, such as performing deep squats followed immediately by vertical jumps. This should be performed 2–3 times per week, with 3–4 sets of 8–10 repetitions per session, to enhance impact resistance and overall stability of the lower limbs. For improving the eccentric contraction ability of the hip extensors, athletes should perform weighted squats at 70%–85% of their one-repetition maximum (1RM), followed immediately by plyometric exercises such as vertical jumps. Each session should include 3–4 sets of 8–10 repetitions, performed 2–3 times per week, with at least 48 h of recovery between sessions. Progression can be achieved by gradually increasing the resistance by 5%–10% every two weeks, ensuring proper form and minimizing injury risk. This protocol aligns with findings from Brown and Wong [16], which emphasize the importance of high-intensity eccentric loading for improving joint stability and impact absorption during athletic movements.

4.2.2. Strengthening the knee flexors and extensors for dynamic contraction transition

The knee joint is vital for transitioning from eccentric to concentric contractions, particularly during the cushioning phase upon ground contact. To improve this rapid conversion ability, include exercises such as depth jumps and squat jumps combined with assisted running drills. Performing 6–8 repetitions per set, for 4–5 sets each session, will significantly enhance the knee joint's force transition and lift-off height. To enhance the knee joint's ability to transition from eccentric to concentric contraction, depth jumps from a height of 30–50 cm are recommended. Start with 3 sets of 6–8 repetitions per session, increasing the jump height by 10% every 2–3 weeks as athletes adapt. Additionally, assisted running drills with resisted bands (light resistance, 10%–15% of body weight) can be incorporated to develop rapid force production. According to Lees et al. [17], combining plyometric and resistance exercises significantly enhances the knee joint's force output and transition speed, which is critical for explosive jumping.

4.2.3. Elevating the push-off moment output of the ankle extensors

The ankle joint plays a pivotal role in generating push-off force as it transitions from dorsiflexion to plantar extension. To increase push-off power, incorporate exercises like weighted calf raises and single-leg weighted tiptoe jumps. Training 2–3 times a week will strengthen the ankle extensors' concentric contraction, ensuring sufficient vertical acceleration during the jump. Ankle extensors' strength can be developed through progressive resistance training, such as weighted calf raises (2–3 sets of 12–15 repetitions at 60%–75% 1RM) and single-leg tiptoe jumps (3 sets of 10–12 repetitions). Progression should involve increasing weights by 5%–10% every two weeks or reducing rest intervals from 60 to 45 s between sets. These exercises should be performed twice a week to allow for recovery and adaptation. Studies such as Liu and Wang [18] highlight the critical role of ankle push-off power in achieving greater vertical acceleration during take-off.

4.2.4. Optimise the synergistic training of the hip, knee and ankle joints

Jumping performance depends on the coordinated work of the hip, knee, and ankle joints. To improve lower limb explosiveness and synchronization, implement joint training exercises like fast deep squats combined with ankle pushes or assisted standing long jumps. These drills promote efficient coordination among the joints, enhancing overall jump efficiency and effectiveness. For joint coordination, circuit training combining fast deep squats (3 sets of 6 repetitions at 85% 1RM), dynamic lunges, and ankle pushes is recommended. Each circuit can be repeated 3 times, with rest periods of 2–3 min between circuits. Weekly training frequency should be 2–3 times, with progression involving either increased resistance or reduced rest intervals. According to Martin and Davies [19], joint coordination exercises significantly improve explosive power and efficiency in athletic movements by enhancing neuromuscular synchronization.

To tailor these recommendations for different competitive levels and age groups, adjustments in training intensity, volume, and progression are necessary. For younger athletes or beginners, exercises such as bodyweight squats, low-height depth jumps (15–20 cm), and unweighted calf raises are recommended to build foundational strength and technique. Intermediate athletes can incorporate moderate resistance (50%–70% 1RM) and increased plyometric volumes (e.g., 3 sets of 8–10 repetitions). Elite athletes should focus on high-intensity loading (70%–90% 1RM) and advanced plyometric exercises, such as single-leg depth jumps, with progression tailored to their competition schedule. These age- and level-specific guidelines ensure safe and effective skill development while reducing injury risk.

5. Conclusion

By analyzing the synergistic mechanisms and moment characteristics of the hip, knee, and ankle joints, this study not only provides a scientific foundation for targeted strength training in gymnasts but also offers practical guidance for enhancing gymnastics techniques and overall sports performance. Future training should focus on improving the rapid contraction and dynamic transition abilities of each joint muscle group. Consistent optimization of lower limb strength training will significantly enhance athletic performance. Long-term enhancement of both eccentric and concentric contractions of the hip joint will aid athletes in stabilizing their center of gravity in complex conditions and minimizing the risk of injury. Strengthening the dynamic transition capability of the knee joint is crucial for boosting vertical explosive power and overall stability [20]. Additionally, augmenting the push-off moment of the ankle joint will improve both the height and control of the athlete during the jump. These findings indicate that the hip joint’s strong eccentric contraction at the jump’s initial phase provides essential impact resistance and stability [21]. The knee joint’s rapid transition from eccentric to concentric contraction during the cushioning phase is pivotal for lift-off height, underscoring the need for knee power and responsiveness in explosive movements. Moreover, the ankle joint’s robust push-off moment generates continued acceleration, enabling athletes to achieve sufficient vertical velocity in a short timeframe. This analysis clarifies the functional roles of each joint during jumping and offers theoretical support for coaches to optimize training techniques, ultimately enhancing gymnasts' performance. Targeted, specialized training will holistically improve gymnasts' physical capabilities, athletic performance, and resistance to impact [22], laying a strong foundation for sustainable career development. This study also delivers new data and strategic directions for gymnastics-specific training and sports biomechanics research, which could be crucial for gymnasts aiming to achieve higher performance levels.

Author contributions: Conceptualization, SL and YB; methodology, ZB; software, SL; validation, SL, SL and ZB; formal analysis, SL; investigation, YB; resources, ZB; data curation, SL; writing—original draft preparation, SL; writing—review and editing, KF; visualization, QL; supervision, ZB; project administration, SL; funding acquisition, ZB. All authors have read and agreed to the published version of the manuscript.

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