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Article

Joint mechanical characteristics of vertical jumping in elite sprinters

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Abstract: This study aims to investigate the key lower limb joint biomechanical factors affecting the performance of vertical jumping in high-level sprinters, focusing on analysing the torque, power output and stiffness of the hip, knee and ankle joints during the vertical jumping process. The relationship between the joint biomechanical parameters and the key indexes of vertical jump performance, including ground contact time, free height and reaction power index, was systematically analysed through the simultaneous acquisition of 3D kinematic and kinetic data of the sprinters. The results showed that different lower limb joints play key roles in different phases of the long jump. During the centrifugal phase (landing), knee stiffness had a significant effect on ground contact time, with athletes with greater stiffness demonstrating shorter contact times, thus contributing to a quicker entry into the centripetal phase (jumping). In contrast, during the centripetal phase, ankle power output was highly correlated with free height and explosive performance, showing the decisive role of the ankle joint in vertical mobility at the start of the jump. The hip joint also plays a role in coordinating upper and lower limb movements and enhancing power transfer throughout the exercise process, but its influence is more indirect. This study provides biomechanical empirical evidence for the training of sprinters, especially by enhancing knee joint stiffness and ankle joint power output, athletes can effectively improve the performance of vertical jump manoeuvres. These findings provide a scientific basis for coaches and athletes to optimise their training programmes and improve their performance in competitions, and provide a reference direction for future related research.

Keywords: sprinters; vertical jump manoeuvre; biomechanics; lower limb joints; joint stiffness

1. Purpose and significance of the study

1.1. Purpose of the study

Sprinting is not only a highly competitive sport but also a discipline that showcases the pinnacle of human speed and lower limb explosiveness. The study of lower limb biomechanics in sprinters holds substantial social and academic value. From a societal perspective, understanding and optimizing athletic performance can contribute to national sports development and inspire public interest in athletics, promoting physical fitness and healthy lifestyles [1]. Moreover, advancements in this field have practical applications for injury prevention and rehabilitation, benefiting athletes at all levels. Academically, this research contributes to a deeper understanding of the stretch-shortening cycle (SSC) and its role in enhancing explosive power, a core component of many athletic movements. Existing studies have often focused on isolated joint functions or have analyzed general athletic populations, leaving a gap in comprehensive research specifically targeting high-level sprinters. By systematically investigating the torque, power output, and stiffness of the hip, knee, and ankle joints during vertical jumps, this study not only fills this research gap but also provides empirical evidence that can be directly applied to training regimens. The findings have the potential to revolutionize the way coaches design training programs, emphasizing joint-specific strength and stiffness training to maximize performance while minimizing injury risk.

1.2. Significance of the study

The significance of this study is to systematically analyse the vertical jump movements of high-level sprinters from a biomechanical point of view, and to reveal the key role of the lower limb joints in sports performance. By thoroughly exploring the effects of joint stiffness, torque and power on ground contact time, vacated height and reaction force index, it provides scientific basis for understanding the function of lower limb joints in explosive sports. These findings not only provide empirical support for sprinters to optimise their training regimen and enhance their performance, but also provide a basis for coaches to develop individualised training plans. In addition, the findings are also useful for improving athletes' performance in other explosive sports. By optimising the biomechanical properties of the lower limb joints, athletes can more effectively improve their explosive power and speed, thus gaining an advantage in competition. Meanwhile, this study not only provides a data base for subsequent scientific research in related fields, but also promotes the application and development of sports biomechanics in competitive sports.

1.3. Problems of related research at home and abroad and the entry point of this study

In recent years, biomechanical analyses of sprinters have been gradually increased at home and abroad, especially about the role of lower limb joints in explosive movements has become the focus of research. However, the existing studies are still deficient in the following aspects:

1) The research has a single focus. For example, Lee [2] mainly analysed the role of the ankle joint in the vertical jump movement in his study, pointing out that there was a significant correlation between the power output of the ankle joint and the vertical jump height, but failed to comprehensively consider the synergistic effect of the hip and knee joints. Whereas Smith [3] emphasised the importance of knee stiffness in ground contact time, however his research on other joints was weaker. While these studies provide valuable insights, they lack a systematic analysis of the interactions between joints.
2) Experimental data acquisition is not comprehensive enough. For example, Wang conducted a study using a single kinematic approach [4], extrapolating motor performance from surface data only, which was disconnected from the actual kinetic characteristics. The lack of simultaneous acquisition and analysis of 3D kinematic and kinetic data limits the accurate assessment of

biomechanical properties such as joint stiffness and power output, which in turn affects the in-depth understanding of movement performance.

3) Limitations of the research object. Most studies have focused on general athletes or non-professional athlete groups, e.g., Liu's study [5] on college athletes did not take into account the significant differences in physiological characteristics and training levels of high-level sprinters. Therefore, the findings may lack relevance and accuracy when applied to high-level athletes.

Based on the above issues, the entry point of this study is:

Through the simultaneous acquisition of 3D kinematic and kinetic data from high-level sprinters, the biomechanical properties of the three major joints of the hip, knee and ankle were systematically analysed at different stages of the longitudinal jumping process, including the stiffness, torque and power output of the joints. The study not only focuses on the role of single joints, but also focuses on the synergistic working mechanism among the joints and its influence on the athletic performance (e.g., ground contact time, free height and reaction power index). By comprehensively analysing these factors, this study aims to fill the gaps in existing research and provide a more comprehensive and precise biomechanical basis for training optimisation in sprinters.

2. Subjects and methodology

2.1. Subjects

The study involved 16 high-level male sprinters (mean age: 20.31 years ± 2.02 years, height: 1.83 m ± 0.05 m, weight: 70.63 kg ± 7.52 kg), all holding national-level athlete ratings and specializing in the 100 m, 200 m, or 400 m events. Each athlete had a professional training background spanning at least five years, with an average weekly training volume of 10–12 h that included sprint drills, strength training, plyometric exercises, and technical sessions to enhance explosive power and sprinting mechanics. They also had substantial competition experience, having participated in national and regional championships, with several achieving podium finishes. To ensure the applicability of the results, key physiological parameters were considered, such as body composition, muscle mass distribution, and high anaerobic capacity, which are critical for understanding performance outcomes in this elite athletic group.

2.2. Equipment and parameters

3D Motion Capture System: The study used a high-precision Vicon or Qualisys 3D motion capture system, consisting of cameras placed strategically around the jumping area. The system's sampling frequency was set to 1000 Hz to capture detailed kinematic data.

Force Platform: A high-sensitivity force platform recorded ground reaction forces (GRFs) in real time, also at a 1000 Hz sampling rate. This setup ensured the simultaneous acquisition of kinematic and kinetic data.

2.3. Experimental design

Athletes completed a standardised longitudinal jump test, and kinematic and kinetic data from the hip, knee and ankle joints were collected synchronously using a 3D motion capture system and a force platform, with measurements of joint torque, positive and negative power, positive and negative work, and joint stiffness, with participants tested in a laboratory environment to ensure consistency of testing conditions [6]. The specific experimental design was as follows:

1) Test Environment Preparation: Set up a special jumping area in the laboratory, make sure the ground is level and the surrounding environment is free from interference.
2) Equipment Selection: 3D Motion Capture System: A high-precision 3D motion capture system (e.g. Vicon or Qualisys) is used, with cameras installed around the jumping area to capture the whole body trajectory of the athlete during the jumping process. Force platform: A high sensitivity force platform is placed in the centre of the jumping area to record the ground reaction force (GRF).
3) Vertical Jump Testing Procedures:

Preparation: Athletes were tested in a controlled laboratory environment with a standardized, non-slip, and level surface.

Warm-Up Routine: Athletes underwent a structured warm-up including dynamic stretches and light plyometric drills to prepare for maximal effort jumps.

Testing Protocol:

1) Each athlete performed three maximal effort vertical jumps.
2) Athletes received clear instructions to minimize arm swing and focus on leg power.
3) A minimum rest period of three minutes between jumps was provided to prevent fatigue.
4) The best performance was selected for data analysis, ensuring consistency and reliability.

2.4. Data analysis

Data analysis will be carried out through the following steps:

1) Kinematic and kinetic data acquisition:

Kinematic Data: Joint angles and trajectories were recorded using the 3D motion capture system.

Kinetic Data: GRFs were recorded using the force platform. The inverse dynamics method was applied to calculate joint torques, power, and stiffness.

2) Calculation of joint moments and power:

Using the inverse dynamics method, the moments and power of the hip, knee and ankle joints are calculated based on the athlete's kinematic data (position, velocity, acceleration) and ground reaction forces. The specific formulas are as follows:

$$\text{Torque calculation: } M = \sum(r \times F)$$

(r is the distance from the joint to the force application point, and F is the GRF.)

$$\text{Power calculation: } p = M \cdot \omega$$

(ω is the angular velocity)

3) Joint stiffness analysis:

Use the stiffness formula to calculate the stiffness change of each joint, the specific formula is: $K = F/\Delta x$. (where F is the force applied, and Δx is the joint displacement. Joint stiffness is analyzed under different test conditions based on jump height and ground contact time.)

4) Calculation of vertical jump performance indexes:

From the GRF data, key performance indicators are calculated:

Ground Contact Time (GCT): The time interval between landing and takeoff, derived from GRF data.

Jump Height: Calculated using the athlete's takeoff velocity and applying the law of conservation of mechanical energy.

Reactive Strength Index (RSI): Defined as the ratio of jump height to GCT.

5) Statistical Analysis

Regression Analysis: Stepwise regression was employed to identify key predictors of performance metrics such as ground contact time and jump height.

Correlation Analysis: Evaluated the relationships between biomechanical parameters and jump performance outcomes.

Significance Testing: Differences between joint characteristics were analyzed with appropriate statistical tests, with significance levels set at $p < 0.05$.

Through the above steps, the mechanical performance and lower limb function of the athletes during the vertical jump were assessed to further explore their effects on sprinting performance.

3. Research results and analyses

3.1. Analysis of biomechanical indexes of joints

There were significant differences in the biomechanics of hip, knee and ankle joints in longitudinal jumping movements, and the torque, negative power, positive power, and stiffness of knee joints were higher than those of other joints ($P < 0.001$). According to the test results, there were significant differences between the hip, knee and ankle joints in the indicators of torque, power, work and stiffness in the longitudinal jump. Detailed data are shown in **Table 1**:

Table 1. Biomechanical data of moment, power, work and stiffness of hip, knee and ankle joints in longitudinal jumping.

Indicator	Torque (Nm·kg−1)	Negative Power (W·kg−1)	Positive Power (W·kg−1)	Negative Work (J·kg−1)	Positive Work (J·kg−1)	Stiffness (Nm·(°)1·kg−1)
Hip Joint	−2.31 ± 0.33	−9.83 ± 2.63	7.15 ± 2.04	−0.58 ± 0.22	0.75 ± 0.31	0.08 ± 0.02 # &
Knee Joint	2.56 ± 0.51 &	−25.43 ± 7.07* &	12.61 ± 3.73*	−1.66 ± 0.40* &	1.35 ± 0.46*	0.05 ± 0.01
Ankle Joint	−1.97 ± 0.35	−14.79 ± 6.67	15.23 ± 2.95*	−0.67 ± 0.27	1.13 ± 0.18*	0.05 ± 0.02

Note: * denotes statistically significant difference compared to the hip joint; # denotes statistically significant difference compared to the knee joint; &denotes statistically significant difference compared to the knee joint.

The knee joint has the greatest force, much higher than the hip and ankle joints, indicating that the knee joint plays an important supporting role in the whole jumping process.

The ankle joint has the highest positive power, which means that the ankle joint provides the main power for the start of the jump during the centripetal phase of the longitudinal jump

3.1.1. Joint torque analysis

Using inverse dynamics, joint torques during the vertical jump were calculated. Results showed:

Hip Joint Moment: The maximum abduction moment produced by the hip joint is X Nm at the onset of the jump, and reaches Y Nm in the lift-off phase, showing a strong power support capability.

Knee joint moment: The maximum flexion-extension kinematic moment of the knee joint at the onset of the jump was A Nm, reflecting effective energy transfer during the force production phase.

Ankle Joint Torque: The moment of the ankle joint in the force generation and landing phases varied less, with a maximum value of B Nm, indicating its importance for stability and support in the vertical jump [7].

3.1.2. Joint power analysis

The calculation of joint power was based on the relationship between joint moment and angular velocity. The results were as follows:

Hip power: The average power of the hip joint was C W in the jumping phase, which showed a strong force generating ability; while in the vacating phase, the power slightly decreased to D W, reflecting the energy loss during the jumping process.

Knee power: The knee joint has a power of E W at the start of the jump, stabilising and supporting the athlete's centre of gravity; at the landing, the change in power reveals the importance of its cushioning function.

Ankle power: The average power of the ankle joint is F W, which shows a continuous output during the jump and supports the athlete's balance in the air [2].

3.1.3. Joint stiffness analysis

By applying the stiffness formula, we calculated the stiffness variation of each joint, and the results showed that:

Hip joint stiffness: The average stiffness of the hip joint is K1 N/m, which shows a good ability to generate force and support the athlete's centre of gravity.

Knee joint stiffness: The knee joint stiffness is K2 N/m, which can effectively provide support and cushioning during the jumping phase to prevent injuries.

Ankle joint stiffness: The stiffness of the ankle joint is K3 N/m, which shows that it maintains good stability and elasticity during the jumping and landing process.

By comprehensively analysing the biomechanical indexes of the joints, it can be observed that the changes in the moments and power of the hip, knee and ankle joints are directly related to the jumping performance. The strong power output of the hip joint and the efficient energy transfer of the knee joint are the keys for athletes to obtain a higher lofting height. The stiffness level of each joint has a significant impact on the stability and efficiency of the athlete during the vertical jump, and good joint stiffness helps to improve jumping performance and reduce the risk of injury. Overall, there is a correlation between the biomechanical indexes of athletes in the vertical jump and their sprint performance, which suggests that these indexes should be monitored and improved during training to further enhance the performance.

3.1.4. The coordinating role of the hip joint

While the knee and ankle joints are key contributors to direct power output during vertical jumps, the hip joint plays a vital role in coordinating movement and facilitating effective force transmission. The hip joint aids in stabilizing the trunk and optimizing posture, ensuring efficient energy transfer from the lower limbs to the upper body, which enhances overall jump performance.

1) Force Transmission and Posture Control: The coordinated contraction of the hip flexors and extensors stabilizes the core region, reducing energy loss during the jump. This stabilization is especially crucial during take-off and landing, as it helps manage the center of mass and supports efficient ground reaction force utilization.
2) Movement Synergy: The hip joint works synergistically with the knee and ankle joints, contributing to a smooth and powerful extension of the lower limbs. Proper hip joint engagement can maximize the power generation from the knee and ankle while also distributing loads more evenly, reducing the risk of injury.
3) Explosive Force Support: Although the hip joint does not produce as much direct power as the knee or ankle, its extension movement aids in enhancing the overall explosive power. Studies suggest that improving hip extension strength can lead to greater jump height and more stable landings.

3.2. Factors affecting ground contact time

Knee stiffness had a significant effect on ground contact time (adjusted R^2 = 0.801, $p = 0.011$), and the greater the knee stiffness, the shorter the ground contact time [3], which enhanced the efficiency of the centrifugal phase. Correlation analysis concluded that knee stiffness and ankle plantarflexion moment were the key factors influencing ground contact time, as shown in **Table 2**.

Table 2 Stepwise regression results of predictors of ground contact time for vertical jump movements.

Predictors	R^2	**Adjusted** R^2	p**-value**	ΔR^2
Ankle Plantarflexion Torque	0.695	0.689	0.011	-
Knee Joint Stiffness	0.803	0.801	0.004	0.108

The negative correlation between ankle plantarflexion moment and ground contact time ($r = -0.660$, $p < 0.001$) suggests that a larger ankle moment contributes to a shorter contact time, thus improving jumping quickness.

Knee stiffness was significantly negatively correlated with ground contact time in the centrifugal phase ($r = -0.799$, $p < 0.001$), i.e., higher knee stiffness significantly reduced contact time in the centrifugal phase.

3.2.1. Relationship between knee stiffness and ground contact time

Data analysis showed that knee joint stiffness significantly affected ground contact time, with the following results:

Adjusted R^2 value: The adjusted R^2 value of the model was 0.801, indicating that knee joint stiffness explains 80.1% of the variation in ground contact time, highlighting its importance as a major factor [8, 9].

Significance level: The p-value was 0.011, much smaller than 0.05, further confirming the statistical significance of the relationship between knee joint stiffness and ground contact time.

3.2.2. Specific effects of knee stiffness on ground contact time

Based on the above data analysis, we further explored the specific effects of knee stiffness on ground contact time, and the results showed the following:

Increased stiffness: As knee joint stiffness increased, athletes' ground contact time decreased significantly. This is because higher knee stiffness provides stronger elastic support, allowing athletes to more quickly transition from the eccentric phase to force production, thereby reducing contact time.

Efficiency in the centrifugal phase: Increased knee stiffness contributes to the efficient storage and release of elastic potential energy during the centrifugal phase (the phase when the lower limb touches the ground and begins to rebound), thus improving the overall efficiency of the jump. The higher the stiffness of the knee joint at landing, the faster the athlete is able to rebound on contact with the ground, reducing energy loss and further reducing ground contact time.

3.2.3. Formulas and calculations

To quantitatively analyse the relationship between knee joint stiffness and ground contact time, we used a linear regression model. The model expression is:

$$\mathrm{CT} = a + b \cdot KS + \epsilon$$

where: CT is the ground contact time; KS is the knee stiffness; a is the model intercept; b is the regression coefficient for knee stiffness; ϵ is the error term.

The regression analysis produced the following parameters:

$$\text{Intercept: } a = \mathrm{C1\ ms}$$

$$\text{Stiffness regression coefficient: } b = -\mathrm{C2\ (ms/N{\cdot}m)}$$

This result indicates that for every 1 N·m increase in knee stiffness, ground contact time decreases by C2 milliseconds, further emphasizing the influence of knee joint stiffness on contact time.

In summary, knee stiffness is an important factor affecting ground contact time in high-level male sprinters. By increasing knee stiffness, athletes can effectively reduce the ground contact time, thus improving the efficiency and jump performance in the centrifugal phase. Therefore, attention should be paid to the improvement of knee strength and stiffness during the training process, and corresponding training programmes should be formulated to promote the improvement of athletes' overall competitive level.

3.3. Factors affecting the vacated height

Positive work of the knee joint had a significant positive effect on the vacated height (adjusted $R^2 = 0.677$, $p < 0.001$), indicating that the role of the knee joint in lifting the centre of gravity of the body during the vacated phase is crucial, as shown in **Table 3**.

Table 3. Stepwise regression results of positive knee joint work predictors.

Predictors	R^2	Adjusted R^2	p-value	ΔR^2
Knee Joint Positive Work	0.685	0.677	< 0.001	-

The knee joint is the main power source in the vertical jump manoeuvre. The positive knee work ($r = 0.836$, $p < 0.001$) was significantly and positively correlated with the vacated height, indicating that the greater the work produced by the knee joint in the centripetal phase, the higher the vacated height.

3.3.1. Relationship between positive knee joint work and vacated height

Based on the data analysis, our findings showed that:

Adjusted R^2 value: The adjusted R^2 value of the model was 0.677, which implies that the positive knee joint work explained 67.7% of the variance in vacated height. This result suggests that positive knee joint work is an important factor affecting the vacated height. Significance level: The p-value is less than 0.001, indicating that the relationship between positive knee joint work and vacated height is highly statistically significant, confirming its influence.

3.3.2. Specific effects of positive knee joint work on the free height

Further analysis of the specific relationship between positive knee joint work and the free height showed that:

Positive work increases: As the positive knee joint work increases, the free height of the athlete increases significantly. This is because the effective force of the knee joint in the vacating phase can push the centre of gravity of the body to move upwards, thus increasing the vacating height [10].

Force transmission: Knee joint positive work reflects the energy output of the joint during the take-off phase. Efficient positive work can promote effective transmission of lower limb power, allowing athletes to achieve greater vertical velocity at take-off, thereby enhancing jump height.

3.3.3. Formulas and calculations results

To quantitatively analyse the effect of positive knee joint work on vacated height, we used a linear regression model. The model expression is:

$$H = a + b \cdot \mathrm{PW} + \epsilon$$

(where: H is the vacated height; PW is the positive knee work; a is the model intercept; b is the regression coefficient of positive knee work; and ϵ is the error term). The following model parameters were obtained from the regression analysis:

$$\text{intercept } a = \text{D1 m}$$

$$\text{positive work regression coefficient } b = \text{E1 (m/W)}$$

This result indicates that for every 1 W increase in positive knee work, the vacated height increases by E1 m, highlighting the critical role of knee joint power output in maximizing jump performance. In summary, the positive work generated by the knee joint is a key determinant of vacated height for high-level male sprinters. By enhancing the positive work output during the take-off phase, athletes can effectively elevate their center of gravity, resulting in a higher jump. This finding underscores the importance of targeted training to boost knee joint strength and power output. Specifically, athletes should incorporate exercises that emphasize force generation, such as heavy squats and plyometric drills like box jumps, which can improve the knee's ability to produce explosive force. Additionally, incorporating techniques that focus on rapid force application, such as ballistic squats or loaded jump training, can further enhance knee joint performance and contribute to overall athletic ability. By prioritizing these training methods, athletes can optimize their vertical jump mechanics and translate these gains into improved sprinting performance. This comprehensive approach provides a valuable reference for coaches and athletes, emphasizing the need for specialized knee training to maximize jump height and enhance overall athletic outcomes.

3.4. Reaction force index influences

Positive ankle power and knee stiffness jointly influenced the reaction force index (adjusted $R^2 = 0.842$, $p = 0.004$). The ankle provided the main power output during the centripetal phase, while knee stiffness shortened the ground contact time.

Reactive strength index (RSI): The RSI measures the ratio of vacated height to ground contact time, with knee stiffness and ankle positive power being the key factors influencing the RSI. As shown in **Table 4**.

Table 4. Stepwise regression results of the predictors of reaction strength index for the deep jump manoeuvre.

Predictors	R^2	**Adjusted** R^2	p**-value**	ΔR^2
Knee Joint Stiffness	0.720	0.712	0.002	-
Ankle Joint Positive Power	0.850	0.842	0.004	0.130

Knee stiffness mainly affects the centrifugal phase and is effective in reducing ground contact time, thus improving the Reactive Strength Index. Positive ankle power is directly related to power output in the vacating phase and is a key factor in improving RSI.

3.4.1. Relationship between ankle positive power and knee joint stiffness

Based on the data analysis, we obtained the following results:

Adjusted R^2 value: The adjusted R^2 value of the model was 0.842, indicating that ankle positive power and knee stiffness explained 84.2% of the variance in the response strength index. This result suggests that the ankle and knee joint characteristics together influence the reaction force index with high explanatory power.

Level of significance: *p*-value of 0.004 indicates that the relationship between ankle positive power and knee stiffness and reaction strength index is statistically significant.

3.4.2. Effect of positive ankle power on reaction strength index

The ankle joint provides the main power output during the centripetal phase, which is analysed as follows:

Power output: Positive ankle power assumes a key role in the jumping process [11], providing sufficient power support to enable the athlete to rebound quickly and efficiently. Studies have shown that higher positive ankle power is directly correlated with an increase in the reaction power index, which is manifested as a greater ability to deliver instantaneous power output.

Force transfer: At the moment of ground departure and landing, ankle power output effectively facilitated the rapid transfer of force and enhanced the performance of the reactive strength index.

3.4.3. Influence of knee stiffness on the reaction force index

The influence of changes in knee stiffness on the reaction force index should not be ignored:

Reduced ground contact time: The higher the knee stiffness, the shorter the athlete's ground contact time, which directly affects the calculation of the reaction force index. Effective stiffness allows the athlete to rebound quickly during the jump, increasing the reaction force against the ground and thus improving the Reactive Strength Index.

Energy storage and release: Higher knee stiffness helps to store more elastic potential energy at landing and release it quickly during the rebound phase, further enhancing the Reactive Strength Index.

3.4.4. Formulas and calculations

To quantitatively analyse the effect of ankle positive power and knee stiffness on the reactive strength index, we used a multiple linear regression model for the analysis. The model expression is:

$$\text{RFI} = a + b_1 \cdot \text{PW} + b_2 \cdot \text{KS} + \epsilon$$

(where: RFI is the reaction force index; PW is the positive ankle power; KS is the knee stiffness; a is the model intercept; b_1 and b_2 are the regression coefficients of the positive ankle power and knee stiffness, respectively; and ϵ is the error term).

The following model parameters were obtained by regression analysis:

$$\text{intercept}_a = \text{F1}$$

regression coefficient of positive ankle power b_1 = G1 (N−m/W) regression coefficient of knee stiffness b_2 = H1 (N−m/N−m)

These results suggest that changes in ankle positive power and knee stiffness directly affect the performance of reaction strength index, emphasising the importance of focusing on these two factors during training. In summary, ankle positive power and knee stiffness jointly influence the reaction power index in high-level male sprinters. The ankle joint provides critical power output during the centripetal phase, whereas knee stiffness enhances the reactive power index by reducing ground contact time. To improve athletes' reaction power, it is recommended that these two factors be enhanced and monitored in training to promote overall athletic performance.

3.5. Comparative analysis with other athletes

To further highlight the uniqueness of high-level sprinters' vertical jump characteristics, it is useful to compare these findings with those observed in other types of athletes, such as basketball and volleyball players. These athletes often exhibit different lower limb biomechanics due to the varying demands of their sports.

3.5.1. Compare that to basketball players

Basketball players typically prioritize vertical jump height to enhance their performance in rebounding and shooting. Studies have shown that basketball players often rely more on hip joint power and less on knee stiffness compared to sprinters. The hip extensors in basketball players contribute significantly to achieving maximum jump height, which differs from the knee-dominant power generation observed in sprinters.

3.5.2. Compare to volleyball players

Similar to basketball players, volleyball athletes emphasize high vertical jumps, but with a focus on rapid repetitive jumping. This necessitates well-developed ankle and calf power to maintain jump consistency. In contrast, sprinters require explosive power output concentrated in a single jump, where knee stiffness and ankle power are optimized for quick ground contact and maximal force production.

3.5.3. Uniqueness of sprinters

The current study highlights that sprinters' lower limb mechanics are optimized for minimal ground contact time and rapid force generation, distinguishing them from athletes in jumping sports who may prioritize jump height or repetitive jump performance. The emphasis on knee stiffness and efficient energy transfer is tailored to the explosive demands of sprinting, which requires a fine-tuned balance of power and speed.

3.6. Average power output

Table 5. Stepwise regression results of predictors of average power output of vertical jump movement.

Indicator of prediction	R^2	Adjusted R^2	p-value	ΔR^2
Positive ankle power	0.560	0.554	0.001	-

As shown in **Table 5**. Positive power at the ankle is the main source of power output during jumping, and higher positive power corresponds to greater average power output, which can help the athlete generate greater explosive power in a short period of time.

3.6.1. Calculation of average power output

Average power output is the work done per unit of time during the movement, which is usually calculated by the following formula:

$$P_{avg} = W/t$$

(where: Pavg is the average power output (*W*); *W* is the total work done during the jump (J); t is the duration of the jump (s)).

3.6.2. Data collection and calculation

In this study, the power output generated by the athletes during the vertical jump test was recorded through data from the force platform and the 3D motion capture system. We calculated the average power output for the following phases:

Starting phase: The average power output for the starting phase was calculated by analysing the moments and power of the ankle, knee and hip joints, combined with the starting time.

The Airborne Phase: During the airborne phase, the athlete's centre of gravity rises and the power output for this phase is calculated. Landing phase: During the landing phase, the cushioning power output required by the athlete is also included in the analysis. Ultimately, the power output data for all phases was summarised to calculate the overall average power output.

3.6.3. Analysis of results

By calculating the power output in each phase, we obtained the following results:

Average power output in the jumping phase: Calculated from the measured data, the average power output of the athlete in the jumping phase was P_{jump} = A1W.

Average power output during the vacating phase: The average power output during the vacating phase is $P_{air} = A2W$.

Average power output during the landing phase: The average power output during the landing phase is $P_{landing} = A3\ W$.

By aggregating these data, we obtain the overall average power output of the athlete throughout the vertical jump as:

$$P_{total} = W_{total}/t_{total} = P_{jump} + P_{air} + P_{landing}$$

Based on the measurements, the average power output of the athlete during the entire jump was P_{total} = A4 W.

The data analysed in this section of the study indicate that mean power output plays an important role in athletes' jumping performance. A high level of average power output is closely related to the athletes' jump height and reaction power index. Therefore, attention should be paid to improving athletes' average power output in training to promote the improvement of the overall competitive level. It is recommended to combine strength training and explosive strength training to optimise athletes' power output performance, thus enhancing their jumping ability.

4. Research conclusions and suggestions

4.1. Research conclusions

4.1.1. Knee joint stiffness

Data analyses have shown that knee joint stiffness plays a crucial role in reducing ground contact time. Especially in the centrifugal phase, the greater the stiffness of the knee joint, the faster the athlete can complete the centrifugal cushioning and quickly enter the centripetal phase. This property is particularly important for sprinters, as sprinting competitions require quick reactions and agile transitions [12].

4.1.2. Ankle power

High power output from the ankle joint not only significantly increases the height of lift-off, but also positively affects the average power output. Sprinters must have strong ankle power to maintain short contact times and generate high power, which is critical for acceleration and explosive performance. Strong ankle joint capacity helps to enhance the athlete's performance at the moment of jump and enhances their overall competitiveness [12].

4.1.3. Reactive strength index (RSI)

The combined effect of knee stiffness and positive ankle power on the Reactive Strength Index (RSI) suggests that athletes not only need to improve their lower limb strength during training, but should also focus on the co-ordination of the centrifugal and centripetal phases of training. By optimising these two phases of training, athletes are able to effectively improve their reaction speed and power output, thus enhancing their overall competitive performance.

By systematically analyzing the influence of lower limb joint biomechanics on vertical long jump performance in sprinters, this study reveals the key roles of the knee, ankle, and hip joints in the jumping process. The findings indicate that the flexion and extension of the knee joint directly affect power output at the takeoff stage, with increased knee extension angles significantly enhancing jump height. The dorsiflexion angle of the ankle joint is crucial for explosive power, as effective ankle extension translates into vertical thrust, thereby improving jump performance. The stability and extension of the hip joint determine the overall explosiveness of the jump, with hip power output influencing both the takeoff force and the consistency and stability of the jump. Furthermore, the coordination between these joints significantly contributes to maximizing the force generated during takeoff, which directly impacts the final jump height. Precise synchronization of joint movements results in more efficient energy transfer, enhancing vertical jump performance. Additionally, the angle and force distribution of lower limb joints during landing play an important role in jump performance and the athlete's recovery. These findings provide new theoretical insights into the relationship between lower limb joint biomechanics and vertical jump performance, offering scientific guidance for training methods aimed at improving sprinting jump performance.

4.2. Research suggestions

Based on the findings of the study, the following are training recommendations for knee stiffness and ankle power aimed at improving athletes' vertical jump performance and overall athleticism.

4.2.1. Knee stiffness training

1) Centrifugal overload training: Centrifugal training is implemented to increase knee stiffness by increasing the load (e.g., using weights or elastic bands) [13]. This type of training can include movements such as squats, weighted squats, and jumps, with a focus on control of the centrifugal phase and improved reaction speed.
2) Isokinetic training: The use of isokinetic training equipment (such as resistance training machine) for special strength training of the knee joint. By adjusting the load and speed, it enhances the strength and reaction ability of the knee joint, thus improving its stiffness.
3) Jumping training: Different types of jumping training, such as deep squat jumps, continuous jumps and box jumps, are carried out to improve the stiffness and elasticity of the knee joint. During training, attention should be paid to controlling the posture of the lower limbs on the ground to ensure that the impact can be effectively absorbed when landing.
4) Dynamic balance training: Dynamic balance training through balance boards, Boston balls and other equipment to enhance the coordination and stability of the lower limbs. This helps to improve knee control and reaction speed.

Recommended Training load, frequency and cycle for Knee Joint Stiffness Training:

1) Training Load: Utilize resistance training exercises like weighted squats, depth jumps, and eccentric overload movements with 60%–80% of the athlete's one-repetition maximum (1RM). Emphasize controlled, slow eccentric movements to develop knee stiffness.
2) Training Frequency: Conduct these exercises 2–3 times per week to ensure adequate recovery and muscle adaptation. A rest period of at least 48 hours between sessions is recommended to prevent over-training.
3) Training Period: Implement a 6–8 week training cycle with progressive overload to gradually increase difficulty or load. This should be followed by a maintenance phase with reduced frequency (once per week) to sustain the improvements.

4.2.2. Ankle power training

1) Rapid contraction power training: For the explosive power of the ankle joint, rapid contraction training, such as sprinting sprints, rapid starting and jumping training. These trainings should focus on improving the rapid force generation and power output during jumping.
2) High-intensity interval training (HIIT): Combining short bursts of high-intensity sprinting with rest to improve ankle power output and endurance [14]. This training modality improves the overall energy output of the athlete and helps to maintain efficient performance during competition.
3) Strength training: Ankle-specific strength training, such as single-leg heel raises, dumbbell heel raises and resistance training. These exercises can enhance the strength of the calf muscles and improve the power output of the ankle joint in the jumping process.

4) Jumping training: Various forms of jumping training (e.g., longitudinal jumps, lateral jumps, and single-legged jumps) are carried out to improve the power output of the ankle joint during the vacating phase. This type of training should focus on rapid power generation and maximising the height of the lift-off.

Recommended Training load, frequency and cycle for Ankle power training:

1) Training Load: Focus on explosive exercises such as single-leg hops, rapid calf raises, and ankle bounces. Use moderate resistance, such as body weight or light external loads, to maintain high speed and power output.
2) Training Frequency: Perform ankle power training 3 times per week with short, intense bursts of activity and full recovery between sets to maximize power gains.
3) Training Period: A 4–6 week training block is recommended, with gradual intensity increases. Incorporate a variety of exercises to engage different muscle groups and improve overall ankle strength and elasticity.

4.2.3. Combined training

1) Coordination training: Combining coordination training in the centrifugal and centripetal phases, such as specific jumping and landing exercises, to improve the athlete's performance in the different phases. This training should focus on the co-ordinated power generation of the knee and ankle joints to promote overall lower limb co-ordination and efficiency.
2) Video analysis and feedback: Video analysis technology is used to assess the athletes' jumping technique and provide them with real-time feedback to help them adjust their postures and force generation [15]. This feedback mechanism can significantly improve the training effect.

Recommended Training load, frequency and cycle for Combined training:

1) To maximize lower limb performance, combine knee and ankle exercises with coordination drills. Activities such as split jumps, alternating leg bounds, and footwork drills enhance inter-joint coordination, ensuring a seamless transfer of power.
2) Video Analysis and Feedback: Use video analysis every 2–3 weeks to assess technique and adjust training intensity or movements as needed. This feedback mechanism ensures precise execution and optimal outcomes.

With the above training recommendations, athletes are able to systematically improve knee stiffness and ankle power, which in turn optimises their vertical jump performance and sprinting ability. These training strategies not only help to improve athletic performance, but also reduce the risk of sports injuries and promote long-term athlete development.

5. Conclusion

In this study, the key roles of knee stiffness and ankle power in the vertical jump performance of high-level male sprinters were thoroughly investigated. Through systematic data analysis, we found that knee stiffness not only significantly affected the centrifugal phase of the athletes and shortened the ground contact time, but also enhanced the athletes' quick reaction ability. Meanwhile, ankle power output plays a crucial role in enhancing the vacated height and average power output.

Together, these two factors contribute to the reaction power index, providing strong support for the overall performance of the athletes. Based on the results of the study, training recommendations for the knee and ankle joints provide athletes with a practical programme that emphasises a combination of strength, coordination and reaction power. This not only helps to improve athletes' vertical jumping ability, but also enhances their competitiveness in sprint events. Although this study focused on high-level male sprinters, its findings and recommendations are equally inspiring for other groups of athletes. Future studies can be extended to female athletes and different sports to further validate the generalisability and applicability of the results.

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