A Biomechanical Analysis of the Relationship between the Joint Powers during the Standing Long Jump and Maximum Isokinetic Strength of the Lower Limb Joints*

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The purpose of this study was to analyze the relationships between the joint power during the propulsion phase of the standing long jump and the maximum isokinetic strength of the lower limb joints. The subjects comprised 11 male athletes specialized in different sport events. The isokinetic strengths of the extensor muscles at the ankle, knee, and hip joints at two angular velocities were evaluated by dynamometry. Joint powers during the propulsion phase of the standing long jump were calculated with two-dimensional coordinate data (50 Hz) and ground reaction force data (500 Hz). Knee and hip joint peak power during the propulsion phase, normalized by the body mass, highly and significantly correlated with the jump distance (knee: \( r = 0.767, p < 0.01 \), hip: \( r = 0.723, p < 0.05 \)). Isokinetic extensor strength of the ankle, knee, and hip joints, normalized by the body mass, did not correlate with peak power during the propulsion phase at the corresponding joint. Additionally, the isokinetic extensor strength did not correlate with the jump distance, with one exception. Although the jump distance depended on lower limb joint power during the propulsion phase, power was not directly modulated by the isokinetic strength. This phenomenon might be derived from the use of strategies that enhance lower limb power, which include a counter-movement and the coupling of an arm swing to the lower limb motion.

Keywords: dynamometry, multi-joint movement, kinetic analyses, counter-movement, arm swing

1. Introduction

The jumping motion is a basic movement of the human body and plays a fundamental role in sports and physical education. Jumping from a standing start with maximum effort exerted at once (e.g., the vertical jump) requires maximum power output by the lower limb muscles. However, in jumping motions that involve complex technical aspects associated with the control of the jump direction, as with the standing long jump (Kubo and Ae, 2005), short-term isokinetic training of the lower limb muscles does not directly lead to improved performance (Morriss et al., 2001), as using the full potential of
the muscles is difficult. Determining the factors limiting performance in jumping exercises (the jump distance in the case of the standing long jump) and their relationships with muscular strength will be useful in evaluating the performance of various types of exercise for which power output is important.

In recent years, numerous studies have evaluated the relationship between the vertical jump height and maximum strength. In various studies that assessed static single-joint strength, the correlation between the isometric strength of the three joints in the lower limbs and the vertical jump height was shown to depend on the presence of countermovement and whether the subjects were athletes (Chang et al., 2015; Rousanoglou et al., 2008; Ugarkovic et al., 2002). Conflicting reports have either shown that the ground reaction force during the mid-thigh isometric clean pull is correlated with the vertical jump height (Kraska et al., 2009), or that no such correlation exists (Thomas et al., 2015). Additionally, a correlation has been reported to exist between the isometric leg-press strength and the jump height (Copic et al., 2014). Furthermore, it has been reported that the vertical jump height is correlated with the knee joint isokinetic strength (Paasuke et al., 2001) and the 1-repetition maximum in the squat or power clean (Nuzzo et al., 2008). However, muscular activity and lower limb kinetics during the jumping motion were not investigated in these previous studies. Therefore, an assessment of the cause of the observed relationship between maximum strength and jump performance is difficult; the roles of the lower limb muscles in jump performance cannot be sufficiently explained based solely upon the observation of a correlation between maximum strength and jumping ability. A biomechanical analysis of the jumping motion is important in the assessment of the roles of the lower limb muscles in the jumping motion.

Research on the relationship between the maximum strength and performance in the standing long jump is scarce compared to that for the vertical jump. Morris et al. (2001) reported that, although the quadriceps femoris muscles showed increased isokinetic strength after isokinetic strength training for 6 weeks, no improvement was observed in the standing long jump performance. However, as in most studies of vertical jumps, the jumping motion was not analyzed. Other studies have biomechanically analyzed the take-off motion in the standing long jump, with comparison between the presence/absence of an arm swing (Ashby and Heegaard, 2002; Harra et al., 2008), starting postures (Cheng and Chen, 2005), or standing long/vertical jumps (Fukahiro et al., 2005; Jones and Caldwell, 2003). In addition, the optimal take-off angle has been evaluated biomechanically (Wakai and Linthorne, 2005). Although the motion characteristics for highly experienced athletes and the changes in biomechanics due to technical training have been investigated (Kubo and Ake, 2005), few studies have investigated the limiting factors for the jump distance.

A clarification of the relationship between the take-off motion in the standing long jump and isokinetic strength may aid in the elucidation of the limiting factors for exercises in which power output is important. Therefore, the purpose of this study was to analyze the take-off technique in the standing long jump biomechanically, and identify the limiting factors for the jump distance and take-off technique. To this end, we evaluated the relationships between joint power during the propulsion phase of the standing long jump and the maximum isokinetic strength of the lower limb joints.

2. Methods

2.1. Data collection

2.1.1. Subjects

The study participants comprised 11 male Japanese student athletes specialized in various sports; their characteristics are shown in Table 1. All subjects had participated in championships at the student regional level or higher.

Prospective subjects were provided sufficient explanation regarding the study objectives and methods, and the risks associated with the measurements. All subjects provided written consent for participation. This study was approved by the local institutional ethics committee.

2.1.2. Measurement of isokinetic strength

The maximum isokinetic joint torques of the ankle, knee, and hip joints were measured by dynamometry (Biodex System 4; Biodex Medical Systems, Inc., Tokyo, Japan). The subjects warmed up sufficiently before the assessment by performing
activities such as running and stretching. Ankle and hip joint torques were measured with the subject in the supine position, while the knee joint torque was measured with the subject in a seated position. The waist area was immobilized at a central position to prevent movement of the trunk, hands, and arms from affecting the measurements (Figure 1).

Angular velocities of 30°/s and 90°/s were selected for the ankle joint torque assessment, while angular velocities of 60°/s and 180°/s were selected for knee and hip joint torques, in accordance with the recommendations in the standard protocol provided by Biodex Medical Systems. The angular velocity selected for the ankle joint was lower than that for the other joints because torque generation in the ankle joint was shown to be low within a range of higher angular velocities in preliminary measurements. The movable ranges were set as follows: (i) ankle joint torque: from the position of maximum plantar flexion to the position of maximum dorsal flexion; (ii) knee joint torque: 100°, set with reference to the maximum extension position; and (iii) hip joint torque: from the position of contact between the thigh and sheet to the position of maximum flexion. For each leg, each joint was assessed in decreasing angular velocity order. Subjects completed approximately 10 practice trials at each angular velocity, with gradually increasing effort. Experimental trials were then completed at maximum effort, with three trials at the higher angular velocity, followed by a rest for 30 s and two trials at the lower angular velocity. Although this study only required extension torque data for each joint,
flexion and extension were performed continuously for smooth repetitions.

Torque data were smoothed using the nine-point moving-average method, and the maximum torque in the extension direction was selected for each angular velocity. In addition, the values were divided by the body mass, and averaged over the left and right legs.

2.1.3. Measurement of the standing long jump motion

Standing long jump assessments were performed after the isokinetic strength assessments, with sufficient rest between the assessments. Reflective markers were attached to the subject at the top of the head, upper margin of the sternum, and seventh cervical vertebra, and, on the left side, at the tragus, acromion, radial landmark, radial styloid landmark, third metacarpal head, lower end of the ribs, greater trochanter, lateral epicondyle of the femur, lateral malleolus, heel, and fifth metatarsal. Using an analog-to-digital converter and video measurement system (TRIAS System; DKH Co., Ltd., Tokyo, Japan), photographs were obtained at a frequency of 100 Hz using a high-speed 1394 camera (A602fc-2; Basler AG, Ahrensburg, Germany), positioned lateral to, and 12 m from the subject. Ground reaction force data were simultaneously collected at a frequency of 500 Hz using a force plate (9287B; Kistler Holding AG, Winterthur, Switzerland) mounted in the take-off position (Figure 2).

The subjects jumped from the take-off line on the force plate, landing as far as possible in the direction of the sandpit. After several practice jumps, the subjects jumped two to five times with maximum effort, and on each occasion, the distance was measured, using a tape measure, as the straight-line distance from the middle point between the toe tips of the two feet at toe-off to the nearest landing position in the sandpit. For each subject, the trial with the greatest distance was analyzed.

2.2. Analysis of the take-off motion

2.2.1. Data processing

We analyzed the period from the start of motion to 10 frames after toe-off. The body landmarks and four reference markers were digitized from the images at one-frame intervals (50 Hz) based on the reflective markers (Frame-DIAS IV; DKH). Two-dimensional coordinates of the body segment endpoints were calculated by scaling from the reference markers, and were smoothed with a

![Figure 2](image-url) Set-up for measurement of standing long jump motion.
Butterworth low-pass digital filter. The cut-off frequency was obtained by using the residual error method proposed by Wells and Winter (1980), and as a result, 3.5 to 7.5 Hz and 3.0 to 7.5 Hz were selected for the horizontal and vertical components, respectively.

Under the assumption that the limb movements were bilaterally symmetric, the coordinates of the left side of the body were applied to the right side without modification. A 15-segment linked model comprised the head, upper trunk, lower trunk, upper arm, forearm, hand, thigh, shank, and foot. In addition, the angles of the joints and segments, coordinates of the centers of mass of the body segments and the whole body, and moments of inertia of the body segments were calculated from the smoothed data (Ae, 1996). Furthermore, velocity, acceleration, and angular velocity and acceleration were obtained by numerical differentiation of the coordinates of the center of mass and angles of the relevant joints and segments.

2.2.2. Calculated parameters

Based on the displacement and velocity of the body center of mass at toe-off, the jump distance \( D \), unaffected by the skill of landing, was calculated using Equation 1 (Hara et al., 2008). The values in the equation were as follows:

\[
D = X + V_X (V_Y + \sqrt{V_Y^2 - 2gY_0 + 2gY}) / g
\]  

(1)

\( X \): Horizontal distance from the toe to the body center of mass at toe-off  
\( V_X \): Horizontal velocity of the body center of mass at toe-off  
\( V_Y \): Vertical velocity of the body center of mass at toe-off  
\( Y_0 \): Lowest point of the body center of mass  
\( Y \): Height of the body center of mass at toe-off  
\( g \): Acceleration of gravity

In addition, the take-off angle was defined as the angle between the velocity vector of the body center of mass at toe-off and a horizontal line.

The joint force and torque were calculated by solving equations of motion based on the body’s two-dimensional coordinates and ground reaction force, and the joint power was determined as the product of the joint torque and joint angular velocity. In addition, the kinetic and potential energy of the body segments were calculated based on the kinematic data for those segments, and the whole-body mechanical energy was obtained by summing the energy over the body segments. The joint torque, joint power, and mechanical energy were divided by the body mass.

2.3. Statistical analysis

The peak powers of the three joints (ankle, knee, and hip) during the propulsion phase of the standing long jump and the isokinetic strengths, normalized by the body mass, were prepared as T-scores. The mean value of the peak power T-scores for the three joints was defined as the “peak power T-score”; the mean value of the six isokinetic strength T-scores for the three joints, at two angular velocities each, was defined as the “strength T-score”. Furthermore, the power output index was defined as the peak power T-score divided by the strength T-score in order to evaluate the power output ability during the propulsion phase of the standing long jump relative to the isokinetic strength.

In addition, Pearson’s correlation coefficients were calculated to investigate the three-way relationships among jump distance, variables relating to the take-off motion in the standing long jump, and isokinetic strength. The significance level was set at <5%.

3. Results

3.1. Standing long jump

Table 2 shows the jump distance for the standing long jump for all subjects. The mean jump distance \( D \) was 2.38 ± 0.20 m. On the other hand, the mean distance, as determined by a tape measure, was 2.61 ± 0.21 m, which was correlated with the jump distance \( r = 0.922; p < 0.01 \).

Table 3 shows the mean, standard deviation, and correlation with the jump distance for the peak power of the lower limb joints, the increase in whole-body mechanical energy (the difference
between the minimum value and the value at toe-off, and the mechanical energy at toe-off. The ankle joint peak power was not correlated with the jump distance, whereas the knee and hip joint peak powers both showed significant positive correlations with the jump distance (knee joint: \( r = 0.767; p < 0.01 \); hip joint: \( r = 0.723; p < 0.05 \)). In addition, the whole-body mechanical energy increase and value at toe-off both showed positive correlations with the jump distance (increase: \( r = 0.743; p < 0.01 \); value at toe-off: \( r = 0.926; p < 0.01 \)).

### 3.2. Relationship between standing long jump performance and isokinetic strength

Table 4 shows the correlations between isokinetic strength and the jump distance and peak power of the corresponding joint during the propulsion phase of the standing long jump. A significant positive correlation was found between the jump distance and the isokinetic strength of the knee joint at the lower angular velocity (\( r = 0.652; p < 0.05 \)), but no significant correlations with jump distance were found for the ankle and hip joints.

![Figure 3](image-url)  
**Figure 3**  Relationships between the jump distance and the absolute value of the velocity of the body center of mass at toe-off and the take-off angle.
Table 5 shows the peak power T-score in the standing long jump strength T-score, and the power output index for each subject. The power output index was defined as the peak power T-score divided by the strength T-score.

| Subject | Sports, Position, etc. | Peak power T-score | Strength T-score | Power output index | Rank of index |
|---------|------------------------|--------------------|------------------|-------------------|--------------|
| A       | Athletics; Sprint      | 49.6               | 48.1             | 1.032             | 4            |
| B       | Athletics; Long distance | 41.9             | 46.0             | 0.911             | 8            |
| C       | Athletics; Triple jump | 58.5               | 64.7             | 0.905             | 9            |
| D       | Athletics; Discus throw | 50.6             | 46.1             | 1.098             | 3            |
| E       | Tennis                 | 41.6               | 36.3             | 1.146             | 2            |
| F       | Volleyball; Middle blocker | 58.1             | 41.9             | 1.387             | 1            |
| G       | Gymnastics             | 47.9               | 46.9             | 1.021             | 5            |
| H       | Cycling; Road          | 42.7               | 50.8             | 0.842             | 11           |
| I       | Cycling; Sprint        | 44.5               | 52.7             | 0.844             | 10           |
| J       | American football; Linebacker | 52.9             | 54.3             | 0.975             | 7            |
| K       | Speed skating; Sprint  | 61.5               | 62.3             | 0.988             | 6            |

observed for the isokinetic strength of the other joints or for other angular velocity condition. In addition, no significant correlations were observed between the isokinetic strength of any of the joints and the peak power of the corresponding joint during the propulsion phase of the standing long jump.

Table 5 shows the peak power T-score in the standing long jump, strength T-score, and power output index for each subject. Subject F showed the highest power output index, while subject H showed the lowest; therefore, these subjects were selected as representative subjects. Figure 4 shows the joint torque, joint angular velocity, and joint power during the propulsion phase for the ankle, knee, and hip joints of subjects F and H. The x-axis starts at 0.8 s before the time of the toe-off. Stick figures depicting the motion of each subject are shown at the top of the graph. Plantar flexion torque increased gently from approximately 0.4 s before toe-off in subject H, whereas it increased rapidly in subject F, whose ankle joint torque, angular velocity, and power all showed two peak profiles. The knee joint showed the greatest difference between the two representative subjects, and the torque from 0.2 s before toe-off was greater for subject F than for subject H. In addition, the knee joint angular velocity was low from 0.4 to 0.2 s before toe-off in subject H, whereas the angular velocity showed a negative value, reflecting flexion, in subject F. Knee joint power in subject F was transiently negative, but then increased rapidly to a high positive value. In addition, hip extension torque in subject H was generated from 0.8 to 0.4 s before toe-off, and the power became negative, whereas both the torque and power were low in subject F during the same phase.

4. Discussion

The present study evaluated the relationships among isokinetic strength, jump distance, and joint power during the propulsion phase of the standing long jump. As shown in Table 4, isokinetic strength, as measured by dynamometry, did not show a significant relationship with the jump distance, or with the peak power of the corresponding joint during the propulsion phase, with one exception. These results suggest that high lower limb strength does not necessarily reflect a large power output during the propulsion phase or a large jump distance in the standing long jump. On the other hand, the jump distance was correlated positively with the velocity of the body center of mass at toe-off and the increase in whole-body mechanical energy (Figure 3, Table 3). Therefore, it appeared that a large power output during the propulsion phase, and thus mechanical energy increase, was important for achieving a large jump distance. In addition, the peak power of the knee and hip joints during the propulsion phase showed significant positive correlations with the jump distance (Table 3), with a particularly high determination coefficient, at 0.59, for the knee joint power. Thus, during the propulsion phase of the standing long jump, the power output centered on the knee extensor muscles was important for the acceleration of the body center of mass, but the magnitude of this power could not be determined by the isokinetic strength of a single joint.

Kubo and Ae (2005) reported that the factors associated with an increase in the jump distance due to technical training for the standing long jump were a decreased take-off angle (before training: 31.0 ± 4.1°; after training: 27.7 ± 3.0°) and increased velocity of the body center of mass at toe-off (before training: 3.48 ± 0.32 m/s; after training: 3.59 ± 0.22 m/s). In the present study, the
determination coefficient of the velocity of the body center of mass at toe-off relative to the jump distance was at least 0.7, re-confirming the importance of the velocity of the body center of mass. However, the take-off angle also showed a positive correlation with the jump distance, which differs from the findings of Kubo and Ae (2005). In the present study, the mean take-off angle was 26.5 ± 4.9°, which is less than that in the post-training results of the study by Kubo and Ae (2005), as well as that in other studies (Ashby and Heegaard, 2002: 38.6 ± 1.1°; Wakai and Linthorne, 2005: 31.4 to 39.1°). Therefore, while some subjects in the present study jumped too low, almost none of the subjects jumped too high, and consequently, the jump distance was more affected by the velocity of the body center of mass than by the take-off angle.

The weak relationship between isokinetic strength and peak power in the propulsion phase of the standing long jump suggests that some subjects made full use of their strength, while others did not. The lower limb joint powers during the propulsion phase were compared between subjects F and H, who had the highest and lowest power output index, respectively (Table 5); the greatest difference between the subjects was in the knee joint behavior during the propulsive phase (Figure 4). In particular, during the leg extension phase immediately before toe-off, subject F showed greater knee joint extension torque and greater power than did subject H. The isokinetic strength of the knee joint at the lower and higher angular velocities was 5.02 and 3.31 N·m/kg, respectively, for subject H, and was 5.75 and 3.81 N·m/kg, respectively, for subject F. Hence, the strength at both angular velocities was approximately 15% higher in subject F. However,
this difference may appear to be rather small given the approximately two-fold difference in knee joint peak torque and peak power during the propulsion phase. Factors other than knee joint extensor muscle strength might have led to the higher knee joint power output during the propulsion phase in subject F than in subject H, as discussed below.

As shown in Figure 4, at approximately 0.2 s before toe-off, when the knee joint extension torque had already started to increase, the power became negative with the flexion angular velocity in subject F, whereas there was no phase during which a clear negative value was observed in subject H. The behavior of the knee joint in subject F may be understood in terms of a counter-movement; that is, movement in the opposite direction immediately before the main movement (Fukashiro, 2000). Fukashiro (2000) summarized the contributions of the counter-movement mechanisms as constituting pre-activation, stretch reflex, potentiation, and elastic components. In these mechanisms, the tension is already elevated when the agonistic muscle is extended and starts to contract. Thus, knee joint extension torque at the start of the knee extension (i.e., maximum knee flexion) was calculated across all subjects, and the relationships between this torque and the jump distance and peak power of the knee joint were investigated to evaluate the effective use of counter-movement. As a result, the extension torque (mean: 1.93 ± 0.91 N·m/kg; subject F: 3.12 N·m/kg; subject H: 1.20 N·m/kg) at maximum knee flexion (i.e., 0.20 ± 0.05 s before toe-off) showed positive correlations with the jump distance ($r = 0.836; p < 0.01$) and peak knee joint power ($r = 0.765; p < 0.01$). Therefore, to achieve a large jump distance, it was important to increase the extension torque of the knee joint, flexing it using the effects of the counter-movement, and then to immediately apply the large knee joint power, as observed in subject F. Since jumpers have to satisfy both upward and forward acceleration in the standing long jump, the effective use of a counter-movement

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**Figure 5** Stick figures of subjects F and H (Top) and the time courses of whole body mechanical energy (Bottom) just before toe-off. The gray arrow represents the ground reaction force (GRF), and the black, dotted arrow represents the shoulder joint force (SJF) acting on the trunk. The force vector lengths are normalized to the body mass.
might be more difficult in the standing long jump than in the vertical jump.

We further investigated the differences between subjects F and H with respect to knee joint power by evaluating the relationships among the ground reaction force, joint force, posture, and whole-body mechanical energy. Stick figures of subjects F and H just before toe-off are shown at the top of Figure 5. The gray arrow represents the ground reaction force, and the black, dotted arrow represents the shoulder joint force acting on the trunk. The force vector lengths are normalized by the body mass. In addition, the time courses of the whole-body mechanical energy are shown at the bottom of Figure 5. The arms were lifted later in subject F than in subject H, and it can be understood that the shoulder joint force had a major effect on suppressing the backward lean of the torso at 0.15 to 0.10 s before toe-off. In addition, the ground reaction force during this phase was larger in subject F than in subject H, and the whole-body mechanical energy of subject F was increased markedly. In contrast, although subject H showed an increased shoulder joint force associated with an arm swing motion at 0.25 to 0.20 s before toe-off, the knee joint did not extend during this phase; hence, the knee joint power did not increase (Figure 4). Therefore, the increase in whole-body mechanical energy was slower in subject H than in subject F. In addition, across all subjects, a positive correlation \( r = 0.654; p < 0.05 \) was found between the shoulder joint force (mean: 10.2 ± 3.0 N/kg; subject F: 13.8 N/kg; subject H: 9.5 N/kg) and the knee joint torque (shown above) at maximum knee flexion. Feltner et al. (1999) found that the hip and knee extensor torques during the final two-thirds of the propulsive phase of a counter-movement jump were greater with an arm swing than without an arm swing. The authors also reported that a forward arm swing slowed the rate of the trunk extension due to the force on the trunk at the shoulder, and thus favored the generation of a resultant joint torque. It is therefore suggested that, even in the case of a forward jump, as made by subjects in the present study, the achievement of a large shoulder joint force by swinging the arms at the same time as the knee extension, as observed in subject F, may be one of the jump techniques allowing a large knee joint power output.

The present findings showed that even though the subjects were instructed to jump with their maximum effort, only some subjects could exert the power commensurate with the corresponding joint isokinetic strength. The subjects who were capable of a large power output during the propulsion phase, and a large jump distance for their isokinetic strength, demonstrated an increased knee joint power due to an increase in the extension torque at the maximum knee flexion and the coupling of an arm swing to the knee extension. Ae (2006) suggested that the total energy output is one of the technique evaluation axes in sports. The results of the present study indicated that techniques to increase the total energy output (i.e., the power output) effectively were important for standing long jump performance. On the other hand, based on the results of the biomechanical analysis in the present study, a counter-movement and arm swing may be considered as factors underlying the lack of a direct connection between isokinetic strength and power output during the propulsion phase. However, other factors may have affected the results, such as the differences in movement (in multiple joints or a single joint) and angular velocities between the standing long jump and the isokinetic strength assessment.

5. Conclusions

The purpose of the present study was to perform a biomechanical analysis of the take-off technique in the standing long jump and identify the limiting factors for the jump distance. To this end, the relationships between joint power during the propulsion phase of the standing long jump and maximum isokinetic strength of the lower limb joints, determined by dynamometry, were evaluated. The results obtained in the present study can be summarized as follows:

(i) The magnitude of the body center of mass velocity and whole-body mechanical energy at toe-off were correlated with the jump distance (velocity: \( r = 0.857, p < 0.01 \), energy: \( r = 0.926, p < 0.01 \)).

(ii) Knee and hip joint peak powers during the propulsion phase, normalized by the body mass, were correlated with the jump distance (knee: \( r = 0.767, p < 0.01 \), hip: \( r = 0.723, p < 0.01 \)).
Knee extension torque at maximum knee flexion of an arm swing to the lower limb motion, which include a counter-movement and the coupling of an arm swing to the lower limb joint power, did not correlate with peak power during the propulsion phase at the corresponding joint. Additionally, the knee extensor strength at an angular velocity of 60°/s was correlated with the jump distance (r = 0.652, p < 0.05); no significant correlations with the jump distance were found for the other joints or at other angular velocities.

Knee extension torque at maximum knee flexion (used as an index of counter-movement) was correlated with the jump distance (r = 0.836, p < 0.01) and peak knee power (r = 0.765, p < 0.01). In the subject with the highest ratio of the peak power during the propulsion phase to the isokinetic strength, knee extensor power was enhanced by increasing the knee extension torque via a counter-movement and the coupling of an arm swing to the knee extension during the propulsion phase.

Therefore, although the jump distance depended on lower limb joint power during the propulsion phase, power was not directly modulated by isokinetic strength. This phenomenon might be derived from the use of strategies that enhance lower limb power, which include a counter-movement and the coupling of an arm swing to the lower limb motion.

References

Ae, M. (1996). Body segment inertia parameters for Japanese children and athletes. Jpn. J. Sports Sci., 15(3): 155-162. (in Japanese)

Ashby, B. M. and Heegaard, J. H. (2002). Role of arm motion in the standing long jump. J. Biomech., 35(12): 1631-1637.

Chang, E., Norcross, M. F., Johnson, S. T., Kitagawa, T., and Hoffman, M. (2015). Relationships between explosive and maximal triple extensor muscle performance and vertical jump height. J. Strength Cond. Res., 29(2): 545-551.

Cheng, K. B. and Chen, W. C. (2005). Optimal standing long jumping simulation from different starting postures. J. Mech. Med. Biol., 5(2): 203-216.

Copić, N., Dopsaj, M., Ivanovic, J., Nesic, G., and Jaric, S. (2014). Body composition and muscle strength predictors of jumping performance: differences between elite female volleyball competitors and non-trained individuals. J. Strength Cond. Res., 28(10): 2709-2716.

Feltner, M. E., Fraschetti, D. J., and Crisp, R. J. (1999). Upper extremity augmentation of lower extremity kinetics during countermovement vertical jump. J. Sports Sci., 17(6): 449-466.

Fukashiro, S. (2000). Biomechanics in stretch-shortening cycle exercise. Jpn. J. Phys. Educ., 45(4): 457-471. (in Japanese)

Fukashiro, S., Besier, T. F., Barret, R., Cochrane, J., Nagano, A., and Lloyd, D. G. (2005). Direction control in standing horizontal and vertical jumps. Int. J. Sport Health Sci., 3: 272-279.

Hara, M., Shibayama, A., Arakawa, H., and Fukashiro, S. (2008). Effect of arm swing direction on forward and backward jump performance. J. Biomech., 41(13): 2806-2815.

Jones, S. L. and Caldwell, G. E. (2003). Mono and biarticular muscle activity during jumping in different directions. J. Appl. Biomech., 19(3): 205-222.

Kraska, J. M., Ramsey, M. W., Haff, G. G., Fethke, N., Sands, W. A., Stone, M. E., and Stone, M. H. (2009). Relationship between strength characteristics and unweighted and weighted vertical jump height. Int. J. Sports Physiol. Perform., 4(4): 461-473.

Kubo, Y. and Ae, M. (2005). Effects of technical training on the takeoff motion and mechanical energy aspect in the standing long jump. Jpn. J Biomech. Sports Exerc., 9(4): 205-216. (in Japanese)

Morris, C. J., Tolfrey, K., and Coppack, R. J. (2001). Effects of short-term isokinetic training on standing long-jump performance in untrained men. J. Strength Cond. Res., 15(4): 498-502.

Nuzzo, J. L., McBride, J. M., Cormie, P., and McCaulley, G. O. (2008). Relationship between countermovement jump performance and multijoint isometric and dynamic tests of strength. J. Strength Cond. Res., 22(3): 699-707.

Paasuke, M., Ereline, J., and Gapeyeva, H. (2001). Knee extension strength and vertical jumping performance in nordic combined athletes. J. Sports Med. Phys. Fitness, 41(3): 354-361.

Roussanoglou, E. N., Georgiadis, G. V., and Boudolos, K. D. (2008). Muscular strength and jumping performance relationships in young women athletes. J. Strength Cond. Res., 22(4): 1375-1378.

Thomas, C., Jones, P. A., Rothwell, J., Chiang, C., and Comport, P. (2015). An investigation into the relationship between maximum isometric strength and vertical jump performance. J. Strength Cond. Res., 29(8): 2176-2185.

Ugarkovic, D., Matavulj, D., Kukolj, M., and Jaric, S. (2002). Standard anthropometric, body composition, and strength variables as predictors of jumping performance in elite junior athletes. J. Strength Cond. Res., 16(2): 227-229.

Wakai, M. and Linthorne, N. P. (2005). Optimum take-off angle in the standing long jump. Hum. Mov. Sci., 24(1): 81-96.

Wells, R. P. and Winter, D. A. (1980). Assessment of signal and noise in the kinematics of normal, pathological and sporting gaits. Hum. Locomotion, 1: 92-93.
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