Mechanical differences in take-off strategies between long jumpers achieving similar distances with different approach velocities

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ABSTRACT

This study presented a detailed biomechanical examination of take-off strategies in two long jumpers who achieved comparable jump distances despite different approach velocities. Two subjects achieving similar distances (approx. 7.70 m) but with different approach velocities (Subject A: 10.21 m/s; Subject B: 9.84 m/s) were compared to elucidate the mechanical differences in their take-off strategies. Subject A, with higher approach velocity, exhibited a larger backward take-off leg angle at touchdown and greater horizontal energy (E_{horiz}) loss in the take-off leg compared to Subject B. Energy analysis revealed that Subject A generated 68% of total effective vertical energy (E_{vert}) generated in the takeoff leg through the direct conversion of E_{horiz} (pivoting mechanism). Conversely, Subject B generated only 50% of E_{vert} via the pivoting mechanism, compensating for the velocity deficit by increasing the contribution of joint work (50%) to the takeoff leg's E_{vert} generation. These results illustrated differing contribution ratios between pivoting mechanism and joint work based on kinematic inputs. In conclusion, this study provided a concrete example showing that distinct mechanical strategies–one relying on velocity conversion and the other on joint work–can successfully lead to equivalent performance outcomes for long jumps.

Keywords: Biomechanics, Pivoting mechanism, Joint work, Energy conversion, Kinetics.

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INTRODUCTION

Long jump is a competitive event in which athletes strive to maximize the horizontal distance by performing a single-leg take-off utilizing the velocity generated during the approach run. Given this characteristic, the take-off phase can be conceptualized as a transducer that converts the kinematic input (approach velocity) into performance output (jump distance).

Muraki et al. (2008) showed in a cross-sectional study that the horizontal velocity (and not vertical velocity) of the centre of mass (CoM) at take-off is the primary determinant of jump distance. Combined with an established significant positive correlation between approach velocity and jump distance (Hay, 1993; Hay et al., 1986; Hay & Miller, 1985; Lees et al., 1994), it can be said that the majority of jump distances are largely dictated by the approach velocity. However, Koyama et al. (2011) showed that similar jump distances could be achieved even when there was a difference of approximately 1 m/s in the approach velocity. Shimizu et al. (2018) conducted a cluster analysis on 29 elite long jumpers and classified them into four types based on the magnitude of approach velocity and take-off angle, indicating that equivalent performance outputs can be attained through different take-off strategies despite variations in approach velocity inputs. This is thought to be caused by differences in strategies during the take-off phase acting as a transducer from approach velocity to jump distance indicating that the choice of take-off strategy in addition to the magnitude of approach velocity, significantly influences the final performance output. Because variability in take-off strategies affects performance, Ramos et al. (2019) highlighted the necessity of selecting an appropriate take-off strategy taking into consideration the possibility of achieving equivalent jump distances with different approach velocity inputs. However, no studies have specifically illustrated the differences in take-off strategies between athletes who achieve similar jump distances using different approach velocity inputs.

Assuming that the long jump is a projectile motion of the body, the determinants of jump distance are CoM height, CoM horizontal velocity, and vertical velocity at the time of take-off (Ward-Smith, 1985). Since CoM height is largely determined by stature, CoM horizontal velocity, and vertical velocity at take-off dictates majority of the jump distance. In addition, the approach velocity which served as input, was also considered. For example, if two athletes achieve similar jump distances with different approach velocity inputs, they are considered to achieve similar jump distances through different take-off strategies. This difference in take-off strategy can be explained by differences in the vertical velocity generation mechanisms. Specifically, we propose that differences in contribution ratio between vertical velocity generation mechanisms that depend on horizontal velocity reduction and do not depend on horizontal velocity reduction determine the differences in take-off strategies.

In terms of the differences in the contribution ratios of the aforementioned vertical velocity generation mechanisms, Sado et al. (2020) demonstrated its quantifiability from mechanical energy perspective, which is a component of velocity. Sado et al. (2020) examined effective energy generation mechanism for vertical height (E_{vert}) during takeoff for running jumps aimed at height. They showed that of the total E_{vert}, the component due to conversion from horizontal energy (E_{horiz}) derived from approach velocity accounts for approximately 35%, and the component derived from joint work of the take-off leg accounts for approximately 40%. The generation of E_{vert} through conversion of E_{horiz} is known as the "*pivoting mechanism*" that converts approach velocity to the vertical direction (Lees et al., 1994), and the magnitude of vertical velocity generated by this mechanism depends on the magnitude of horizontal velocity reduction during take-off (Ramos et al., 2019). In contrast, the component derived from the joint work of the take-off leg can generate E_{vert} without accompanying a reduction in E_{horiz}. If two athletes achieving similar jump distances with different approach velocities are observed, it is predicted that in their E_{vert} generation, the athlete with the lower approach velocity suppresses the reduction of E_{horiz} by increasing the contribution ratio of the component derived from joint work compared to the athlete with the higher approach velocity.

Based on the above, it is predicted that athletes who achieve similar jump distances with different approach velocity inputs in long jump select different strategies for the amount of change in E_{vert} and E_{horiz} during takeoff, and for contribution ratios of the component due to direct conversion from E_{horiz} and the component derived from joint work to the total E_{vert} generated by the take-off leg. Specifically, we hypothesized that: 1) in athletes with higher approach velocity, majority of total E_{vert} generated by the take-off leg is achieved by a pivoting mechanism accompanied by a large reduction in E_{horiz}; and 2) in athletes with lower approach velocity, the reduction in E_{horiz} is small, and the deficit in approach velocity input is compensated by E_{vert} generation through the component derived from joint work of the takeoff leg. However, detailed mechanisms of takeoff strategy in two individuals achieving similar jump distances with different approach velocity inputs have not yet been elucidated.

In this study, using longitudinal measurements, we identified two athletes who achieved similar jump distances despite different approach velocities. Therefore, this study aimed to provide a detailed mechanistic examination of take-off strategies in these two athletes to illustrate how distinct mechanical solutions can lead to equivalent long jump performance outcomes.

MATERIAL AND METHODS

A total of 16 male collegiate long jumpers participated in the study. (Age: 20 ± 2 yrs; Height: 1.75 ± 0.05 m). The participants' personal best records were 7.33 ± 0.30 m (6.88 m – 7.85 m). The estimated jumping distance recorded in this experiment was 6.96 m ± 0.54 m (5.72 m – 7.75 m) (Figure 1). Among the trials performed, two subjects who achieved the highest jump distances (Subject A: 22 yrs; 1.74 m; 67.6 kg; PB: 7.69 m, Subject B: 20 yrs; 1.68 m; 65.5 kg; PB: 7.59 m) attained comparable performance, and these were selected as the trials for analysis. The two selected subjects were national collegiate-level long jumpers.

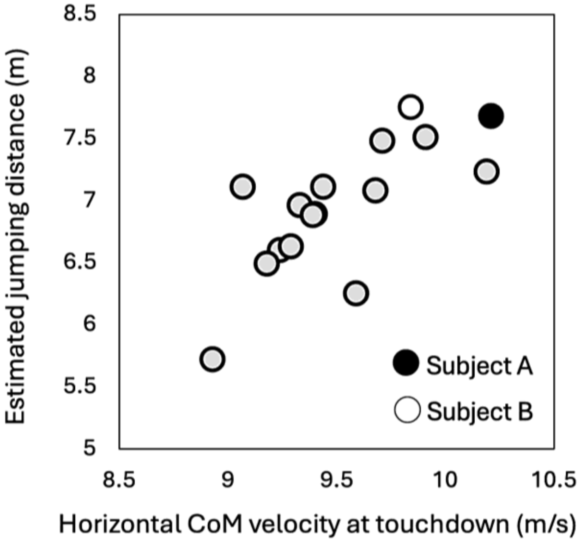

Figure 1. Scatter plot illustrating the relationship between Horizontal CoM velocity at touchdown and estimated jump distance. The two trials selected for detailed analysis (Subject A and Subject B) are highlighted.

For the analysed trials, Subject A had a horizontal CoM velocity at touchdown of 10.21 m/s and an estimated jump distance of 7.75 m, and Subject B had a horizontal CoM velocity at touchdown of 9.84 m/s and an estimated jump distance of 7.68 m. The estimated jumping distance was calculated by utilizing the take-off velocity, take-off height, and take-off angle of the centre of mass (CoM). The reasoning behind this method was to exclude the effects of technical variables occurring after take-off, for instance, landing efficiency (Hubbard, 2000; Linthorne et al., 2005; Mestre, 1990). The estimation formula is as follows:

$$Estimated\ Jumping\ distance\ = \frac{V\ cos\theta}{g}\ (V\ sin\theta + \sqrt{(V\ sin\theta)^{\ 2} + 2gh})$$

V: Resulting CoM velocity at take-off (m/s), θ*:* Take-off angle (deg), *h*: CoM height at take-off (m); *g*: 9.81 m/s^2

Prior to their participation in the study, all subjects were provided an explanation of the purpose and experimental protocol, and all subjects provided written informed consent. The Human Research Ethics Committee of the University of Tsukuba, Japan approved the study protocol (reference number: PE 025-39).

Measurements were conducted five times between September 2021 and July 2025, and 4 of the 16 athletes participated in multiple measurements. The subjects prepared for the experiment as they would for competition and performed from three to four jumps on a force platform (0.9 × 0.6 m, Kistler, Switzerland) covered with an artificial surface, landing in a sand pit. The take-off motions of the subjects were videotaped using a high-speed camera operating at 240 Hz (LUMIX DC-GH5S, Panasonic) for two-dimensional motion analysis. The camera was placed 20 m away from the right side of the runway. The y and z axes of the global coordinate system (GCS) define the anteroposterior and superinferior directions, respectively. The ground reaction force during the take-off phase was sampled using a force platform at 1000 Hz. The forward and backward components of the force platform (Fy) were set parallel to the runway. An LED synchronizer was used to synchronize the video tape data with the ground reaction force data. We defined take-off phase as the instant of foot contact to the instant of toe-off. These instants were determined using vertical ground reaction force data at a threshold of 10 N.

Jumps were analysed in which the participants fully planted their take-off foot on the force platform. For analysis, the trial exhibiting the longest jump distance was chosen from the valid jumps for every participant. The two dimensional coordinates for 23 anatomical landmarks (including the hands, wrists, elbows, shoulders, toes, first metatarsals, heels, ankles, greater trochanters, head, ears, and suprasternale) were acquired by digitizing every video frame using the Frame-DIAS system (DKH Co., Japan), spanning from 10 frames prior to touchdown until 10 frames following toe-off.

Kinematic and kinetic data analyses were conducted using MATLAB 2025b (MathWorks, Inc., Natick, MA, USA). Digitized coordinates were converted to real coordinates using reference markers placed on both sides of the approach lane and the take-off area. The coordinate data were smoothed using a second-order Butterworth digital filter with a cutoff frequency of 10 Hz, and the velocity of the athlete's CoM was calculated via direct differentiation of the coordinate data. The choice of the cutoff frequency was based on residual analysis and visual inspection of power spectra of the coordinate and velocity data (Winter, 1990). Ground reaction force data were smoothed using the same Butterworth low-pass digital filter to prevent artifacts immediately after contact (Bezodis et al., 2013; Bisseling & Hof, 2006).

To calculate linear and angular kinematics, a link model consisting of 14 segments (including hands, forearms, upper arms, feet, shanks, thighs, head, and trunk) was employed. This model was also used with ground reaction force data to estimate the joint torque and power of the take-off leg joints. The take-off leg posterior angle at take-off, projected in the sagittal plane, was determined at the instant of touchdown and was defined as the angle of the segment connecting the ankle joint centre to the hip joint centre (greater trochanter) relative to the vertical axis. An increase in the joint angle in this study indicated that the joint rotated counterclockwise. Similarly, a counterclockwise rotation was defined as a positive segment angle (Figure 1). The mass, location of the CoM, and moment of inertia of the body segments were estimated from the body segment parameters of Japanese athletes developed by Ae (1996).

Velocity of the whole-body CoM was determined as the time derivative of its position. Take-off speed and angle were calculated as the vector norm of the CoM velocity and the arctangent of the vertical versus horizontal CoM velocity components at toe-off, respectively. The posterior angle of the take-off leg was defined and calculated as the inclination of the segment linking the ankle joint to the greater trochanter. The segment angular velocities were calculated as time derivatives of the Segment Angles. The joint torque was calculated using inverse dynamics. The increase in joint torque in this study indicated that the joint rotated counterclockwise. The segment torque power, defined as the rate of energy transfer (inflow or outflow) via joint torque, was determined as the scalar product of segment angular velocities and joint torques (Muraki et al., 2008).

E_{vert} and E_{horiz} in the takeoff leg segments were calculated using the methods described by Sado et al. (2020; 2023). E_{vert} and E_{horiz} are the effective vertical and horizontal energy, respectively, generated by the rotation of the segments. Theoretically, the total E_{vert} and E_{horiz} gained by all body segments should be equivalent to the change in E_{vert} and E_{horiz} of CoM. Mechanically, the changes in E_{vert} and E_{horiz} are consistent with vertical and horizontal external work (time integration of the vertical and horizontal external powers (P_{vert} and P_{horiz})). $P_{vert}$and P_{horiz} in the takeoff leg segments are the products of the vertical/horizontal ground-reaction forces (F_{vert} and F_{horiz}) and vertical/horizontal velocity generated by the rotation of the takeoff leg segments ($\dot{Z}_{segment}$ and $\dot{Y}_{segment}$). The velocity generated by the rotation of a take-off leg segment ($\dot{Z}_{segment}$ and $\dot{Y}_{segment}$) is the value obtained by subtracting the velocity of the joint center at the segment's distal end from the velocity of the segment's CoM. The power calculation method for the three segments of the take-off leg is defined as follows:

$$\begin{aligned}
P_{vert\,foot} &= F_{vert} \cdot \dot{Z}_{foot} \\
P_{horiz\,foot} &= F_{horiz} \cdot \dot{Y}_{foot} \\
P_{vert\,Shank} &= F_{vert} \cdot \dot{Z}_{Shank} \\
P_{horiz\,Shank} &= F_{horiz} \cdot \dot{Y}_{Shank} \\
P_{vert\,Thigh} &= F_{vert} \cdot \dot{Z}_{Thigh} \\
P_{horiz\,Thigh} &= F_{horiz} \cdot \dot{Y}_{Thigh}
\end{aligned}$$

The magnitude of total E_{vert} component gained in the take-off leg via conversion from E_{horiz} was calculated by subtracting the energy inflow to each segment via joint work from the E_{vert} gained in each segment of the take-off leg. If the energy inflow to a segment was negative, we established that the entirety of the E_{vert} gained by that segment was acquired through conversion from E_{horiz}. Furthermore, if the energy inflow to a segment was greater than that gained by that segment, we established that the entire E_{vert} gained by that segment was acquired through the energy inflow to each segment via joint work (Sado et al., 2020).

RESULTS

In both subjects, the foot, shank, and thigh segments were rotated forward throughout the take-off phase (Figure 2). The posterior angle of the take-off leg at touchdown was 35.5° for Subject A 28.2° for Subject B.

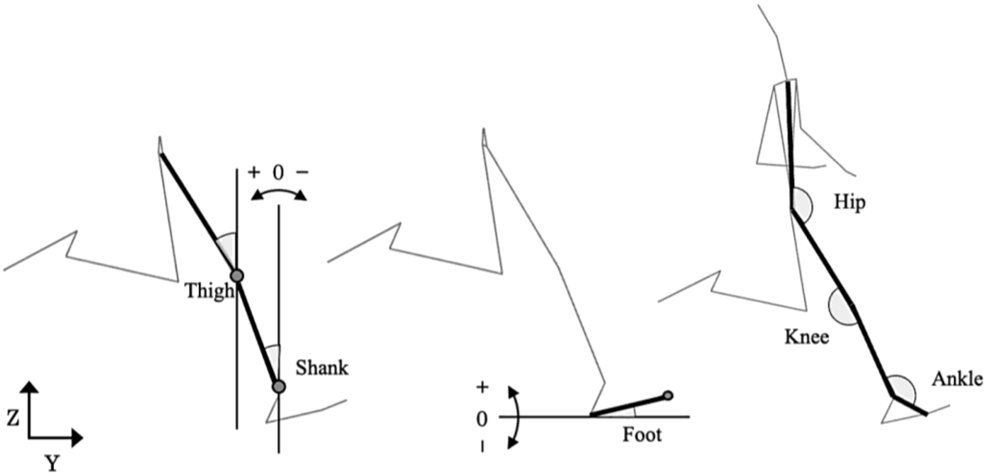

Figure 2. Definition of the segment angle and link model used in this study. Counter-clockwise rotation was defined as positive for segment angles.

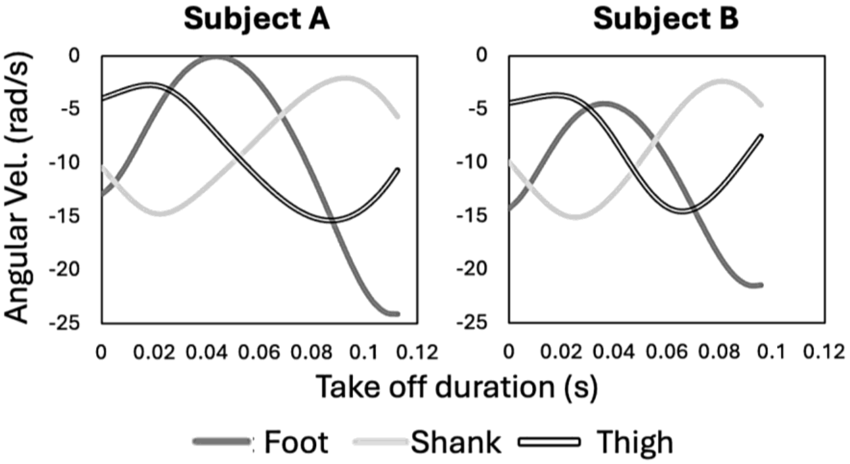

Figure 3. Time courses of the segment angular velocity for the foot, shank, and thigh during the take-off phase for Subject A and Subject B.

Differences were observed between the two subjects in the amount of change in E_{vert} and E_{horiz} generated by the take-off leg during take-off. The total E_{vert} by the entire take-off leg was 3.6 J/kg for Subject A and 3.2 J/kg for Subject B (Figure 4). The total E_{horiz} lost by the entire take-off leg was 5.8 J/kg for Subject A and 4.8 J/kg for Subject B (Figure 5).

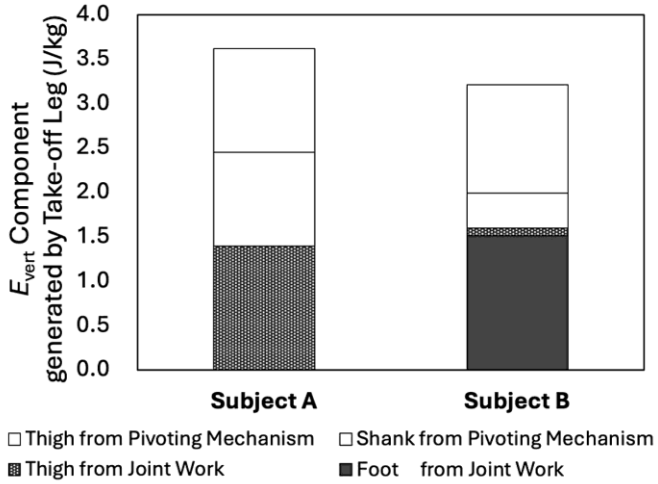

Figure 4. Comparison of effective vertical energy (E_{vert}) generation for Subject A and Subject B. The graph illustrates specific contributions of combined segments and E_{vert} generation mechanisms.

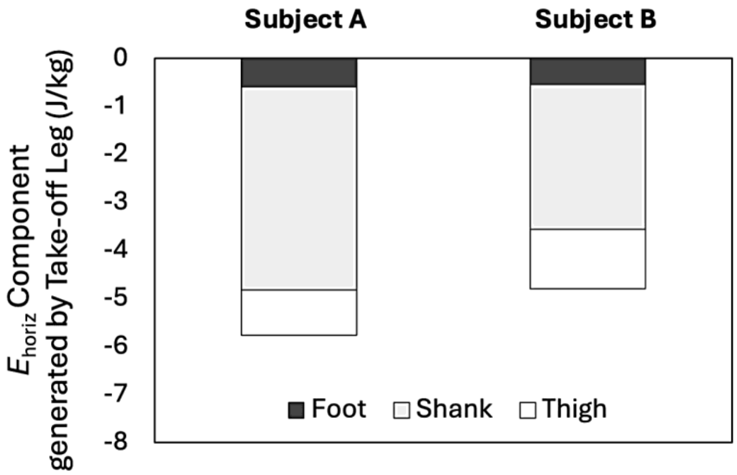

Figure 5. Comparison of the total horizontal energy (E_{horiz}) lost by the takeoff leg during the takeoff phase for Subject A and Subject B.

Furthermore, differences were observed between the two subjects in the contribution ratios of the component due to direct conversion from E_{horiz} and the component derived from joint work to the total E_{vert} generated by the take-off leg (Figure 4). Subject A generated 2.3 J/kg of E_{vert} through direct conversion from E_{horiz} and 1.4 J/kg through the component derived from joint work, generating approximately 68% of the total E_{vert} generated by the take-off leg through direct conversion from E_{horiz}. On the other hand, Subject B generated 1.6 J/kg of E_{vert}through direct conversion from E_{horiz} and 1.6 J/kg through the component derived from joint work, with the contribution ratios of the component due to direct conversion from E_{horiz} and the component derived from joint work being 50% each. Additionally, Subject A showed a pattern of generating large E_{vert} through the component due to direct conversion from E_{horiz} in the first half of the take-off and through the component derived from joint work in the middle of the take-off, whereas Subject B showed a pattern of generating large E_{vert} through the component derived from joint work in the middle of the take-off and through the component due to direct conversion from E_{horiz} in the latter half of the take-off (Figure 6).

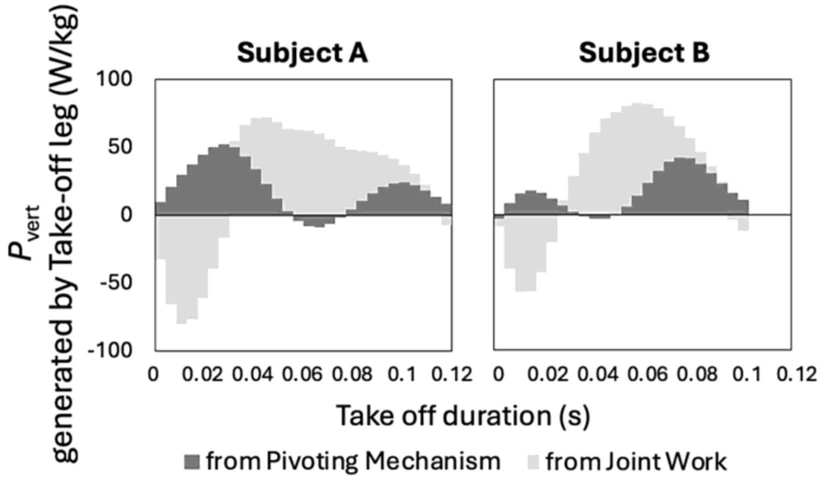

Figure 6. Contribution patterns of the component via the pivoting mechanism and joint work to effective vertical energy (E_{vert}) generation during the takeoff phase. Subject A utilized the component via the pivoting mechanism primarily in the first half, whereas Subject B relied more on joint work in the middle phase.

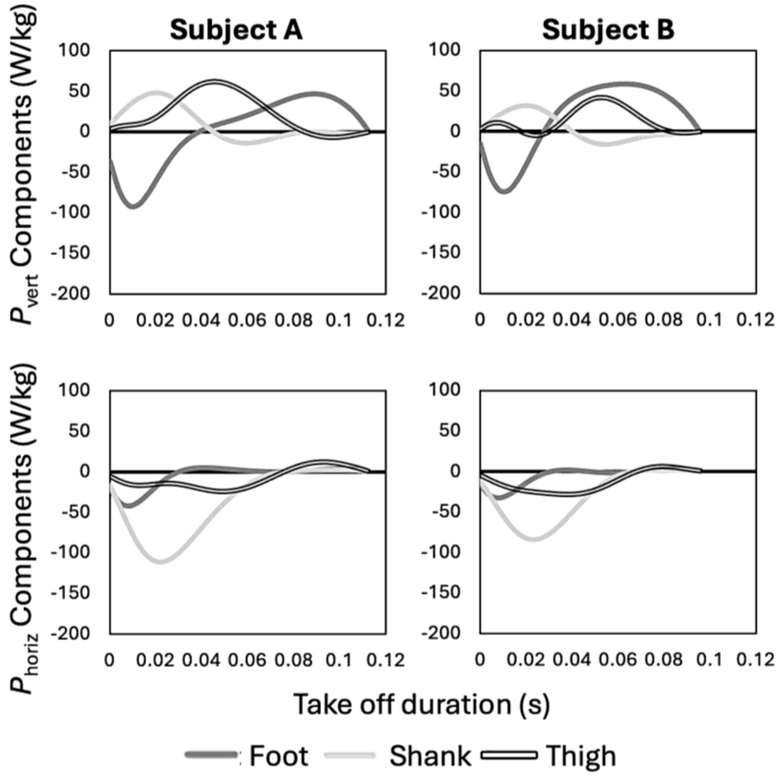

Figure 7. Time series of vertical (P_{vert}, Upper Panel) and horizontal (P_{horiz}, Lower Panel) external powers for the foot, shank, and thigh segments during the takeoff phase.

E_{vert} in the take-off leg of Subject A was the largest in the thigh (2.6 J/kg), followed by the shank (1.0 J/kg). The foot did not gain E_{vert}. In Subject B, E_{vert} was largest in the foot (1.5 J/kg), followed by the thigh (1.3 J/kg) and shank (0.4 J/kg) (Figure 4). For Subject A, P_{vert} was obtained in the order of the shank, thigh, and foot. In Subject B, the foot and thigh simultaneously gained P_{vert} after the shank (Figure 7, Upper Panel).

The E_{horiz} lost in the takeoff leg of both subjects was greatest in the order of the shank, thigh, and foot. This value approximately matched differences in the total E_{horiz} lost by the entire takeoff leg (1.0 J/kg). The acquisition pattern of P_{horiz}showed an approximately similar pattern in both subjects (Figure 7, Lower Panel).

The power flowing into the segments derived from the joint torque exhibited a similar pattern for both the shank and thigh. For the foot, Subject A showed a positive power exertion pattern from the middle to the latter half of the take-off phase, whereas Subject B showed a positive power exertion pattern throughout the entire take-off phase (Figure 8).

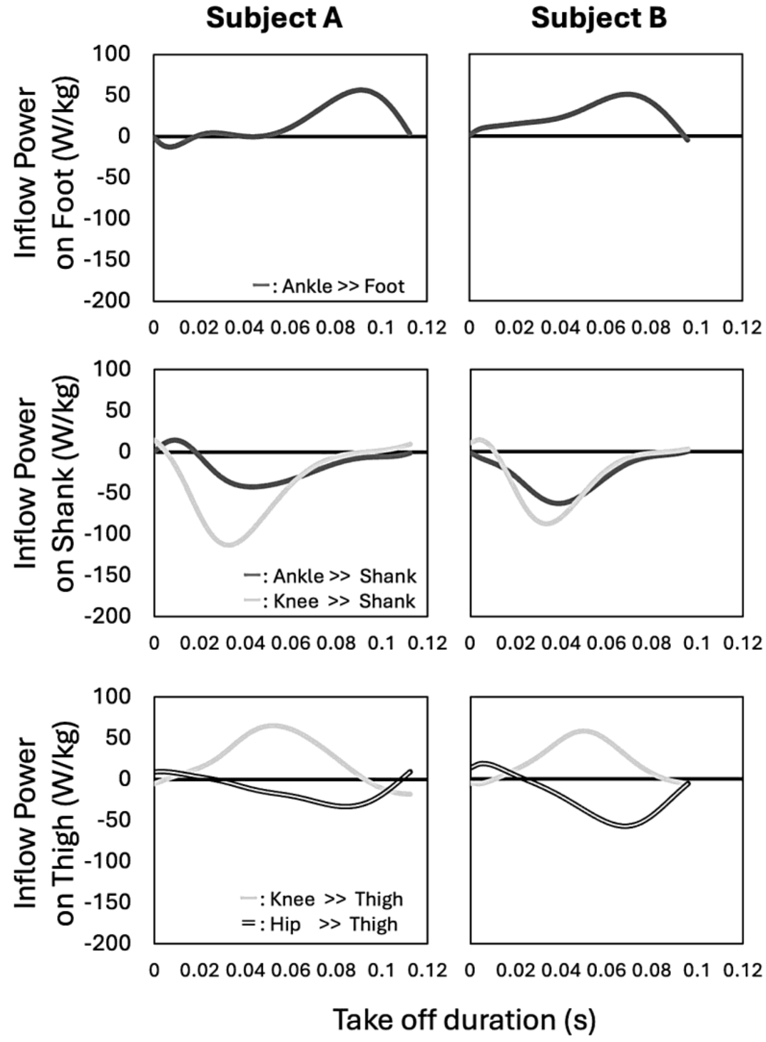

Figure 8. Time series of segment torque power for the foot, shank, and thigh segments. Positive values indicate energy generation (energy outflow), and negative values indicate energy absorption (energy inflow).

DISCUSSION

In this study, we conducted a detailed mechanistic analysis of the take-off strategies in two athletes who achieved similar jump distances despite different approach velocities, focusing on the differences observed during the take-off phase.

The results confirmed that the magnitude of E_{horiz} lost in the take-off leg during take-off differed between the two athletes, and that the contribution ratios of the component due to a pivoting mechanism and the component derived from joint work to the total E_{vert} generated by the take-off leg differed. Based on the above, the hypotheses of this study that 1) in the athlete with higher approach velocity, the majority of the total E_{vert} generated by the take-off leg is achieved by the pivoting mechanism accompanied by a large decrease in E_{horiz} in the take-off leg, and 2) in the athlete with lower approach velocity, the decrease in E_{horiz} in the take-off leg is small, and the deficit in approach velocity input is compensated by E_{vert} generation through the component derived from joint work of the take-off leg, were supported by the observations in these two athletes. This study also illustrated the mechanical differences in the take-off strategies of the two athletes.

This study is the first one to mechanically illustrate the differences in take-off strategies where similar jump distances were achieved with different approach velocity inputs, and targeted trials with a higher performance level compared to other kinetic studies (6.96 ± 0.49 m; 6.95 ± 0.15 m) (Luhtanen & Komi, 1979; Muraki et al., 2008). Although full-approach long jump trials were recorded by 16 athletes in this study, this was the only example where similar jump distances with different approach velocity inputs were observed at a high performance level. Thus, although the trials analysed were limited to two subjects, this study is significant as it presented concrete examples of achieving similar jump distances with different approach velocity inputs in long jumpers with high performance levels and clarified the detailed mechanical mechanisms.

The present analysis was based on two individual cases and was not intended to provide statistically generalizable conclusions. Rather, the findings should be interpreted as a mechanistic illustration of how distinct take-off strategies can lead to equivalent performance outcomes despite the differences in approach velocity conditions.

This study confirmed that the magnitude of E_{horiz} lost in the take-off leg during take-off differed between the two athletes. Subject A, with a higher approach velocity, had the take-off leg tilted backward by 8.5° more at touchdown than Subject B, who had a lower approach velocity. In addition, Subject A had a 1.0 J/kg larger decrease in E_{horiz} in the takeoff leg than Subject B (Figure 5). Furthermore, the magnitude of the total E_{vert} generated by the entire take-off leg was 0.4 J/kg larger in Subject A than in Subject B (Figure 4). These results are consistent with those reported by Ramos et al. (2019), who reported a positive correlation between magnitude of the backward angle of the take-off leg at touchdown and the amount of vertical velocity change during take-off, and between the decrease in horizontal velocity and vertical velocity change during take-off. This confirmed that Subject A, with a higher approach velocity, adopted a strategy of tilting the take-off leg significantly backward at touchdown and generating a large E_{vert} accompanied by large E_{horiz} reduction compared to Subject B.

It was also confirmed that contribution ratios of the component due to the pivoting mechanism and the component derived from joint work to the total E_{vert} generated by the take-off leg differed. In Subject A, with a higher approach velocity, 68% of the total E_{vert} generation by the take-off leg was the component due to direct conversion from E_{horiz} by the pivoting mechanism, and the remaining 32% was the component derived from joint work. In Subject B, with a lower approach velocity, 50% of the total E_{vert} generation by the take-off leg was the component due to direct conversion from E_{horiz} by the pivoting mechanism, and the remaining 50% was the component derived from joint work (Figure 4). Based on the above, it was confirmed that the contribution ratios of the component was attributed to the pivoting mechanism, and the component derived from the joint work to the total E_{vert} generated by the takeoff leg differed.

A factor distinguishing the take-off strategies of the two athletes was the difference in the geometric contribution for each take-off leg segment. Subject A generated all of the total E_{vert} in the take-off leg through the shank and thigh. By contrast, in Subject B, the contribution of the foot was the largest, and the contributions of the shank and thigh were smaller than those in Subject A (Figure 4). This study confirmed that all take-off leg segments rotated forward throughout all phases of take-off (Figure 3). Therefore, "*standing segments*" such as shanks and thighs can generate E_{vert} through their forward rotation by the pivoting mechanism by landing with a backward tilt. Therefore, it is considered that in Subject A, where the backward tilt of the take-off leg at touchdown was large, the E_{vert} generated by the shank and thigh was large. On the other hand, in Subject B, where the backward tilt of the take-off leg at touchdown was small, there was a limit to E_{vert} generation by the pivoting mechanism of the shank and thigh owing to geometric constraints, and this limit may have been compensated for by E_{vert} generation by the foot. Sado et al. (2020) showed that as an E_{vert} generation mechanism in the foot, an SSC action was observed, with energy absorption in the shank due to ankle joint work in the first half of the take-off and energy generation in the foot due to ankle joint work in the latter half of the take-off. In this study, Subject A showed SSC action similar to that in previous studies, but in Subject B, where E_{vert} generation in the foot was large, energy generation in the foot due to ankle joint work was observed from the first half of the take-off (Figure 8). This indicated the possibility that energy generation by active muscle contraction not relying on the SSC of the ankle plantar flexor muscles in the early phase of take-off achieved a large E_{vert} generation derived from ankle joint work in the foot.

CONCLUSIONS

In conclusion, this study presented concrete examples of the differences in take-off strategies between two athletes who achieved similar jump distances with different approach velocity inputs and provided detailed mechanical mechanisms underlying these strategic differences. The mechanical differences between the two cases are characterized as follows:

1) Differences in the amount of E_{horiz} decrease and E_{vert} generation in the take-off leg during take-off was associated with the magnitude of the backward tilt angle at touchdown; and
2) Differences in the contribution ratios of the component due to direct conversion from E_{horiz} and the component derived from joint work in E_{vert} generation in the take-off leg associated with geometric constraints.

AUTHOR CONTRIBUTIONS

All authors meet the criteria for authorship in accordance with established ethical guidelines. Conceptualization: T.M. and K.K.; Methodology: T.M. and K.K.; Software: T.M.; Validation: T.M. and S.F.; Formal analysis: T.M.; Investigation: T.M. and S.F.; Resources: K.K.; Data Curation: T.M.; Writing – original draft preparation: T.M.; Writing – review and editing: T.M., S.F., and K.K.; Visualization: T.M.; Supervision: K.K.; Project administration: K.K. All authors have critically reviewed and approved the final version of the manuscript and agree to be accountable for all aspects of the work.

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CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this manuscript.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, artificial intelligence (AI) tools were used solely to assist with translation and language editing, with the aim of improving clarity and readability. No AI tools were used in the generation of scientific content, including the study design, data collection, analysis, interpretation of results, or the formulation of conclusions. The authors retain full responsibility for the content of the manuscript and confirm its originality, integrity, and accuracy.

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