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ORIGINAL ARTICLE

Shank and thigh kinematics in long-jump take-offs with similar horizontal velocity but different velocity-vector angles: A within-athlete case study

Shuya Fukuchi. *Graduate School of Comprehensive Human Sciences. University of Tsukuba. Tsukuba, Japan.*
Kiyomi Sugiura. *Institute of Health and Sport Sciences. University of Tsukuba. Tsukuba, Japan.*
Taku Masaki. *Graduate School of Comprehensive Human Sciences. University of Tsukuba. Tsukuba, Japan.*
Kiyonobu Kigoshi ✉ **.** *Institute of Health and Sport Sciences. University of Tsukuba. Tsukuba, Japan.*

ABSTRACT

This within-athlete case study compared long-jump take-offs with similar touchdown and toe-off horizontal velocities but different toe-off velocity-vector angles of the trunk-segment center of mass. To generate hypotheses, we described when the higher-angle trial's angle began to exceed the others' and how shank motion, thigh motion, and vertical-velocity components differed. A male long jumper's five take-offs (240 Hz) were digitized twice. Trials 1 and 6 were compared with Trial 5 (longest jump) because, in both digitizations, their horizontal-velocity differences were below the minimal detectable change (MDC), whereas angle differences exceeded it. Differences had to exceed the MDC and one-frame event-shift effects in both digitizations. No angle or vertical-velocity difference was detected at one-third of contact. Trial 5's angle began to exceed the others' in the middle third; at two-thirds, both variables were greater, with over half the toe-off angle difference present. No touchdown thigh-angle difference was detected, but Trial 5's thigh rotated forward more slowly in the middle third and was less forward-inclined at toe-off. Both thigh differences survived a stricter criterion and 6–25-Hz cutoffs (vs. 10-Hz MDC); against cutoff-specific MDCs, differences at two-thirds and the middle-third thigh difference from Trial 6 were lost at higher cutoffs. No shank variable differed in both comparisons; of the vertical-velocity components, only trunk − thigh did. We hypothesize that, among this athlete's trials with similar horizontal velocities, a higher-angle trial has a greater angle and vertical velocity by two-thirds and shows both thigh differences. These post hoc observations imply neither causation nor generality.

Keywords: performance analysis; biomechanics; segment angle; lower limb; reliability; track and field.

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✉ **Corresponding author.** *Institute of Health and Sport Sciences. University of Tsukuba. 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8574, Japan.*
E-mail: kiyonobu.kigoshi.gn@u.tsukuba.ac.jp
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INTRODUCTION

Jump distance in the long jump comprises the take-off, flight, and landing distances. Of these, flight distance is determined mainly by the speed and velocity-vector angle of the whole-body center of mass (CoM) at toe-off of the take-off foot and by the difference in whole-body CoM height between toe-off and landing (Hay et al., 1986). During the take-off, athletes must therefore gain vertical velocity at the expense of some of the horizontal velocity acquired during the approach (Lees et al., 1994) and direct the velocity vector of the whole-body CoM upward.

The gain in vertical velocity during the take-off has been explained mainly in terms of the forward rotation—about the take-off foot—of a single line segment connecting the take-off foot and the whole-body CoM (Graham-Smith & Lees, 2005; Lees et al., 1993; Lees et al., 1994). This line segment shortens after touchdown and then lengthens toward toe-off (Muraki et al., 2005). However, this segment's orientation and length depend not only on the shank and thigh segment angles but also on the positions of the trunk, swing leg, and upper limbs; thus, knowing its orientation and length does not uniquely determine the shank and thigh segment angles. To understand the gain in vertical velocity in terms of take-off-leg motion, it is therefore necessary to examine the take-off leg segment by segment.

Recent studies have divided the take-off leg into segments to examine how the rotation of these segments relates to vertical motion and mechanical energy. In running single-leg jumps performed by high jumpers, movements other than lower-limb extension accounted for 59% of the increase in the mechanical energy directly contributing to jump height during the take-off (Sado et al., 2020). In the long jump, a comparison of two athletes with similar jump distances showed that in the athlete whose take-off leg was more backward-inclined at touchdown, all of the effective vertical mechanical energy generated in the take-off leg was attributable to the motion of the shank and thigh (Masaki et al., 2026). Kigoshi et al. (2026) used the trunk-segment CoM, which excludes the head, upper limbs, and swing leg (except for its greater trochanter), as a representative point for examining the motion from the take-off leg up to the trunk. Using this point, that study analyzed one high-jump trial and one long-jump trial. In the long-jump take-off, the shank rotated forward in the first half and the thigh thereafter, and the relative vertical velocity (the difference in vertical velocity between the CoMs of adjacent segments) that contributed positively to the vertical velocity of the trunk-segment CoM likewise shifted from shank − foot to thigh − shank and trunk − thigh. This sequence reflects the fact that, when a backward-inclined segment rotates forward, its proximal end moves upward relative to its distal end until the segment reaches the vertical, and downward once it passes the vertical (Kigoshi et al., 2026; Sado, 2025). However, because Kigoshi et al. (2026) analyzed only one trial per event, it remains unknown how shank and thigh motion, as well as the components of the vertical velocity of the trunk-segment CoM, differ between trials with different velocity-vector angles. Moreover, the motion of segments making large contributions does not necessarily explain inter-athlete differences. In the high jump, the thigh and shank accounted for the largest shares of the increase in the mechanical energy directly contributing to jump height during the take-off; however, the inter-athlete differences in the total increase were associated with the thorax and foot, whose shares were small (Sado et al., 2024). Identifying the motion that corresponds to differences in velocity-vector angle therefore requires comparing trials with different velocity-vector angles. In such comparisons, because the shank and thigh rotate forward at different times (Kigoshi et al., 2026), examining when the velocity-vector angle of the trial with the greater velocity-vector angle at toe-off begins to exceed that of the other trial would provide a basis for comparing shank and thigh motion from that time onward.

Two factors must be considered when comparing trials with different velocity-vector angles. First, comparisons between athletes are affected by inter-individual differences, such as body dimensions and

take-off strategy. A modeling study showed that the same jump distance can be achieved with different combinations of leg angle at touchdown and leg stiffness (Seyfarth et al., 1999). Second, the velocity-vector angle changes with approach speed (Bridgett & Linthorne, 2006). Because the velocity-vector angle is determined by the ratio of vertical to horizontal velocity, it cannot be determined whether a difference in velocity-vector angle between trials with different horizontal velocities arises from a difference in vertical or horizontal velocity.

Regarding the first factor, differences in body dimensions can be eliminated by comparing trials of the same athlete. For trials performed on the same day, physical fitness and training status are also broadly comparable across trials. Regarding strategy, when different strategies are used for the same task, the group mean may not represent the movement of any individual (Bates, 1996). Analyses comparing multiple trials of the same individual have been called for as a complement to group studies (Bartlett et al., 2007). Such within-individual analyses can be used to generate new hypotheses, which can then be supported or refuted by applying the same analysis to other individuals and comparing the results (Bates, 1996). The present analysis is intended to describe an athlete's movement characteristics to generate hypotheses (athlete-specific profiling).

The influence of the second factor—differences in horizontal velocity—can be reduced by selecting trials with similar horizontal velocities at touchdown and toe-off; a difference in velocity-vector angle at toe-off then mainly reflects a difference in vertical velocity. Even skilled athletes move differently from trial to trial (Bartlett et al., 2007; Preatoni et al., 2013). However, within an individual, performance-related biomechanical variables typically vary within a narrow range (Glazier & Mehdizadeh, 2019); consequently, differences between trials are easily obscured by measurement error. It is therefore necessary to assess measurement reliability and, based on the measurement error, to show both that horizontal velocity is similar and that the differences in the compared variables exceed that error.

Accordingly, the purpose of this study was to compare trials of the same long jumper that had similar horizontal velocities at touchdown and toe-off but different velocity-vector angles of the trunk-segment CoM at toe-off. By describing when the velocity-vector angle of the trial with the greater velocity-vector angle at toe-off began to exceed that of the other trial and how shank and thigh motion, as well as the vertical velocity of the trunk-segment CoM and its components, differed from that time onward, we aimed to generate hypotheses for future testing.

MATERIALS AND METHODS

Participant

One male track-and-field athlete specializing in the long jump participated in this study (age, 23 years; height, 1.74 m; body mass, 67.6 kg; personal best, 7.69 m). The participant was informed of the purpose of the study, the experimental procedures, and the safety considerations, and he provided written informed consent. Data were collected with the approval of the Human Research Ethics Committee of the University of Tsukuba (approval number: PE 025-39) and in accordance with the ethical principles of the Declaration of Helsinki and the applicable laws and regulations of Japan. The participant was also one of the athletes analyzed in previous reports (Kigoshi et al., 2026; Masaki et al., 2026); however, the trials analyzed in the present study differ from those analyzed previously.

Trials and selection of the trials for comparison

The participant performed six full-approach long jumps under near-competition conditions, with sufficient rest between trials. The trials were numbered 1–6 in the order performed. The five trials other than Trial 3, in

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which the participant ran through without taking off, were analyzed using the same procedure. The effective jump distance was defined as the horizontal distance from the toe of the take-off foot at toe-off to the landing mark in the sand closest to the take-off line (6.85, 6.95, 7.39, 7.40, and 6.83 m for Trials 1, 2, 4, 5, and 6, respectively).

Trial 5, which yielded the greatest effective jump distance, served as the reference trial. The effective jump distance was used only for this selection; it was used neither to interpret the compared variables nor to analyze its relationships with them. The trials compared with Trial 5 were those whose absolute differences from Trial 5 were, in both digitizations, below the minimal detectable change (MDC) for the horizontal velocity of the trunk-segment CoM at touchdown and at toe-off and above the MDC for the velocity-vector angle at toe-off (the trunk-segment CoM, the two digitizations, and the MDC are described below). All trials that met these conditions were compared. These conditions were set after the five trials had been analyzed. As a supplementary check (also added after the analysis), the same selection conditions for horizontal velocity and velocity-vector angle were applied to all other pairs among the five trials, whether or not they included Trial 5; for pairs that met them, the main-result variables (defined below) and the thigh segment angle at touchdown were compared using the MDC alone, because the ±1-frame change (defined below) was not evaluated for Trials 2 and 4. Values whose absolute difference was below the MDC are referred to as "similar." This means that the difference cannot be distinguished from measurement error; it implies neither that there was no difference nor that the time course of horizontal velocity during contact was also matched. Figure A1 shows, for the five trials, the horizontal velocities at touchdown and toe-off, the speed and velocity-vector angle at toe-off, and the root-mean-square (RMS) difference (calculated from waveforms normalized to contact time) between each trial's horizontal-velocity waveform and that of Trial 5. The RMS difference was not a selection condition; rather, it served as a reference value to be compared with the range of RMS differences between the two digitizations of the same trial.

Data collection and processing

All trials were recorded with a digital video camera (LUMIX DC-GH5S, Panasonic; lens, LUMIX G X VARIO PZ 14–42 mm; focal length, 42 mm) at 240 frames per second (1 frame ≈ 4.2 ms), with a shutter speed of 1/1000 s and a resolution of 1920 × 1080 pixels. The camera was fixed approximately 20 m lateral to the take-off board, with its optical axis approximately perpendicular to the approach direction. Calibration points were placed at two locations, 2 m before the take-off board (on the runway side) and 2 m beyond it (on the sand-pit side), with one point on each of the near and far sides of the runway at each location (four points in total). The rotation and scale of the coordinates were determined from the 4-m line segment connecting the midpoints of the near- and far-side points at the two locations, and the same scale was applied in the vertical direction. Because all calibration points were used for this determination, reconstruction error was not assessed with independent checkpoints. The scales obtained from the near-side and far-side points (3.62 and 3.91 mm per pixel) differed by approximately 8%, and all landmarks during contact were within the 4-m range. As an indirect index of calibration accuracy, the coefficients of variation for the take-off-leg segment lengths during contact were calculated. To examine the effect of an error in the ratio of the vertical to the horizontal scale, the toe-off velocity-vector angle and its differences from Trial 5 were also recalculated with the vertical coordinates multiplied by 0.98 and 1.02 (i.e., assuming a ±2% error). A two-dimensional sagittal-plane analysis was performed, with the approach direction defined as the positive horizontal direction (X-axis) and the upward direction as the positive vertical direction (Y-axis).

Twenty-three landmarks (the left and right fingertips, wrists, elbows, acromia, toes, first metatarsal heads, heels, lateral malleoli, knee joint centers, and greater trochanters, as well as the tragion, vertex, and suprasternale) were digitized from 10 frames before touchdown to 10 frames after toe-off using a video

motion analysis system (Frame-DIAS VI, DKH). The coordinates were smoothed with a second-order Butterworth low-pass digital filter applied in the forward and reverse directions, and the reduction in the cutoff frequency caused by the two passes was corrected by a factor of 0.802 (Winter, 2009). Before filtering, 20 points were added to each end of the data by point-symmetric reflection about the end point to reduce end effects. Following previous long-jump studies that mainly used 10 Hz on the basis of residual analysis and visual inspection of power spectra (Bridgett & Linthorne, 2006; Linthorne et al., 2005), a cutoff frequency of 10 Hz was used for all trials and landmarks so that differences in filtering would not confound the comparisons between trials. To assess robustness, the cutoff frequency was varied from 6 to 25 Hz in 1-Hz steps. This range extends from below the 8–10 Hz used in previous long-jump studies filmed at 100 Hz (Bridgett & Linthorne, 2006; Graham-Smith & Lees, 2005; Lees et al., 1994) and includes the median optimal cutoff frequencies yielded by the residual analysis described below for all three fitting ranges. At each cutoff frequency, we checked whether the between-trial differences exceeded the MDC at 10 Hz in both digitizations (or, for the horizontal velocities used for selection, remained below it) and whether their signs remained unchanged. In this sensitivity analysis, the MDC used for the judgments was fixed at its 10-Hz value, and the ±1-frame change was not applied. For reference, the differences in the main-result variables and in the velocity-vector angle and vertical velocity at toe-off were also compared with the MDCs calculated from the typical error at each cutoff frequency (hereafter, cutoff-specific MDCs). In addition, for the horizontal and vertical coordinates of the eight landmarks digitized twice (described below; 8 landmarks × 2 coordinates × 5 trials × 2 digitizations = 160 series), the optimal cutoff frequency was determined by residual analysis (Winter, 2009). Three analyst-specified ranges were used to fit a straight line to the residuals (5%–20%, 10%–20%, and 15%–30% of the sampling frequency), and the median for each range is reported. However, because residual analysis selects a cutoff frequency for displacement that is not necessarily optimal for derivatives (Winter, 2009), 10 Hz was used regardless of the results.

Calculated variables

The main variables were the horizontal velocity, vertical velocity, and velocity-vector angle of the trunk-segment CoM, which excludes the head, upper limbs, and swing leg (except for its greater trochanter). The trunk-segment CoM is a representative point for examining the motion from the take-off leg up to the trunk; it is not a substitute for the whole-body CoM in interpreting jump performance. Hereafter, velocity and velocity-vector angle refer to those of the trunk-segment CoM unless otherwise stated. The positions of the segment CoMs (including the trunk-segment CoM) and the whole-body CoM were calculated using the body segment inertia parameters reported by Ae (1996) for Japanese athletes. The trunk was modeled as a single segment connecting the midpoint between the left and right greater trochanters and the suprasternale (excluding the head and upper limbs and not divided into upper and lower parts), with its CoM located at 49.3% of the segment length from the suprasternale (Ae, 1996). The toe-off velocity-vector angle was also calculated with this location changed to 47.7% and 50.9% (i.e., 49.3% ± 1.6% of the segment length, where 1.6% is the standard deviation reported for 49.3% in Ae [1996]). The velocity and velocity-vector angle of the whole-body CoM were also calculated; however, only values from the first digitization are reported because certain landmarks required for this calculation were not digitized in the second digitization. Velocities (including that of the whole-body CoM) were obtained from the smoothed coordinates by five-point numerical differentiation based on a least-squares fit of a second-order polynomial (Savitzky & Golay, 1964). Speed was calculated as the magnitude of the velocity vector.

Segment angles and angular velocities of the take-off leg and trunk

The trunk, thigh, and shank segment angles were defined as the angles between the vertical (Y-axis) and the vectors from the midpoint between the left and right greater trochanters to the suprasternale, from the knee joint center to the greater trochanter, and from the lateral malleolus to the knee joint center, respectively,

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with backward inclination positive (Figure 1). The foot segment angle (the angle between the horizontal and the vector from the heel to the toe, positive when the toe is higher than the heel) was also calculated but is not reported in the Results. Angular velocities were obtained by differentiating the segment angles using the same numerical differentiation method applied to the velocities; forward rotation was defined as negative. The magnitude of the angular velocity of forward rotation is referred to as the forward angular velocity.

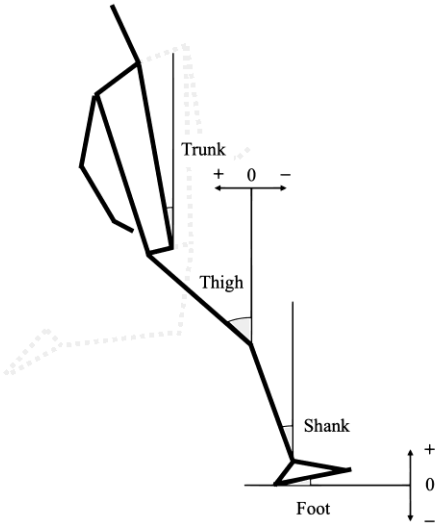


Figure 1. Definition of the segment angles of the take-off leg and trunk. The upper limbs and head are not used to define the angles. The gray dotted lines show the swing leg and the upper limb on the side opposite to that drawn with black solid lines. The trunk, thigh, and shank segment angles are measured relative to the vertical, with backward inclination positive. The foot segment angle is not reported in the Results.

Decomposition of the vertical position and vertical velocity of the trunk-segment CoM

The vertical position of the trunk-segment CoM was expressed as the sum of the absolute vertical position of the foot CoM and the relative vertical positions of shank − foot, thigh − shank, and trunk − thigh (Equation 1). This decomposition follows the same approach as Bobbert and van Ingen Schenau (1988), who partitioned the vertical motion of the body among segments in vertical jumping. The equation and landmark definitions are identical to those in a previous report (Kigoshi et al., 2026).

$$CGH_{foot} + (CGH_{shank} - CGH_{foot}) + (CGH_{thigh} - CGH_{shank}) + (CGH_{trunk} - CGH_{thigh}) = CGH_{trunk} \quad (1)$$

Here, CGH_{trunk}, CGH_{thigh}, CGH_{shank}, and CGH_{foot} denote the vertical positions of the CoMs of the trunk and of the thigh, shank, and foot of the take-off leg, respectively. Each relative vertical position was defined as the vertical position of the proximal segment CoM minus that of the distal segment CoM, and the velocity of each component was obtained by differentiating the corresponding position component. “Absolute” refers to a quantity in the stationary coordinate system, not to a mathematical absolute value. A positive relative vertical velocity indicates that the proximal segment CoM is moving upward relative to the distal one. Equation 1 is an identity and does not indicate a causal contribution of any component.

Definitions of events, phases, and the velocity-vector angle

Touchdown was defined as the first frame in which the take-off foot touched the take-off board, and toe-off as the last frame in which the foot was in contact with the board (this differs by one frame from studies that define toe-off as the first frame after the foot has left the board; Lees et al., 1994; Linthorne et al., 2005). The time from touchdown to toe-off (contact time) was divided into thirds: the early, middle, and late phases.

Dividing contact at events such as maximum knee flexion would make the duration of each phase relative to contact time differ between trials, confounding differences in phase duration with differences in motion; the phases were therefore defined as proportions of contact time. This division does not correspond to any specific mechanical phase. Because the phase boundaries do not coincide with video frames, the early-, middle-, and late-phase means were calculated as the means of the points at 0%–33%, 33%–67%, and 67%–100% of the waveform linearly interpolated at 1% intervals of contact time (101 points). The velocity-vector angle was defined as the angle between the horizontal axis and the velocity vector. The decrease in horizontal velocity during contact was calculated as the horizontal velocity at touchdown minus that at toe-off.

Variables compared

For the velocity-vector angle and vertical velocity, the values at the end of the early phase, the end of the middle phase, and toe-off were compared, and the ratio of the difference in velocity-vector angle at the end of the middle phase to that at toe-off was also calculated. The time at which Trial 5's velocity-vector angle began to exceed that of the compared trial was defined as the first time after touchdown when Trial 5's value exceeded that of the compared trial and remained higher until the earlier of the two trials' toe-offs (this is not the time at which the judgment criterion, defined below, was met). The vertical velocity and its four components were compared using the middle-phase change (the value at the end of the middle phase minus that at the end of the early phase) and the late-phase mean. The decrease in horizontal velocity during contact was also compared. The shank, thigh, and trunk segment angles were compared at touchdown, the end of the middle phase, and toe-off. For the shank and thigh, the middle- and late-phase mean angular velocities, the peak forward angular velocity during contact, and the time at which each segment became vertical (time from touchdown and percentage of contact time) were also compared. For the thigh, the time from thigh vertical to toe-off and the mean angular velocity over that period (the toe-off segment angle divided by that time) were also calculated. Values at specific time points (the ends of the early and middle phases, i.e., at 1/3 and 2/3 of contact time) and event times were obtained by linear interpolation between adjacent frames. The middle-phase changes in the vertical velocity and its four components, as well as the time from thigh vertical to toe-off and the mean angular velocity over that period, were added after the results had been obtained. The decisions to restrict the comparison of the four components to the middle and late phases and to use the early-phase means only as a check for interpreting the middle-phase changes were also made after the results had been obtained. For the same check, the value of the trunk − thigh relative vertical velocity at the end of the early phase was also examined after the results had been obtained.

Reliability assessment and comparison criteria

The same operator digitized the five trials a second time, 1 day after the first digitization, without reference to the coordinates or results obtained in the first digitization. The second digitization covered the seven landmarks used to calculate the trunk-segment CoM and the take-off-leg variables (the toe, heel, lateral malleolus, knee joint center, and greater trochanter of the take-off leg; the greater trochanter of the swing leg; and the suprasternale) and the first metatarsal head. The touchdown and toe-off frames were also identified again. From the differences between the two digitizations, the typical error (TE; standard error of measurement; standard deviation of the differences ÷ $\sqrt{2}$; Hopkins, 2000) and the MDC (the smallest difference that can be regarded as exceeding the measurement error associated with digitization; TE × 1.96 × $\sqrt{2}$; Weir, 2005) were calculated. The MDC does not represent a magnitude that is meaningful for performance. Because the TE was estimated from only five pairs of differences and is therefore imprecise, the judgments were also checked using a criterion in which the coefficient 1.96 × $\sqrt{2}$ was replaced by 3.93 (2.78 × $\sqrt{2}$, based on the two-tailed 95% critical t value with 4 degrees of freedom; hereafter, the 3.93 criterion; Hopkins, 2000). In addition, because uncertainty in identifying touchdown and toe-off can affect the values

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of variables (Bridgett & Linthorne, 2006), the magnitude of change in each variable was calculated for the four cases in which the touchdown or the toe-off frame in the first digitization was individually shifted one frame earlier or later, and the maximum across the four cases and the three trials (Trials 1, 5, and 6) was used (hereafter, the ±1-frame change).

Because observations from the same athlete are not necessarily independent of one another (Reboussin & Morgan, 1996), no statistical tests were performed, and the trials were compared descriptively. When the magnitude of the difference from Trial 5 exceeded both the MDC and the ±1-frame change in both digitizations and the difference had the same sign in both, the variable was reported as having "differed"; otherwise, it was reported that "no difference was detected" (hereafter, the judgment criterion; the latter does not indicate that no difference exists). Variables that differed in both the comparison with Trial 1 and the comparison with Trial 6, with Trial 5 having the greater value in both or the smaller value in both, were treated as the main results (excluding the toe-off velocity-vector angle, which was a selection condition, and the toe-off vertical velocity, whose difference follows from that in the toe-off velocity-vector angle when horizontal velocity is similar). This treatment was decided after the results had been obtained. The early-phase means of the four components are not included in the tables; only the differences that met the judgment criterion are reported in the Results. Unless otherwise stated, values are from the first digitization, and differences were calculated from unrounded values.

RESULTS

For all five trials, the touchdown and toe-off frames identified in the second digitization were identical to those in the first. The coefficients of variation for the foot, shank, and thigh segment lengths during contact were 0.7%–3.6%; changing the ratio defining the position of the trunk-segment CoM altered the toe-off velocity-vector angle by no more than 0.04°; and changing the vertical scale by ±2% altered the differences in the toe-off velocity-vector angle by less than 0.1°. The median optimal cutoff frequency yielded by the residual analysis was 14.4–24.0 Hz, depending on the fitting range. The TEs of the speed and velocity-vector angle at toe-off were 0.14 m/s and 0.43°, respectively, which did not exceed the standard deviations reported for repeated digitization by the same operator (approximately 0.15 m/s for take-off speed and 1.5° for take-off angle; Bridgett & Linthorne, 2006).

Trials 1 and 6 met the selection conditions; they were the first and last trials of the day and the two trials with the shortest effective jump distances among the five trials (Table 1, Figure A1). When the 3.93 criterion was used for the selection, Trials 1 and 6 were again the only trials that met the conditions. The differences from Trial 5 in toe-off speed were also below the MDC for Trials 1 and 6 in both digitizations. Of the RMS differences in the horizontal-velocity waveform between Trial 5 and Trials 1 and 6, only that for the second digitization of Trial 6 (0.269 m/s) exceeded the range obtained when the same trial was digitized twice (0.072–0.235 m/s). Trial 5 had a greater toe-off velocity-vector angle and vertical velocity than Trials 1 and 6. The decrease in horizontal velocity during contact was greater in Trial 5 only in the comparison with Trial 1.

For the whole-body CoM, the between-trial differences in the touchdown horizontal velocity and in the decrease in horizontal velocity during contact were larger than those for the trunk-segment CoM. The toe-off velocity-vector angle of the whole-body CoM was 3.4°–4.3° greater than that of the trunk-segment CoM, and the rank order of the three trials was identical to that for the trunk-segment CoM (Table 1).

Table 1. Effective jump distance; contact time; velocity and velocity-vector angle of the trunk-segment center of mass (at touchdown, at the ends of the early and middle phases, and at toe-off); and velocity and velocity-vector angle of the whole-body center of mass in the three trials.

Variable	Trial 5	Trial 1	Trial 6	Trial 5 − Trial 1	Trial 5 − Trial 6	MDC	±1F
Effective jump distance (m)	7.40	6.85	6.83	0.55	0.57	–	–
Contact time (s)	0.117	0.113	0.117	0.004/0.004	0.000/0.000	–	–
Horizontal velocity at touchdown (m/s)	10.03	9.83	10.01	0.20/0.23	0.02/0.03	0.32	0.18
Horizontal velocity at toe-off (m/s)	8.79	8.94	8.91	−0.15/−0.04	−0.12/−0.23	0.37	0.05
Speed at toe-off (m/s)	9.20	9.17	9.19	0.03/0.13	0.00/−0.10	0.39	0.05
Vertical velocity at toe-off (m/s)	2.71	2.04	2.27	0.68/0.63	0.44/0.47	0.22	0.03
Velocity-vector angle at toe-off (°)	17.17	12.84	14.30	4.33/3.94	2.87/3.24	1.18	0.23
Decrease in horizontal velocity during contact (m/s)	1.24	0.89	1.11	0.35/0.27	0.14/0.26	0.20	0.18
Velocity-vector angle at the end of the early phase (°)	9.17	9.38	10.45	−0.21/−1.98	−1.28/−0.60	2.13	0.68
Velocity-vector angle at the end of the middle phase (°)	13.38	11.19	10.64	2.19/2.25	2.74/1.94	0.95	0.36
Vertical velocity at the end of the early phase (m/s)	1.34	1.38	1.54	−0.04/−0.32	−0.21/−0.15	0.32	0.10
Vertical velocity at the end of the middle phase (m/s)	2.19	1.79	1.76	0.39/0.40	0.43/0.39	0.08	0.06
Whole-body CoM: horizontal velocity at touchdown (m/s)	10.38	10.03	10.21	0.35	0.17	–	–
Whole-body CoM: horizontal velocity at toe-off (m/s)	8.45	8.65	8.60	−0.20	−0.15	–	–
Whole-body CoM: speed at toe-off (m/s)	9.03	9.06	9.05	−0.03	−0.02	–	–
Whole-body CoM: vertical velocity at toe-off (m/s)	3.16	2.67	2.82	0.50	0.35	–	–
Whole-body CoM: decrease in horizontal velocity during contact (m/s)	1.93	1.38	1.61	0.55	0.32	–	–
Whole-body CoM: velocity-vector angle at toe-off (°)	20.52	17.14	18.14	3.39	2.39	–	–

Note. Values are from the first digitization. The effective jump distance is given for reference. Because contact time is determined by the touchdown and toe-off frames, its MDC and ±1F are not shown. Differences are given as first/second digitization and were calculated from unrounded values. The MDC was calculated from the differences between the two digitizations of the five trials. ±1F is the change when the touchdown or toe-off frame was shifted one frame earlier or later (maximum across the three trials). Trials 1 and 6 were the trials whose differences from Trial 5 in horizontal velocity at touchdown and at toe-off were below the MDC, and whose differences in the toe-off velocity-vector angle exceeded the MDC, in both digitizations. The ends of the early and middle phases are the time points at 1/3 and 2/3 of contact time. For the whole-body CoM, only first-digitization values are shown because some of the landmarks required for its calculation were not digitized in the second digitization. MDC, minimal detectable change; ±1F, ±1-frame change; CoM, center of mass.

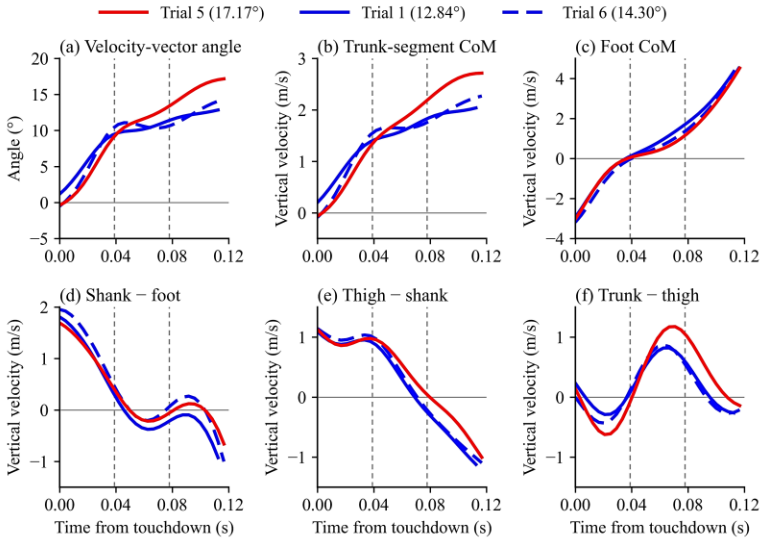


Figure 2. (a) Velocity-vector angle of the trunk-segment CoM, (b) vertical velocity of the trunk-segment CoM, and (c)–(f) the four components of the vertical velocity, whose sum equals (b), in Trial 5 (red solid line), Trial 1 (blue solid line), and Trial 6 (blue dashed line). Values in parentheses in the legend are the toe-off velocity-vector angles. The horizontal axis is the time from touchdown. The gray vertical dashed lines indicate the times dividing Trial 5's contact time into thirds. Each line ends at toe-off. Values are from the first digitization. CoM, center of mass.

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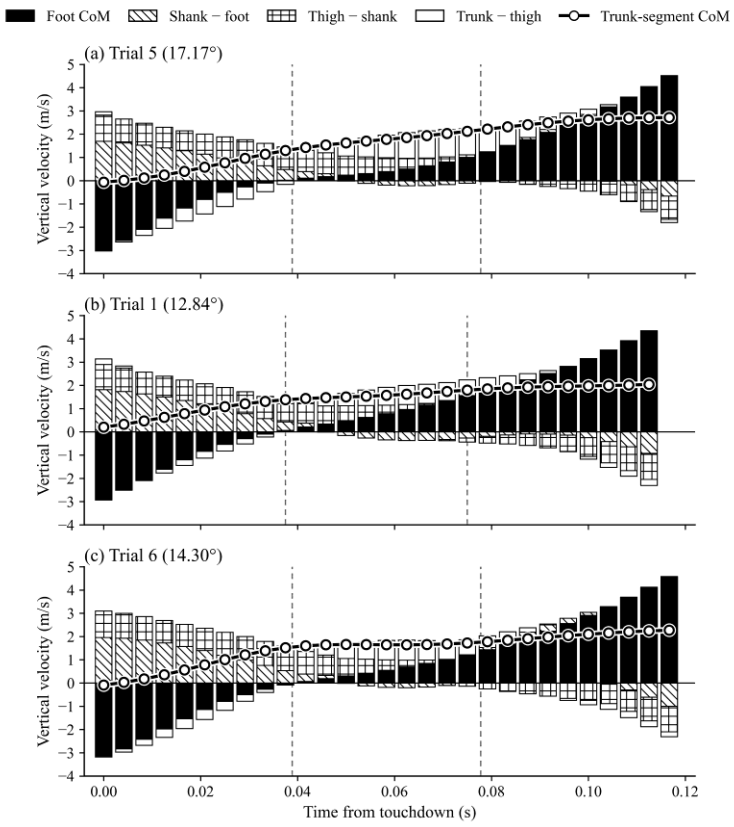


Figure 3. Breakdown of the vertical velocity of the trunk-segment CoM in (a) Trial 5, (b) Trial 1, and (c) Trial 6. Bars show the absolute vertical velocity of the foot CoM (black) and the relative vertical velocities of shank − foot (hatched), thigh − shank (cross-hatched), and trunk − thigh (white); positive values are stacked upward from 0, and negative values are stacked downward from 0. The line with open circles shows the vertical velocity of the trunk-segment CoM, which equals the sum of the four components. Between-trial comparisons are shown in Figure 2 and Table 3. Values in parentheses in the panel titles are the toe-off velocity-vector angles. The horizontal axis is the time from touchdown, and the gray vertical dashed lines indicate the times dividing each trial's contact time into thirds. Values are from the first digitization. CoM, center of mass.

The time series of the velocity-vector angle, the vertical velocity, and its four components are shown in Figure 2, and the breakdown of the vertical velocity in each trial is shown in Figure 3. At the end of the early phase, no difference was detected in either the velocity-vector angle or the vertical velocity (Table 1). In both comparisons, Trial 5's velocity-vector angle began to exceed that of the compared trial in the middle phase (41–62 ms after touchdown). This time differed by up to 21 ms (approximately five frames) between the digitizations but fell within the middle phase in both. However, this time indicates when Trial 5's value began to exceed that of the compared trial, not when a difference meeting the judgment criterion arose. At the end of the middle phase, both the velocity-vector angle and vertical velocity were greater in Trial 5, and the difference in velocity-vector angle was 51%–57% (comparison with Trial 1) and 60%–95% (comparison with Trial 6) of the difference at toe-off (ranges across the two digitizations).

The shank, thigh, and trunk variables are shown in Table 2, and the time series of the segment angles and angular velocities are shown in Figure 4. For the thigh, both the middle-phase forward angular velocity (phase mean) and the forward inclination at toe-off were smaller in Trial 5 in both comparisons. No difference was detected in either comparison for the thigh segment angle at touchdown, the late-phase mean angular velocity of the thigh, or the peak forward angular velocity of the thigh during contact. In all three trials, the thigh became vertical in the late phase (72.0%–77.2% of contact time). Only in the comparison with Trial 1

did Trial 5 exhibit greater backward inclination of the thigh at the end of the middle phase, a later time at which the thigh became vertical, and a shorter time from thigh vertical to toe-off. Only in the comparison with Trial 6 was the mean forward angular velocity of the thigh from vertical to toe-off smaller in Trial 5.

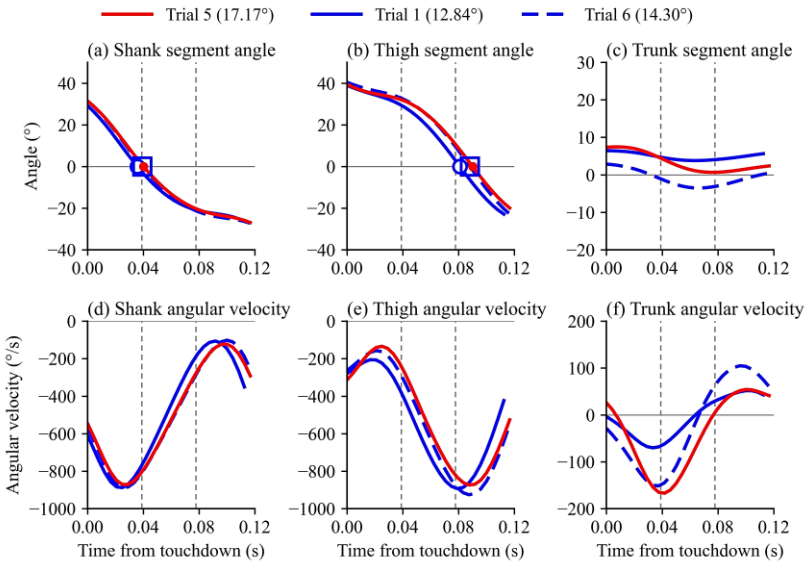


Figure 4. (a)–(c) Segment angles and (d)–(f) angular velocities of the shank, thigh, and trunk in Trial 5 (red solid line), Trial 1 (blue solid line), and Trial 6 (blue dashed line). Angles are positive for backward inclination, and angular velocities are negative for forward rotation (the forward angular velocity in the text is the magnitude of a negative angular velocity; the more negative the value, the greater the forward angular velocity). Values in parentheses in the legend are the toe-off velocity-vector angles. The horizontal axis is the time from touchdown. The gray vertical dashed lines indicate the times dividing Trial 5's contact time into thirds. Each line ends at toe-off. The markers in (a) and (b) indicate when the shank and thigh became vertical (filled circle, Trial 5; open circle, Trial 1; open square, Trial 6). The times at which the segments became vertical are given in Table 2. Values are from the first digitization.

No difference common to the comparisons with Trials 1 and 6 was detected in the shank variables. In all three trials, the shank became vertical around the boundary between the early and middle phases (31.8%–34.5% of contact time). The middle-phase angular velocity of the shank (phase mean) and the time at which the shank became vertical differed only in the comparison with Trial 1 (in Trial 5, the forward angular velocity was greater and the shank became vertical later).

The trunk segment angle differed in both comparisons at the end of the middle phase and at toe-off; however, the direction of the difference was opposite in the two comparisons (in Trial 5, the trunk was inclined less backward than in Trial 1 and more backward than in Trial 6). At touchdown, the trunk was inclined more backward in Trial 5 only in the comparison with Trial 6.

The vertical velocity and its four components are shown in Table 3. The middle-phase change in vertical velocity was greater in Trial 5 in both comparisons. Of the four components, only the trunk − thigh relative vertical velocity differed in the middle-phase change, being greater in Trial 5 in both comparisons. For the early-phase means of the four components, only the trunk − thigh relative vertical velocity in the comparison with Trial 1 differed, being smaller in Trial 5 (Trial 5, −0.36 m/s; Trial 1, −0.12 m/s; differences of −0.24 and −0.31 m/s in the two digitizations; MDC, 0.14 m/s; ±1-frame change, 0.05 m/s). No difference was detected in either comparison for the value of this component at the end of the early phase, from which the middle-phase change is calculated, because the differences did not exceed the MDC in the first digitization

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(differences in the first and second digitizations of −0.10 and −0.37 m/s in the comparison with Trial 1 and −0.19 and −0.32 m/s in the comparison with Trial 6; MDC, 0.30 m/s).

Table 2. Segment angles of the shank, thigh, and trunk; angular velocities of the shank and thigh; times at which the shank and thigh became vertical; and time from thigh vertical to toe-off in the three trials.

Variable	Trial 5	Trial 1	Trial 6	Trial 5 − Trial 1	Trial 5 − Trial 6	MDC	±1F
Shank segment angle at touchdown (°)	31.5	29.2	31.4	2.3/3.7	0.1/1.0	1.2	2.7
Shank segment angle at the end of the middle phase (°)	−20.2	−20.3	−21.2	0.1/0.5	1.0/1.8	1.2	0.8
Shank segment angle at toe-off (°)	−26.9	−26.3	−27.2	−0.6/−0.8	0.3/0.1	0.5	1.6
Middle-phase mean angular velocity of the shank (°/s)	−547	−504	−553	−43/−63	6/−8	24	31
Late-phase mean angular velocity of the shank (°/s)	−181	−174	−165	−7/−24	−16/−42	25	23
Time at which the shank became vertical (ms)	40.2	35.8	39.3	4.4/5.9	0.9/2.6	1.5	4.2
Time at which the shank became vertical (%)	34.5	31.8	33.7	2.7/4.0	0.8/2.2	1.3	2.6
Peak forward angular velocity of the shank (°/s)	871	887	887	−17/−4	−16/−21	24	–
Thigh segment angle at touchdown (°)	39.4	39.0	40.4	0.4/1.1	−1.0/−0.5	0.5	1.4
Thigh segment angle at the end of the middle phase (°)	10.7	5.4	9.5	5.3/5.2	1.1/2.6	1.6	2.5
Thigh segment angle at toe-off (°)	−19.9	−22.9	−22.8	2.9/3.4	2.9/3.8	0.9	2.5
Middle-phase mean angular velocity of the thigh (°/s)	−548	−650	−595	103/81	47/47	25	32
Late-phase mean angular velocity of the thigh (°/s)	−775	−740	−819	−35/−22	45/28	26	50
Time at which the thigh became vertical (ms)	90.1	81.0	88.2	9.1/8.9	1.9/3.1	1.2	4.2
Time at which the thigh became vertical (%)	77.2	72.0	75.6	5.3/5.0	1.6/2.7	1.1	2.9
Time from thigh vertical to toe-off (ms)	26.6	31.5	28.5	−5.0/−4.7	−1.9/−3.1	1.2	4.2
Mean angular velocity of the thigh from vertical to toe-off (°/s)	−750	−725	−801	−25/5	51/52	28	41
Peak forward angular velocity of the thigh (°/s)	874	892	926	−19/−3	−52/−16	38	–
Trunk segment angle at touchdown (°)	7.3	6.5	2.9	0.9/−0.8	4.5/3.1	1.7	0.1
Trunk segment angle at the end of the middle phase (°)	0.7	4.0	−3.1	−3.3/−2.4	3.8/2.7	1.7	0.2
Trunk segment angle at toe-off (°)	2.4	5.6	0.5	−3.3/−3.3	1.9/2.2	1.0	0.3

Note. Segment angles are relative to the vertical, with backward inclination positive. Angular velocities are negative for forward rotation (only the peak values are shown as positive magnitudes of forward rotation). The end of the middle phase is the time point at 2/3 of contact time. The times at which the segments became vertical are given as the time from touchdown (ms) and as a percentage of contact time (%). The mean angular velocity of the thigh from vertical to toe-off is the toe-off thigh segment angle divided by the time from thigh vertical to toe-off. One frame is approximately 4.2 ms. Because the peak angular velocities did not change when the touchdown or toe-off frame was shifted by one frame, ±1F is shown as "–". Values and differences are presented as in Table 1. MDC, minimal detectable change; ±1F, ±1-frame change.

For the late-phase mean, both the vertical velocity and the trunk − thigh relative vertical velocity were greater in Trial 5 in both comparisons. For the other components, no difference was detected in either comparison for the absolute vertical velocity of the foot CoM or the shank − foot relative vertical velocity. The thigh − shank relative vertical velocity, which was negative in all three trials, was smaller in magnitude in Trial 5 only in the comparison with Trial 1.

We examined whether the differences were maintained when the 3.93 criterion was applied and when the cutoff frequency was varied from 6 to 25 Hz (with the differences compared with the MDC at 10 Hz). Among the main results, the differences in the velocity-vector angle and vertical velocity at the end of the middle phase, the middle-phase mean angular velocity of the thigh, the toe-off thigh segment angle, and the late-phase means of the vertical velocity and the trunk − thigh relative vertical velocity were maintained in all cases. The same was true of the differences in the toe-off velocity-vector angle, which was used as a selection condition, and in the toe-off vertical velocity. However, when the cutoff-specific MDCs were used instead, the only main results for which the differences exceeded these MDCs at all cutoff frequencies were the toe-off thigh segment angle and the late-phase means of the vertical velocity and the trunk − thigh relative vertical velocity. At higher cutoff frequencies, the differences fell below these MDCs in at least one digitization

for the velocity-vector angle and vertical velocity at the end of the middle phase (both comparisons), for the middle-phase mean angular velocity of the thigh (comparison with Trial 6), and for the toe-off velocity-vector angle and vertical velocity (comparison with Trial 6); the lowest cutoff frequency at which this occurred ranged from 14 to 23 Hz, depending on the variable and comparison (Supplementary Material). Unlike the other main results, the differences in the middle-phase changes (in the vertical velocity and the trunk − thigh relative vertical velocity) were not maintained under the 3.93 criterion, at certain cutoff frequencies, or both. Among the variables that differed in only one comparison, the same was true of the decrease in horizontal velocity during contact and the late-phase mean of the thigh − shank relative vertical velocity in the comparison with Trial 1 and of the mean forward angular velocity of the thigh from vertical to toe-off in the comparison with Trial 6. In addition, the difference from Trial 1 in the trunk segment angle at the end of the middle phase was not maintained under the 3.93 criterion. All other differences were maintained in all of these cases (with the differences compared with the MDC at 10 Hz). Note that the difference from Trial 6 in the decrease in horizontal velocity during contact exceeded the 10-Hz MDC in both digitizations at 16 Hz and above. Certain differences from Trial 5 in the horizontal velocity at touchdown or toe-off exceeded the 10-Hz MDC at 14 Hz and above.

Table 3. Late-phase means and middle-phase changes in the vertical velocity of the trunk-segment center of mass and its four components in the three trials (m/s).

Variable	Trial 5	Trial 1	Trial 6	Trial 5 − Trial 1	Trial 5 − Trial 6	MDC	±1F
Vertical velocity: late-phase mean	2.53	1.94	2.04	0.59/0.65	0.49/0.54	0.10	0.05
Vertical velocity: middle-phase change	0.85	0.41	0.21	0.44/0.71	0.63/0.54	0.38	0.06
Absolute vertical velocity of the foot CoM: late-phase mean	2.66	2.78	2.79	−0.13/−0.01	−0.14/−0.03	0.15	0.32
Absolute vertical velocity of the foot CoM: middle-phase change	1.10	1.49	1.39	−0.39/−0.03	−0.29/−0.10	0.25	0.13
Shank − foot relative vertical velocity: late-phase mean	−0.06	−0.30	−0.05	0.23/0.11	−0.02/0.04	0.16	0.14
Shank − foot relative vertical velocity: middle-phase change	−0.46	−0.63	−0.40	0.17/−0.25	−0.06/−0.26	0.39	0.18
Thigh − shank relative vertical velocity: late-phase mean	−0.43	−0.65	−0.68	0.23/0.22	0.26/0.13	0.17	0.10
Thigh − shank relative vertical velocity: middle-phase change	−0.93	−1.11	−1.22	0.18/0.13	0.29/0.16	0.19	0.07
Trunk − thigh relative vertical velocity: late-phase mean	0.37	0.11	−0.02	0.26/0.34	0.39/0.41	0.07	0.11
Trunk − thigh relative vertical velocity: middle-phase change	1.13	0.65	0.43	0.47/0.87	0.69/0.74	0.39	0.20

Note. The early, middle, and late phases are the thirds of each trial's contact time from touchdown to toe-off. The late-phase rows show phase means. The middle-phase change is the value at the end of the middle phase minus that at the end of the early phase. Each relative vertical velocity is the vertical velocity of the proximal segment CoM minus that of the distal segment CoM. The sum of the four components equals the vertical velocity of the trunk-segment CoM. Values and differences are presented as in Table 1. MDC, minimal detectable change; ±1F, ±1-frame change; CoM, center of mass.

Among the other pairs of trials, Trials 4 and 6 and Trials 2 and 1 also met the selection conditions (Supplementary Material). When the differences were judged against the MDC alone, in both pairs the trial with the greater toe-off velocity-vector angle (Trial 4 and Trial 2, respectively) had a greater vertical velocity at the end of the middle phase, a smaller middle-phase forward angular velocity of the thigh, and greater late-phase means of the vertical velocity and the trunk − thigh relative vertical velocity. For Trials 2 and 1, however, no difference was detected in the toe-off thigh segment angle, in the middle-phase changes in the vertical velocity and the trunk − thigh relative vertical velocity, or, in the first digitization, in the velocity-vector angle at the end of the middle phase. In both pairs, the thigh at touchdown was inclined more backward in the trial with the greater toe-off velocity-vector angle.

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DISCUSSION

In this study, we compared trials of the same athlete that had similar horizontal velocities at touchdown and toe-off but different velocity-vector angles at toe-off. The new findings from these comparisons can be summarized in three points. First, beyond the toe-off velocity-vector angle difference, we identified when Trial 5's velocity-vector angle began to exceed those of the compared trials: this occurred in the middle phase, and at the end of that phase, both the velocity-vector angle and vertical velocity were greater in Trial 5. Second, the take-off-leg differences common to the two comparisons were detected in the thigh but not in the shank. Third, the thigh differences were detected not in posture at touchdown but in rotation after touchdown (the middle-phase forward angular velocity) and in posture at toe-off (the forward inclination), both of which were smaller in Trial 5. In addition, among the vertical-velocity components, the trunk − thigh relative vertical velocity exhibited a difference common to the two comparisons. In what follows, after examining the horizontal-velocity conditions of the three trials, we discuss these three points and the relation between thigh motion and vertical velocity, and we finally comment on the trunk − thigh relative vertical velocity as a supplementary observation.

Because the three trials had similar horizontal velocities at touchdown and toe-off, the difference in the toe-off velocity-vector angle can be considered to correspond mainly to the difference in the vertical velocity of the trunk-segment CoM. However, because Trial 5 also had a greater decrease in horizontal velocity during contact than Trial 1, the difference in vertical velocity in this comparison cannot be interpreted separately from the difference in the decrease in horizontal velocity. Similar caution is needed in the comparison with Trial 6, because the difference in the decrease in horizontal velocity exceeded the 10-Hz MDC in the second digitization (Table 1) and in both digitizations at cutoff frequencies of 16 Hz and above (Results).

At the end of the middle phase, Trial 5's velocity-vector angle was already greater in both comparisons. Therefore, in these comparisons, it seems appropriate to include the middle phase, in addition to the period immediately before toe-off, when examining the shank and thigh motion that corresponded to the differences in velocity-vector angle.

By comparing the shank and thigh separately, this study found that the take-off-leg differences common to the two comparisons were detected in the thigh but not in the shank. This distinction cannot be made with variables that treat the take-off leg as a single line segment connecting the take-off foot and the whole-body CoM (Graham-Smith & Lees, 2005; Lees et al., 1993; Lees et al., 1994). In the high jump, the shank, together with the thigh, accounted for a large share of the increase in the mechanical energy directly contributing to jump height during the take-off; however, the segments that accounted for a large share did not necessarily explain the inter-athlete differences (Sado et al., 2024). Although the variables evaluated differ, in the present within-athlete comparisons, too, no difference common to the two comparisons was detected in the shank. The middle phase, during which Trial 5's velocity-vector angle began to exceed those of the compared trials, started around the time the shank became vertical and ended before the thigh became vertical. The finding that the forward angular velocity of the thigh differed in the middle phase in both comparisons is consistent with the sequence in which the shank rotates forward in the first half of the take-off and the thigh rotates forward thereafter (Kigoshi et al., 2026). However, this indicates only that the difference in thigh rotation was observed during the period when Trial 5's velocity-vector angle began to exceed those of the compared trials; it does not show that the difference in thigh rotation produced the difference in vertical velocity.

The thigh differences common to the two comparisons were detected not in posture at touchdown but in rotation after touchdown (the middle-phase forward angular velocity) and in the forward inclination at toe-off.

A modeling study showed that jump distance depends on both the leg angle at touchdown (the orientation of the line connecting the CoM and the foot) and leg stiffness (Seyfarth et al., 1999); however, no difference common to the two comparisons was detected for the thigh or shank segment angle at touchdown. Note that, when the differences were judged against the MDC alone, in both of the other pairs of this athlete's trials that met the selection conditions, the thigh at touchdown was inclined more backward in the trial with the greater toe-off velocity-vector angle (Results); thus, the lack of a detected difference in thigh posture at touchdown may be specific to the comparisons of Trial 5 with Trials 1 and 6. In both comparisons, Trial 5 exhibited a smaller forward inclination of the thigh at toe-off. The manner in which this occurred differed between the comparisons: compared with Trial 1, Trial 5 had a shorter time from thigh vertical to toe-off, whereas compared with Trial 6, it had a smaller mean forward angular velocity over that period. Thus, no difference common to the two comparisons was detected for the time from thigh vertical to toe-off or for the mean forward angular velocity over that period. Note that the mean forward angular velocity is the angle through which the thigh rotated from vertical to toe-off divided by that time, so the toe-off thigh segment angle, the time from thigh vertical to toe-off, and the mean forward angular velocity over that period are not independent findings. In addition, because the toe-off thigh segment angle also reflects the cumulative rotation during the middle phase, it is related to the middle-phase forward angular velocity.

The differences in the middle-phase forward angular velocity of the thigh and in its forward inclination at toe-off can be related geometrically to the vertical motion of the greater trochanter relative to the knee. If the thigh is regarded as a segment of constant length, this relative motion is determined by the thigh segment angle and the angular velocity of the thigh. During the middle phase, the thigh was still inclined backward, so its forward rotation moved the greater trochanter upward relative to the knee; at a given thigh angle, a smaller forward angular velocity raises the greater trochanter relative to the knee more slowly. In the late phase, the thigh was already past the vertical for most of the phase, and forward rotation of the thigh after it passes the vertical moves the greater trochanter downward relative to the knee (Kigoshi et al., 2026; Sado, 2025). The smaller forward inclination of the thigh at toe-off in Trial 5 therefore means that the greater trochanter descended less relative to the knee between thigh vertical and toe-off. Other things being equal, this downward motion acts to reduce the vertical velocity of the trunk-segment CoM. However, the vertical velocity of the greater trochanter is the sum of the vertical velocity of the knee joint center and the vertical velocity of the greater trochanter relative to the knee joint center, and the vertical velocity of the trunk-segment CoM also depends on the trunk segment motion. Moreover, the toe-off thigh segment angle indicates only the amount of descent between thigh vertical and toe-off, and the magnitude of its effect also depends on the time course of the rotation and on the shank and trunk motion. Therefore, the smaller middle-phase forward angular velocity of the thigh alone cannot explain Trial 5's greater vertical velocity at the end of the middle phase, and the present results cannot determine whether the smaller descent of the greater trochanter in the late phase produced the difference in the vertical velocity of the trunk-segment CoM.

Of the four components of the vertical velocity of the trunk-segment CoM, only the trunk − thigh relative vertical velocity exhibited a difference common to the two comparisons. Because the components represent only the breakdown given by Equation 1 and the cause of the difference in vertical velocity cannot be identified from the component differences, we treat this difference not as direct evidence for the main hypothesis but as a supplementary observation. The difference in its late-phase mean was maintained under the 3.93 criterion and across cutoff frequencies, whereas the difference in its middle-phase change was not always maintained. In the comparison with Trial 1, the early-phase mean of this component was smaller in Trial 5. However, the early-phase mean is not the value from which the middle-phase change is calculated, and no difference was detected in either comparison for the value at the end of the early phase, which was additionally examined. In the long-jump trial analyzed by Kigoshi et al. (2026), the shank − foot relative vertical

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velocity contributed positively to the vertical velocity of the trunk-segment CoM in the first half of the take-off, and the thigh − shank and trunk − thigh relative vertical velocities did so thereafter. For the late-phase mean, the trunk − thigh relative vertical velocity was greater in Trial 5 in both comparisons, and the thigh − shank relative vertical velocity, which was negative in all three trials, was smaller in magnitude in Trial 5 only in the comparison with Trial 1. These differences are consistent with the smaller descent of the greater trochanter relative to the knee after the thigh became vertical and, in the comparison with Trial 1, with the later time at which the thigh became vertical. However, the thigh − shank relative vertical velocity also reflects shank rotation, and its difference was not maintained under the 3.93 criterion or at certain cutoff frequencies. Moreover, because the lower end of the trunk segment was defined as the midpoint between the left and right greater trochanters, the trunk − thigh relative vertical velocity reflects not only the motion of the trunk segment but also any elevation of the pelvis on the swing-leg side. In running single-leg jumps for distance performed by long jumpers, elevation of the pelvis on the swing-leg side increased vertical kinetic energy without reducing horizontal kinetic energy (Sado et al., 2023), but this motion cannot be examined with the two-dimensional analysis used here. In the present decomposition, the portion of the component differences attributable to thigh rotation was not separated, and the component differences do not show that these differences were the mechanical cause of the difference in the vertical velocity of the trunk-segment CoM.

From a practical perspective, the middle-phase forward angular velocity of the thigh and the toe-off thigh segment angle are candidate variables for characterizing differences in this athlete's toe-off velocity-vector angle. However, what this study showed was a correspondence, across trials, between these variables and the toe-off velocity-vector angle. We did not examine how the differences in the toe-off velocity-vector angle (2.87°–4.33°) affect jump distance or how the toe-off vertical velocity and the decrease in horizontal velocity during contact change when thigh motion is altered. Thus, the present results provide no basis for treating the middle-phase forward angular velocity of the thigh or the toe-off thigh segment angle as targets to be changed in technical coaching. In addition, because differences in vertical velocity may be accompanied by differences in the decrease in horizontal velocity, it is advisable to check the two together.

Although thigh posture at toe-off can be observed visually in lateral-view video, comparing the thigh segment angle, the middle-phase angular velocity of the thigh, and the velocity of the trunk-segment CoM with the same judgment criterion used in this study requires not only digitization and computation but also an evaluation of measurement error. Future studies should examine whether the correspondence of the thigh segment angle and angular velocity with the velocity-vector angle is also observed in this athlete's trials with similar horizontal velocities at touchdown and toe-off on other days. Because differences between trials of the same athlete can be as small as the measurement error, the comparison conditions and the judgment of between-trial differences, including those in the decrease in horizontal velocity during contact, will then need to be based on measurement error. If a sufficient number of trials were recorded for each condition, waveform-based tests such as statistical parametric mapping (Pataky, 2010) could also complement such comparisons.

This study has some limitations. First, the data consisted of three trials from one athlete on a single day, and the results cannot be generalized to other trials from this athlete or to other athletes. Second, the conditions for selecting the compared trials and the treatment of differences common to the two comparisons as the main results were decided after the analysis. Because both comparisons used Trial 5 as the reference, the observed differences may reflect motion specific to Trial 5. Moreover, Trials 1 and 6 were the first and last trials of the day and also the two trials with the shortest effective jump distances. The observed differences may therefore also be confounded by differences in readiness or fatigue associated with trial order, and by differences in motion associated with trials of shorter effective jump distance. Furthermore, because the MDC

is a criterion based on measurement error, it cannot be determined whether the observed differences exceed this athlete's usual trial-to-trial variability. In addition, the two other pairs that met the selection conditions (Results) were judged against the MDC alone, that is, not as strictly as the comparisons of Trial 5 with Trials 1 and 6 were; even so, in one of them (Trials 2 and 1), not every item of the hypothesis presented in the Conclusions showed a difference exceeding the MDC. Moreover, neither pair conformed to the finding that the thigh differences were detected in rotation after touchdown but not in posture at touchdown.

Third, the judgment of similar horizontal velocity was based on the touchdown and toe-off values calculated from coordinates filtered at 10 Hz. In the second digitization, the RMS difference between the horizontal-velocity waveforms of Trials 5 and 6 exceeded the range obtained when the same trial was digitized twice. Additionally, at higher cutoff frequencies, certain differences in horizontal velocity at touchdown or toe-off exceeded the 10-Hz MDC (Results). Therefore, the differences in velocity-vector angle may also reflect differences in horizontal velocity. Furthermore, as described in the Results, when the cutoff-specific MDCs were used, the differences from Trial 6 in the toe-off velocity-vector angle and vertical velocity, the differences in the velocity-vector angle and vertical velocity at the end of the middle phase (both comparisons), and the difference from Trial 6 in the middle-phase mean angular velocity of the thigh fell below these MDCs in at least one digitization at higher cutoff frequencies. Thus, the selection of the compared trials and the parts of the hypothesis concerning the end of the middle phase and the middle-phase angular velocity of the thigh may also depend on how the cutoff frequency is chosen, and the support for these parts of the hypothesis is correspondingly limited. Fourth, the whole-body CoM values are reference values for which reliability was not evaluated, and it cannot be determined whether horizontal velocity was also similar for the whole-body CoM. In addition, the trunk-segment CoM does not coincide with the whole-body CoM, and because jump distance is determined by factors such as the velocity and height of the whole-body CoM at toe-off (Hay et al., 1986), results obtained for the trunk-segment CoM cannot be used directly to explain jump distance. Fifth, projection and scale errors associated with the two-dimensional analysis and four-point calibration, and errors in CoM positions resulting from applying population-based body segment inertia parameters (Ae, 1996), whose validity for this participant was not verified, to one individual, are not included in the MDC derived from the two digitizations, although a ±2% change in the vertical scale altered the differences in the toe-off velocity-vector angle by less than 0.1°. Sixth, this study described kinematic differences and identified neither the indirect effects of upper-limb and swing-leg motion nor the mechanical factors that produced the differences in motion. Investigating these mechanical factors requires analyses of, for example, ground reaction forces, joint kinetics, the flow of mechanical energy between segments, and induced acceleration. A musculoskeletal modeling study showed that the vasti produced about one-third of the muscle-induced increase in the vertical velocity of the whole-body CoM but also about half of the muscle-induced decrease in its horizontal velocity (Yang et al., 2023). The present results may provide a basis for focusing on thigh rotation from the middle phase to toe-off in such analyses.

CONCLUSIONS

This study was conducted to generate hypotheses for future testing by comparing trials of the same long jumper that had similar horizontal velocities at touchdown and toe-off but different velocity-vector angles at toe-off. On the basis of the differences in the velocity-vector angle, vertical velocity, and thigh kinematics in the comparisons of Trial 5 with Trials 1 and 6, we derived the following hypothesis. For this athlete, among trials with similar horizontal velocities at touchdown and toe-off, a trial with a greater velocity-vector angle at toe-off already has a greater velocity-vector angle and vertical velocity of the trunk-segment CoM by the end of the middle phase, together with a smaller middle-phase forward angular velocity of the thigh and a smaller forward inclination of the thigh at toe-off. A difference common to the two comparisons was also found in the

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trunk − thigh relative vertical velocity (late-phase mean); however, it was not included in the hypothesis because it represents a breakdown of the vertical velocity. No difference common to the two comparisons was detected in the shank.

If the thigh is regarded as a segment of constant length, the smaller forward inclination of the thigh at toe-off means that the greater trochanter descended less relative to the knee between thigh vertical and toe-off. Other things being equal, this downward motion acts to reduce the vertical velocity of the trunk-segment CoM; however, the present decomposition did not separate the portion of the measured component differences attributable to this motion.

This hypothesis and interpretation are based on three trials from one athlete, selected using conditions determined after the analysis, and they do not indicate causality. Moreover, the selection of the compared trials and the parts of the hypothesis concerning the end of the middle phase and the middle-phase angular velocity of the thigh may depend on the choice of cutoff frequency. In addition, in one of the two other pairs of this athlete's trials that met the selection conditions (Trials 2 and 1), not every item of the hypothesis showed a difference exceeding the MDC. The hypothesis and interpretation must be tested in trials from this athlete on other days and in other athletes, with the conditions for selecting the compared trials and the main comparison variables specified in advance.

AUTHOR CONTRIBUTIONS

All authors meet the established criteria for authorship. Contributions are reported according to the CRediT taxonomy as follows:

Conceptualisation: Shuya Fukuchi, Kiyomi Sugiura, Kiyonobu Kigoshi. Methodology: Shuya Fukuchi, Kiyonobu Kigoshi. Formal analysis: Shuya Fukuchi. Investigation: Shuya Fukuchi, Kiyomi Sugiura. Data curation: Shuya Fukuchi, Kiyomi Sugiura. Writing – original draft: Shuya Fukuchi, Kiyonobu Kigoshi. Writing – review & editing: Shuya Fukuchi, Kiyomi Sugiura, Taku Masaki, Kiyonobu Kigoshi. Supervision: Kiyonobu Kigoshi.

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.

ETHICS APPROVAL AND INFORMED CONSENT

This study was approved by the Human Research Ethics Committee of the University of Tsukuba (approval number: PE 025-39) and was conducted in accordance with the ethical principles of the Declaration of Helsinki and the applicable laws and regulations of Japan. Written informed consent was obtained from the

participant after the purpose, experimental procedures, and safety considerations of the study had been explained.

DATA AVAILABILITY STATEMENT

The values of the main variables for all five trials from both digitisations, with their minimal detectable changes, and a summary of the robustness of the judgments of the between-trial differences are provided as Supplementary Material. The processed, non-identifying time-series data supporting the findings of this study (smoothed two-dimensional landmark coordinates and calculated variables for the five trials) are available from the corresponding author upon reasonable request, subject to approval by the research ethics committee. The video recordings are not available because they could identify the participant.

AI USE DISCLOSURE

In accordance with current publishing ethics and transparency recommendations, during manuscript preparation and revision, the authors used ChatGPT (OpenAI) and Claude (Anthropic) to assist with Japanese-to-English translation and language editing of text written by the authors. Claude (Anthropic) was also used to assist with writing the Python scripts that computed the author-defined variables from the authors' digitized coordinates and that plotted the figures (Figures 2–4 and Figure A1 were generated by running these scripts on the measured data; Figure 1 was drawn by the authors; no AI image-generation tool was used), to check the consistency of numbers and statements across the manuscript, tables, and figures, and to suggest edits to the wording of the manuscript. 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.

REFERENCES

Ae, M. (1996). Body segment inertia parameters for Japanese children and athletes [in Japanese]. *Japanese Journal of Sports Sciences, 15*(3), 155–162.

Bartlett, R., Wheat, J., & Robins, M. (2007). Is movement variability important for sports biomechanists? *Sports Biomechanics, 6*(2), 224–243. https://doi.org/10.1080/14763140701322994

Bates, B. T. (1996). Single-subject methodology: An alternative approach. *Medicine & Science in Sports & Exercise, 28*(5), 631–638. https://doi.org/10.1097/00005768-199605000-00016

Bobbert, M. F., & van Ingen Schenau, G. J. (1988). Coordination in vertical jumping. *Journal of Biomechanics, 21*(3), 249–262. https://doi.org/10.1016/0021-9290(88)90175-3

Bridgett, L. A., & Linthorne, N. P. (2006). Changes in long jump take-off technique with increasing run-up speed. *Journal of Sports Sciences, 24*(8), 889–897. https://doi.org/10.1080/02640410500298040

Glazier, P. S., & Mehdizadeh, S. (2019). Challenging conventional paradigms in applied sports biomechanics research. *Sports Medicine, 49*(2), 171–176. https://doi.org/10.1007/s40279-018-1030-1

Graham-Smith, P., & Lees, A. (2005). A three-dimensional kinematic analysis of the long jump take-off. *Journal of Sports Sciences, 23*(9), 891–903. https://doi.org/10.1080/02640410400022169

Hay, J. G., Miller, J. A., Jr., & Canterna, R. W. (1986). The techniques of elite male long jumpers. *Journal of Biomechanics, 19*(10), 855–866. https://doi.org/10.1016/0021-9290(86)90136-3

Hopkins, W. G. (2000). Measures of reliability in sports medicine and science. *Sports Medicine, 30*(1), 1–15. https://doi.org/10.2165/00007256-200030010-00001

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Kigoshi, K., Fukuchi, S., Sugiura, K., Masaki, T., & Matsui, T. (2026). An examination of takeoff movement styles that transform the velocity vector angle in high jump and long jump [in Japanese]. Japan Journal of Studies in Athletics, 24(1), 19-28.

Lees, A., Fowler, N., & Derby, D. (1993). A biomechanical analysis of the last stride, touch-down and take-off characteristics of the women's long jump. *Journal of Sports Sciences, 11*(4), 303–314. https://doi.org/10.1080/02640419308730000

Lees, A., Graham-Smith, P., & Fowler, N. (1994). A biomechanical analysis of the last stride, touchdown, and takeoff characteristics of the men's long jump. *Journal of Applied Biomechanics, 10*(1), 61–78. https://doi.org/10.1123/jab.10.1.61

Linthorne, N. P., Guzman, M. S., & Bridgett, L. A. (2005). Optimum take-off angle in the long jump. *Journal of Sports Sciences, 23*(7), 703–712. https://doi.org/10.1080/02640410400022011

Masaki, T., Fukuchi, S., & Kigoshi, K. (2026). Mechanical differences in take-off strategies between long jumpers achieving similar distances with different approach velocities. Journal of Human Sport and Exercise, 21(3), 901-913. https://doi.org/10.55860/0fx4v385

Muraki, Y., Ae, M., Yokozawa, T., & Koyama, H. (2005). Mechanical properties of the take-off leg as a support mechanism in the long jump. *Sports Biomechanics, 4*(1), 1–15. https://doi.org/10.1080/14763140508522848

Pataky, T. C. (2010). Generalized n-dimensional biomechanical field analysis using statistical parametric mapping. *Journal of Biomechanics, 43*(10), 1976–1982. https://doi.org/10.1016/j.jbiomech.2010.03.008

Preatoni, E., Hamill, J., Harrison, A. J., Hayes, K., van Emmerik, R. E. A., Wilson, C., & Rodano, R. (2013). Movement variability and skills monitoring in sports. *Sports Biomechanics, 12*(2), 69–92. https://doi.org/10.1080/14763141.2012.738700

Reboussin, D. M., & Morgan, T. M. (1996). Statistical considerations in the use and analysis of single-subject designs. *Medicine & Science in Sports & Exercise, 28*(5), 639–644. https://doi.org/10.1097/00005768-199605000-00017

Sado, N. (2025). Biomechanical inter-relationships between physical and motor features in maximal effort locomotion. *Sports Biomechanics*. Advance online publication. https://doi.org/10.1080/14763141.2025.2596762

Sado, N., Fujimori, T., & Tobe, N. (2024). Discrepancy between "contributing to" and "sharing variance with" the effective energy for height in high jump. *Journal of Sports Sciences, 42*(5), 425–433. https://doi.org/10.1080/02640414.2024.2335086

Sado, N., Yoshioka, S., & Fukashiro, S. (2020). Non-extension movements inducing over half the mechanical energy directly contributing to jumping height in human running single-leg jump. *Journal of Biomechanics, 113*, Article 110082. https://doi.org/10.1016/j.jbiomech.2020.110082

Sado, N., Yoshioka, S., & Fukashiro, S. (2023). Pelvic elevation induces vertical kinetic energy without losing horizontal energy during running single-leg jump for distance. *European Journal of Sport Science, 23*(7), 1146–1154. https://doi.org/10.1080/17461391.2022.2070779

Savitzky, A., & Golay, M. J. E. (1964). Smoothing and differentiation of data by simplified least squares procedures. *Analytical Chemistry, 36*(8), 1627–1639. https://doi.org/10.1021/ac60214a047

Seyfarth, A., Friedrichs, A., Wank, V., & Blickhan, R. (1999). Dynamics of the long jump. *Journal of Biomechanics, 32*(12), 1259–1267. https://doi.org/10.1016/S0021-9290(99)00137-2

Weir, J. P. (2005). Quantifying test-retest reliability using the intraclass correlation coefficient and the SEM. *Journal of Strength and Conditioning Research, 19*(1), 231–240. https://doi.org/10.1519/15184.1

Winter, D. A. (2009). *Biomechanics and motor control of human movement* (4th ed.). John Wiley & Sons. https://doi.org/10.1002/9780470549148

Yang, K., Tang, W.-T., Liu, S.-H., & Pandy, M. G. (2023). Muscle contributions to take-off velocity in the long jump. *Medicine & Science in Sports & Exercise, 55*(8), 1434–1444. https://doi.org/10.1249/MSS.0000000000003175

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SUPPLEMENTARY MATERIAL. Values of the main variables for the five trials and robustness of the judgments.

Table S1. Values of the main variables for the five trials (first and second digitisations) and their minimal detectable changes (MDCs). In the main text, Trial 5 was the reference trial and was compared with Trials 1 and 6. Trials 2 and 4 were not compared with Trial 5; their values are given for reference and were used for the comparisons of the other pairs reported in the Results. Trial 3 is not included because the participant ran through without taking off.

Table S2. For every difference between Trial 5 and Trials 1 and 6 reported in the main text, whether the difference was maintained under the 3.93 criterion and when the cutoff frequency was varied from 6 to 25 Hz (compared with the MDC at 10 Hz and, for reference, with the MDC calculated at each cutoff frequency).

The processed time-series data are available from the corresponding author upon reasonable request, subject to approval by the research ethics committee. Video recordings are not available because they could identify the participant.

Table S1. Trunk-segment centre-of-mass and take-off-leg variables for the five trials in the first and second digitisations, with minimal detectable changes (10-Hz cutoff).

Variable	Unit	Trial 1 1st	Trial 1 2nd	Trial 2 1st	Trial 2 2nd	Trial 4 1st	Trial 4 2nd
Effective jump distance (reference)	m	6.85		6.95		7.39	
Contact time	s	0.113	0.113	0.117	0.117	0.125	0.125
Horizontal velocity at touchdown	m/s	9.83	9.68	9.69	9.89	9.95	10.05
Horizontal velocity at toe-off	m/s	8.94	8.73	8.68	8.98	8.57	8.58
Speed at toe-off	m/s	9.17	8.96	9.00	9.32	9.02	9.08
Vertical velocity at toe-off	m/s	2.04	2.01	2.37	2.48	2.81	2.98
Velocity-vector angle at toe-off	°	12.84	12.99	15.29	15.41	18.12	19.14
Decrease in horizontal velocity during contact	m/s	0.89	0.95	1.01	0.91	1.37	1.47
Velocity-vector angle at the end of the early phase	°	9.38	11.36	11.42	10.82	11.59	11.08
Velocity-vector angle at the end of the middle phase	°	11.19	10.87	12.14	12.90	14.50	14.46
Vertical velocity at the end of the early phase	m/s	1.38	1.69	1.65	1.56	1.65	1.55
Vertical velocity at the end of the middle phase	m/s	1.79	1.75	1.96	2.02	2.26	2.26
Shank segment angle at touchdown	°	29.2	28.7	31.6	32.5	35.8	36.3
Time at which the shank became vertical	ms	35.8	34.8	43.6	43.3	54.3	54.6
Thigh segment angle at touchdown	°	39.0	38.7	41.4	41.4	44.9	44.9
Middle-phase mean angular velocity of the thigh	°/s	-650	-636	-611	-590	-499	-496
Thigh segment angle at toe-off	°	-22.9	-22.5	-22.5	-21.7	-18.6	-17.5
Time at which the thigh became vertical	ms	81.0	80.6	88.3	87.8	101.9	101.6
Vertical velocity: middle-phase change	m/s	0.41	0.06	0.31	0.45	0.61	0.71
Vertical velocity: late-phase mean	m/s	1.94	1.91	2.21	2.27	2.61	2.71
Trunk − thigh relative vertical velocity: middle-phase change	m/s	0.65	0.47	1.03	1.20	1.36	1.72
Trunk − thigh relative vertical velocity: late-phase mean	m/s	0.11	0.11	0.28	0.29	0.54	0.59

Variable	Unit	Trial 5 1st	Trial 5 2nd	Trial 6 1st	Trial 6 2nd	MDC
Effective jump distance (reference)	m	7.40		6.83		
Contact time	s	0.117	0.117	0.117	0.117	
Horizontal velocity at touchdown	m/s	10.03	9.91	10.01	9.88	0.32
Horizontal velocity at toe-off	m/s	8.79	8.69	8.91	8.92	0.37
Speed at toe-off	m/s	9.20	9.08	9.19	9.18	0.39
Vertical velocity at toe-off	m/s	2.71	2.65	2.27	2.17	0.22
Velocity-vector angle at toe-off	°	17.17	16.94	14.30	13.70	1.18
Decrease in horizontal velocity during contact	m/s	1.24	1.22	1.11	0.96	0.20
Velocity-vector angle at the end of the early phase	°	9.17	9.38	10.45	9.98	2.13
Velocity-vector angle at the end of the middle phase	°	13.38	13.11	10.64	11.17	0.95
Vertical velocity at the end of the early phase	m/s	1.34	1.37	1.54	1.52	0.32
Vertical velocity at the end of the middle phase	m/s	2.19	2.15	1.76	1.76	0.08
Shank segment angle at touchdown	°	31.5	32.4	31.4	31.3	1.2
Time at which the shank became vertical	ms	40.2	40.8	39.3	38.2	1.5
Thigh segment angle at touchdown	°	39.4	39.8	40.4	40.3	0.5
Middle-phase mean angular velocity of the thigh	°/s	-548	-555	-595	-603	25
Thigh segment angle at toe-off	°	-19.9	-19.1	-22.8	-22.8	0.9
Time at which the thigh became vertical	ms	90.1	89.4	88.2	86.3	1.2
Vertical velocity: middle-phase change	m/s	0.85	0.78	0.21	0.24	0.38
Vertical velocity: late-phase mean	m/s	2.53	2.56	2.04	2.02	0.10
Trunk − thigh relative vertical velocity: middle-phase change	m/s	1.13	1.33	0.43	0.60	0.39
Trunk − thigh relative vertical velocity: late-phase mean	m/s	0.37	0.44	-0.02	0.04	0.07

Note. Values are trunk-segment centre-of-mass and take-off-leg variables calculated with a 10-Hz cutoff frequency, using the definitions in the main text. Segment angles are relative to the vertical, with backward inclination positive; angular velocity is negative for forward rotation. MDC (minimal detectable change) = typical error × 1.96 × √2, calculated from the differences between the two digitisations of the five trials. Contact time was determined by the touchdown and toe-off frames, which were identical in the two digitisations. The effective jump distance is defined in the main text (reference only). 1st and 2nd denote the first and second digitisations. Trials 2 and 4 were not compared with Trial 5; their values are given for reference and were used for the comparisons of the other pairs reported in the Results.

Table S2. Summary of the robustness of the judgments of the between-trial differences.

Variable	Comparison	Category	3.93 criterion	Cutoff frequency 6–25 Hz (MDC at 10 Hz)	Reference: MDC at each cutoff frequency
Velocity-vector angle at the end of the middle phase	5−1	Main result	Maintained	Maintained	Below: 14–25 Hz (1st); 18–25 Hz (2nd)
	5−6		Maintained	Maintained	Below: 14–25 Hz (2nd)
Vertical velocity at the end of the middle phase	5−1	Main result	Maintained	Maintained	Below: 17–25 Hz (1st); 25 Hz (2nd)
	5−6		Maintained	Maintained	Below: 22–25 Hz (2nd)
Middle-phase mean angular velocity of the thigh	5−1	Main result	Maintained	Maintained	Maintained
	5−6		Maintained	Maintained	Below: 23–25 Hz (2nd)
Thigh segment angle at toe-off	5−1	Main result	Maintained	Maintained	Maintained
	5−6		Maintained	Maintained	Maintained
Vertical velocity: late-phase mean	5−1	Main result	Maintained	Maintained	Maintained
	5−6		Maintained	Maintained	Maintained
Trunk − thigh relative vertical velocity: late-phase mean	5−1	Main result	Maintained	Maintained	Maintained
	5−6		Maintained	Maintained	Maintained
Vertical velocity: middle-phase change	5−1	Main result	Below: 1st	Below: 12–25 Hz (1st)	Below: 11–25 Hz (1st); 17–25 Hz (2nd)
	5−6		Below: 2nd	Below: 6 Hz (1st); 6 Hz (2nd)	Below: 17–25 Hz (1st); 13–25 Hz (2nd)
Trunk − thigh relative vertical velocity: middle-phase change	5−1	Main result	Below: 1st	Below: 6–7, 24–25 Hz (1st)	Below: 12–25 Hz (1st)
	5−6		Maintained	Below: 6 Hz (1st); 6 Hz (2nd)	Below: 20–25 Hz (1st); 20–25 Hz (2nd)
Velocity-vector angle at toe-off	5−1	Toe-off	Maintained	Maintained	Maintained
	5−6		Maintained	Maintained	Below: 22–25 Hz (1st)
Vertical velocity at toe-off	5−1	Toe-off	Maintained	Maintained	Maintained
	5−6		Maintained	Maintained	Below: 17–25 Hz (1st)
Trunk segment angle at the end of the middle phase	5−1	Opposite direction	Below: 2nd	Maintained	Maintained
	5−6		Maintained	Maintained	Below: 20–25 Hz (2nd)
Trunk segment angle at toe-off	5−1	Opposite direction	Maintained	Maintained	Maintained
	5−6		Maintained	Maintained	Maintained
Decrease in horizontal velocity during contact	5−1	One comparison	Below: 2nd	Below: 22–25 Hz (1st)	Below: 18–25 Hz (1st); 25 Hz (2nd)
Middle-phase mean angular velocity of the shank	5−1	One comparison	Maintained	Maintained	Maintained
Time at which the shank became vertical (ms)	5−1	One comparison	Maintained	Maintained	Maintained
Time at which the shank became vertical (%)	5−1	One comparison	Maintained	Maintained	Maintained
Thigh segment angle at the end of the middle phase	5−1	One comparison	Maintained	Maintained	Maintained
Time at which the thigh became vertical (ms)	5−1	One comparison	Maintained	Maintained	Maintained
Time at which the thigh became vertical (%)	5−1	One comparison	Maintained	Maintained	Maintained
Time from thigh vertical to toe-off	5−1	One comparison	Maintained	Maintained	Maintained
Thigh − shank relative vertical velocity: late-phase mean	5−1	One comparison	Below: 1st and 2nd	Below: 6 Hz (1st); 6–7 Hz (2nd)	Below: 22–25 Hz (1st)
Trunk − thigh relative vertical velocity: early-phase mean	5−1	One comparison	Maintained	Maintained	Maintained
Mean angular velocity of the thigh from vertical to toe-off	5−6	One comparison	Maintained	Below: 6 Hz (2nd)	Below: 19–25 Hz (1st)
Trunk segment angle at touchdown	5−6	One comparison	Maintained	Maintained	Maintained

Note. Comparisons are Trial 5 − Trial 1 (5−1) and Trial 5 − Trial 6 (5−6). The table lists all differences between Trial 5 and Trials 1 and 6 reported in the main text (those whose magnitude exceeded both the MDC and the ±1-frame change in both digitisations, with the same sign). "Maintained" indicates that the difference exceeded the criterion in both digitisations and that its sign was the same as at 10 Hz. "Below" lists the cutoff frequencies and digitisations (1st, first; 2nd, second) at which the difference fell below the criterion or its sign changed. 3.93 criterion: the difference was judged against both the typical error × 3.93 (i.e., MDC × 3.93/2.77) and the ±1-frame change, at 10 Hz. Cutoff frequency 6–25 Hz (MDC at 10 Hz): the difference at each cutoff frequency was compared with the MDC calculated at 10 Hz. Reference: the difference at each cutoff frequency was compared with the MDC calculated from the typical error at that cutoff frequency (given here for all listed differences; the main text reports this comparison only for the main results and the toe-off velocity-vector angle and vertical velocity). The ±1-frame change is not used in the two columns in which the cutoff frequency was

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varied. Category: Main result, a difference common to both comparisons (as defined in the main text); Toe-off, the toe-off velocity-vector angle (a selection condition) and vertical velocity; Opposite direction, variables that differed in both comparisons but for which Trial 5's value was larger in one comparison and smaller in the other; One comparison, variables that differed in only one comparison.

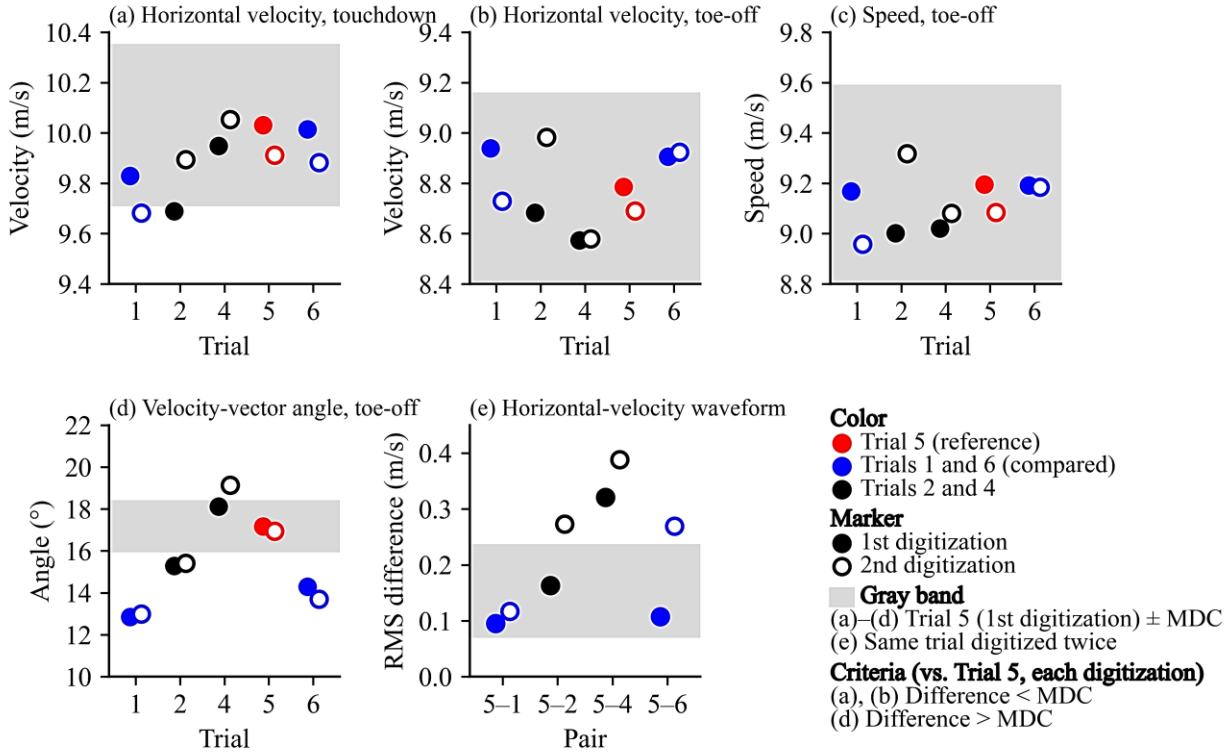


Figure A1. (a) Horizontal velocity at touchdown, (b) horizontal velocity at toe-off, (c) speed at toe-off, (d) velocity-vector angle at toe-off, and (e) RMS difference between each trial's horizontal-velocity waveform and that of Trial 5 (calculated from waveforms normalized to contact time) for the five trials. The meanings of the colours, markers, and grey bands, and the conditions for the compared trials, are given in the legend at the lower right. The grey bands in (a)–(d) show the value of Trial 5 (first digitization) ± the MDC, and the grey band in (e) shows the range of RMS differences obtained when the same trial was digitized twice. Because the conditions were judged based on the differences from Trial 5 in each digitization, the markers for the second digitization do not correspond directly to the grey bands. MDC, minimal detectable change; RMS, root mean square.

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