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Original Article

Characteristics of ground reaction force and frontal body movement during failed trials of single-leg lateral drop jump-landing task

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ABSTRACT

Background: /objectives: For biomechanical studies using jump-landing tasks, many researchers set the criteria for judging success or failure of the trial. Failed trials are usually removed from the analysis. However, the kinetics and kinematics during tasks included in failed trials might be important for understanding the mechanisms and risk factors of non-contact sports injuries. However, few studies have attempted to analyze failed trials. Therefore, the main objective of this study was to investigate the characteristics associated with ground reaction force (GRF) and two-dimensional frontal body movements during a failed trial of single-leg lateral drop jump-landing.

Methods: Ten healthy women and 16 healthy men participated in this study. Spearman's rank correlation coefficients were calculated using the total number of failed trials and GRF data of successful trials. The association between frontal body movement and kinetics data was identified using correlation analyses. Wilcoxon signed-rank tests were performed to compare the GRF data of successful trials and failed trials of the same subject. Additionally, a two-way repeated measure analysis of variance was used to determine significant interactions of each trial and time after initial contact in the frontal body movement.

Results: A total of 137 trials including successful and failed trials were recorded. There were 59 failed jump trials. There was a significant negative correlation between the number of failed jump trials and the elapsed time from initial contact to peak vertical GRF (peak vGRF time) during successful trials ($r = -0.427$). The majority of failed trials were judged to be due to rearfoot movement patterns (rearfoot medial slip or rearfoot lateral slip). During rearfoot medial slip, we observed shorter peak vGRF time, larger trunk medial motions, and larger hip adduction movements after landing than that during successful trials. During rearfoot lateral slip, we observed larger trunk lateral motions and hip abduction movements after landing than that during successful trials.

Conclusions: Athletes who frequently failed during single-leg lateral drop jump-landing had poor skills absorbing jump-landing impact, which is related to various sports injuries. It is possible to identify the risk factors for sports injuries by analyzing failure patterns.

1. Background

Ankle sprains and knee ligament injuries as a result of non-contact often occur during jump landing and cutting movements.[1–5] Therefore, to understand these injury mechanisms and risk factors, many researchers have analyzed the kinetics and kinematics of these movements.[1,6–8] Previous studies used ground reaction force (GRF) and trunk and hip kinematics as the main parameters for analyzing athletic movements.[9–14] In order to understand the mechanisms of typical sports injuries, such as anterior cruciate ligament (ACL) injuries and ankle sprains, it is important to analyze GRF as well as trunk and hip kinematics.

In a previous study using jump-landing and cutting as the motion tasks, a significant association between GRF and increased ACL strain was reported. ACL strain reaches a peak at the same time as the vertical GRF (vGRF) peaks.[15] Non-contact ACL injuries during

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cutting and jump landings involve peak vGRF generated at approximately 40 msec from initial contact (IC), which is a very short time.[2] These vGRF variables, including temporal elements, are important factors related to ACL injury onset and excessive increases in the strain applied to the ACL.

Frontal body movements during sports activities are related to symptoms, mechanical stress, and injury risk of the lower limb. During single-leg drop jumping and side-step cutting, excessive lateral trunk motion is one of the risk factors for non-contact knee injury.[12,16] Therefore, it is also important to analyze frontal body movements during jump-landing and cutting motions to understand the mechanisms of sports injury onset.

Kinematics and kinetics during sports motions change depending on the direction of the movement. During single-leg jump-landings, the knee valgus angle is greater during lateral jump-landings than during forward jump-landings.[17] The time to stabilization during single-leg landings is significantly longer during lateral jump-landings than during forward jump-landings.[18] This demonstrates the importance of analyzing lateral movements.

In biomechanical studies using jump-landing and cutting tasks, to enhance the general versatility of the data, many researchers have set the criteria for judging whether the trial is a success or failure. During most biomechanical research, the failed jump trials were removed or discarded, and only the data of successful trials were analyzed to minimize variation and allow better explanations of the data sets.[18,19] However, many sports injuries occur during uncontrollable situations.[20] For a better understanding of the mechanisms of and risk factors for non-contact sports injuries, the kinetics and kinematics during tasks, including those during failed trials, might be important.[21,22]

The criteria for judging success or failure in previous studies were as follows: foot movement or hopping[17,19]; loss of balance[17,18]; unable to keep the upper limbs structured (e.g., keeping the arms folded across the chest or hands on the hips)[23]; and touching down the contralateral foot.[18,21,24] Wikstrom et al. defined their criteria as "loss of balance forcing stepping off the force plate to regain balance" and measured electromyography (EMG) variables. This included muscle activation, average EMG amplitudes (preparative and reactive) of the vastus medialis, semimembranosus, lateral gastrocnemius, and tibial anterior muscles during the jump-landing.[21] They suggested that an earlier onset of muscle activity is needed in the jump-landing trials that are successful in order for the lower extremity to avoid collapse. Nishino et al. defined their criteria as "foot moved after landing" and "cannot keep the landing posture" and analyzed the biomechanics of the pelvis and lower extremities during single-leg medial-side landing of female basketball players.[22] They observed that pelvic contralateral tilt and knee valgus moment during failed trials were larger than those during successful trials. They suggested that the screening for failed trials could have a role in knee injury prevention. However, biomechanical analyses of failed trials of jump-landing tasks are necessary, and there has been no study of single-leg lateral jump-landing tasks.

The main objective of this study was to analyze patterns during single-leg lateral jump-landing tasks judged to have ended in failure, including GRF and frontal body movement.

We hypothesized that subjects who had high rates of failed trials had greater vertical GRF peaks or more sharply increased vertical GRF, and that the characteristics of GRF parameters, frontal trunk movements, and hip joint movements of jump landings during failed trials vary according to failure patterns.

2. Methods

2.1. Participants

We recruited 10 healthy women and 16 healthy men with the following characteristics: mean age of 23.4 (standard deviation [SD], 3.5) years; mean height of 165.6 (SD, 7.7) cm; mean weight of 60.3 (SD, 8.6) kg; mean body mass index of 21.9 (SD, 2.1) kg/m^2; mean sports participation time of 5.4 (SD, 6.0) hours/week; and mean Tegner activity scale of 5.9 (SD, 1.4). The inclusion criteria of subjects were as follows: physically active, at least 18 years of age, and no history of serious injuries or surgery in the lower extremities or lumber region. We received Institutional Review Board approval of the study design (approval no. 1885). All participants provided written informed consent prior to participating in the study. The subjects in this study had graduated middle school and capable of choosing whether or not to participate in the study; therefore, we did not require parental approval.

2.2. Measurement procedure

The athletic attire worn by the subjects, including shorts, spandex shirts, and shoes without air cushions. Reflective markers were placed on the skin and on the shorts. Markers were placed on the jugular notch of the sternum and bilaterally on the acromioclavicular joints, the anterior superior iliac spines (ASIS), and the center of the patella. Before placing the markers, participants warmed-up for 5 min. This involved a stationary bicycle without resistance and light stretching. The subjects were then instructed and shown the procedure for the jump-landing task. All subjects practiced three single-leg lateral jump landings with both legs to familiarize themselves with the movements prior to data collection. Subjects stood on a step on a single leg with the other knee bent at approximately 90°, with neutral hip rotation and arms crossed to eliminate the effects of arm movement.[25,26] Subjects were instructed to jump sideways, with no deliberate upward action, and to make as natural a landing as possible on the same leg in the center of the force plate, and to maintain their balance for 5 s. Subjects were also verbally instructed to face forward during the jump-landing task. A 25-cm high step (RBK-B001; Reebok, Canton, MA, USA) was placed 60 cm from the center of the force plate (260AA6; Kistler Instrument AG, Winterthur, Switzerland). The force plate surface was 5 cm above floor level. The task was randomly repeated three times in succession with both legs. A trial was deemed to have failed if the foot moved or slipped after landing, if the sole of the opposite foot touched the floor or force plate, or the hands pulled away from the axillae.[17–19,21,23,24] A visual determination was made of success or failure and subjects were not made aware of their assessment. Regardless of whether any failed trials occurred, measurements were completed after three successful trials.

2.3. Data extraction

The reliability of data collection using the following method has been reported in the past, and good reliability with ICC (1,1) between 0.73 and 0.74 have been confirmed.[26,27]

GRF data were collected at a sampling rate of 1000 Hz. A butterworth filter with a cut-off frequency of 50 Hz was used with a low-pass and canonicalized by body weight (%) using specific software (IFS-4J/3J; DKH, Tokyo, Japan). Extracted GRF data included the IC time, peak value, and time of vGRF. The moment at which vGRF exceeded 10 N was defined as the IC.

Single-leg lateral jump-landing tasks were observed and recorded by a high-speed video camera (GC-LJ20B; Sports Sensing, Minami, FUK, Japan) at a sampling rate of 120 Hz to enable two-dimensional kinematic analysis of frontal angles. The camera was positioned 335 cm from the lens to the center of the force plate at a height of 1 m from the center of the lens to the floor. We measured the frontal angles of the trunk side lean and hip adduction-abduction (HAA) during the seven instances of time during the task. One of these instances was during the flight phase defined as 100 msec before IC. Other instances were set at 100-msec intervals during the period from IC to 500 msec. Frontal angles of the trunk side lean and HAA indicated by markers in each frame were measured using Image J software (National Institutes of Health, Bethesda, MD, USA) (Fig. 1). The trunk side lean angle was defined as the angle that formed between a line joining the acromio-clavicular joint and the ASIS of the non-test limb side and a vertical line that intersected the ASIS.[28] The smaller trunk side lean angle represented a larger lateral trunk motion in the direction of the testing limb. The trunk side lean angle was negative when the medial acromio-clavicular joint was more lateral than the ipsilateral ASIS. HAA angle was defined as the angle that formed between a line joining the ASIS and a line joining the ASIS and the midpoint of the patella of the test limb side.[29] A smaller HAA angle represented larger hip adduction.

2.4. Data analysis

Failed trials were classified according to the failure patterns: foot slip after landing (slip failure), hopping, and loss of balance (the sole of the opposite foot touched the floor or force plate, could not keep the armed crossed). Moreover, the failed trials involving slip failure were divided into four patterns: rearfoot medial slip (RM-slip), rearfoot lateral slip (RL-slip), forefoot medial slip (FM-slip), and forefoot lateral slip (FL-slip). RM-slip was defined as movement of the sliding heel medially around the forefoot ball. RL-slip was defined as movement of the sliding heel laterally around the forefoot ball. FM-slip was defined as movement of the sliding toe medially around the heel. FL-slip was defined as movement of the sliding toe laterally around the heel. Slip failure was defined as foot movement following landing that occurred before trunk movement or opposite leg grounding rather than foot movement as a result of trunk lean movement.

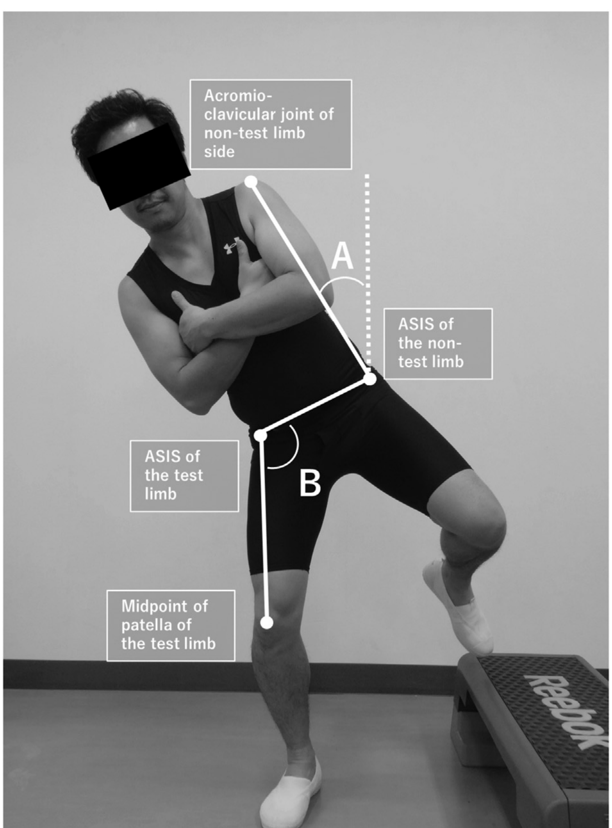


Fig. 1. The frontal angle definitions of trunk side lean and hip adduction-abduction. angle A = trunk side lean angle; angle B = hip adduction-abduction angle.

GRF parameters and frontal kinematics during a second trial of the three successful jump-landing trials were analyzed.[26] The Pearson's correlation coefficients or Spearman's rank correlation coefficients were calculated for parametric or non-parametric variables. Correlation analyses were undertaken to investigation the strength of association between the total number of failed trials and GRF data of successful trials. Additionally, the association between frontal body movement (trunk side lean angle and HAA angle) and kinetics data was identified using correlation analyses. The strength of these correlations were described as trivial (0.0–0.1), small (0.1–0.3), moderate (0.3–0.5), large (0.5–0.7), very large (0.7–0.9), or extremely large (0.9–1.0).[30] Wilcoxon signed-rank tests were performed to compare the GRF data of successful trials and failed trials of the same subject. Additionally, analyses were conducted to confirm the changes in frontal body movements over time before and after the landing. A two-way repeated measure analysis of variance (ANOVA) was used to determine significant interactions of each trial and time after IC in the frontal trunk side lean angle and HAA angle; then, a post hoc test was performed (Table 1). The significance level was set at 0.05. Data were analyzed using SPSS for Windows (version 23.0; IBM., Chicago, IL, USA).

All power analyses were performed using G*power statistical software (Universität Düsseldorf, Düsseldorf, Germany). For within-subject analyses, a power analysis using data from previous study that investigated differences in GRF parameters during jump-landing under the two conditions.[31] As the result, the minimum number of trials required to compare variables between successful and failed trials was 13 to attain a power of 0.80.

3. Results

A total 137 trials including successful and failed trials were recorded. The failed jump trials were recorded for 18 of 26 subjects. There were 59 failed jump trials, comprising 43 % of the total trials. The average number of failed jump trials was 2.3 per subjects (Fig. 2). For successful trials, the average peak vGRF was 387.4 ± 63.4 % of body weight, and the average elapsed time from IC to peak vGRF (peak vGRF time) ranged from 47.0 to 96.0 msec (mean, 67.3 msec). A significant negative correlation was found between the number of failed jump trials and the peak vGRF time during successful trials ($\rho = -0.427$; $p = 0.03$).

Of 59 failed jump trials, 41 (69 %) were judged to be slip failures. The majority of slip failures were RM-slip and RL-slip (Fig. 3). Regarding rearfoot movement patterns, RM-slip was observed most frequently, followed by RL-slip (Table 2).

Table 1
The factors and varables considered in two-way ANOVA.[a].

Factors	trials (successful trials or failed trials)
Variables	time after IC[b] Frontal body movement (trunk side lean and HAA[c] angle)

[a] ANOVA, analysis of variance.
[b] IC, initial contact.
[c] HAA, hip adduction-abduction.

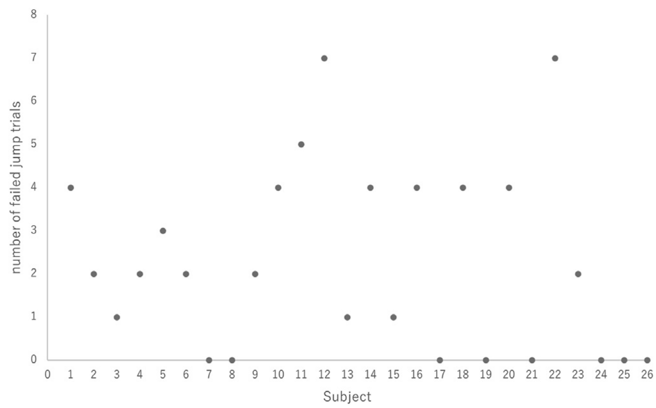


Fig. 2. Fail jump trials per subject. This figure shows the number of failed jump trials that observed before three successes.

Table 2
Breakdown of failed pattern during single-leg lateral jump-landing tasks.

Pattern	Details	Number of trials
Slip error	RM-slip[a]	22
	RL-slip[b]	13
	FM-slip[c]	4
	FL-slip[d]	2
Losing balance	the opposite foot touched the floor	9
	the hands pull away from axillae	8
Hopping	hopping	1
	Total	59

[a] RM-slip, rearfoot medial-slip.
[b] RL-slip, rearfoot lateral-slip.
[c] FM-slip, forfoot medial-slip.
[d] FL-slip, forefoot lateral-slip.

The average peak vGRF time was significantly shorter for RM-slip trials than for successful trials ($p = 0.004$). There were no significant differences in peak vGRF and peak vGRF time for RL-slip trials and successful trials.

Regarding the trunk side lean angle and HAA angle, two-way repeated ANOVA showed significant interactions between successful or failed trials and time phase. Using the post hoc test, the trunk side lean angles at 400 msec and 500 msec after IC for RM-slip were significantly larger than those during successful trials (Fig. 4). Regarding RL-slip, during the post hoc test, the trunk side lean angles were significantly smaller at 300 msec, 400 msec, and 500 msec after IC than those during successful trials (Fig. 4). HAA angles were significantly smaller at 400 msec and 500 msec after IC for RM-slip than those during successful trials (Fig. 5). Regarding RL-slip, HAA angles were significantly larger at 300 msec, 400 msec, and 500 msec after IC than those during successful trials (Fig. 5). Regarding RM-slip, HAA angles at 400 msec ($r = 0.496$; $p = 0.036$) and 500 msec ($r = 0.6$; $p = 0.011$) after IC correlated with peak vGRF.

4. Discussion

This study was designed to analyze the correlations between GRF variables and frontal body movement during failed trials of single-leg lateral drop jump-landing. There were negative correlations between the number of failed trials and peak vGRF time during successful trials performed by the same subject. The results supported our hypothesis that subjects with a higher number of failures had a lower ability to absorb landing impact. We were also able to confirm characteristic differences in GRF generated during landing for each failure pattern and physical movement after landing.

During a total of 59 failed trials, slip failure was most often observed. The most commonly observed instances of slip failure were RM-slip and RL-slip, which involve the rearfoot slipping medially or laterally using the forefoot as an axis. Therefore, we analyzed the trunk side lean angle and HAA angle with these two failure patterns.

For the same subjects, peak vGRF time during RM-slip was shorter than during successful trials. For RM-slip, larger hip adduction angles at 400 msec and 500 msec after IC were associated with increased peak vGRF. For RM-slip, the trunk medial lean angle and hip adduction at 400 msec and 500 msec after IC were larger than those during successful trials. These results demonstrated a correlation between the line of sight during frontal plane body movement and the line of sight during landing and vGRF variables. In this study, there were negative correlations between the number of failed trials and peak vGRF times during successful trials by the same subject. These results indicated that many failures were caused by RM-slip during lateral single-leg jump-landing evaluation and training, suggesting that larger hip adduction movements during such movements were associated with greater impact on landing.

For the same subjects, no significant differences were noted in RL-slip kinetics data (peak vGRF and peak vGRF time) and kinetics data of successful trials. Regarding RL-slip, the angle of trunk lateral lean and hip abduction at 300 msec and 400 msec after IC were greater than those during successful trials. The pivoting internal rotational motion of the ankle, which is similar to RL-slip, occurred rapidly at 0.06–0.11 s from IC during lateral ankle sprains that occurred during side-step cutting.[1] The internal rotation of the ankle and supination without ankle plantar flexion contribute to sprains.[3,4] Because the rearfoot moves laterally during RL-slip and

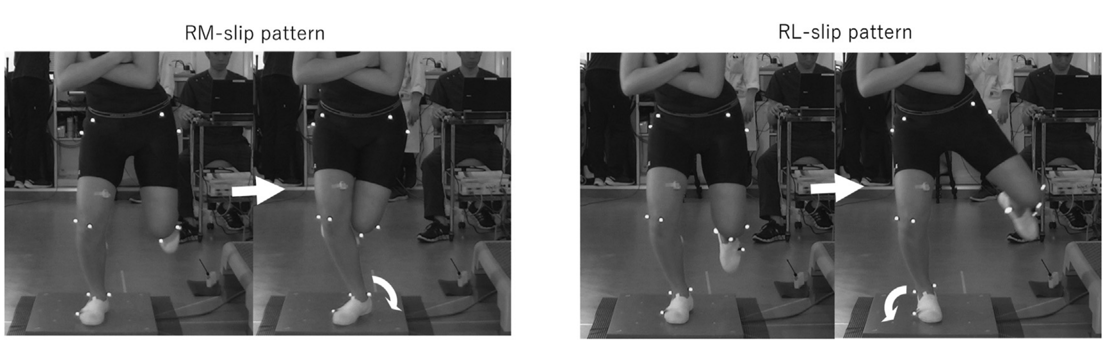
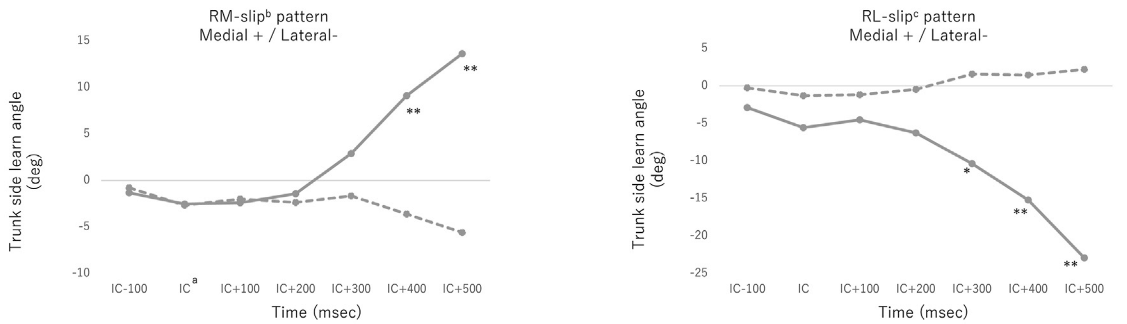


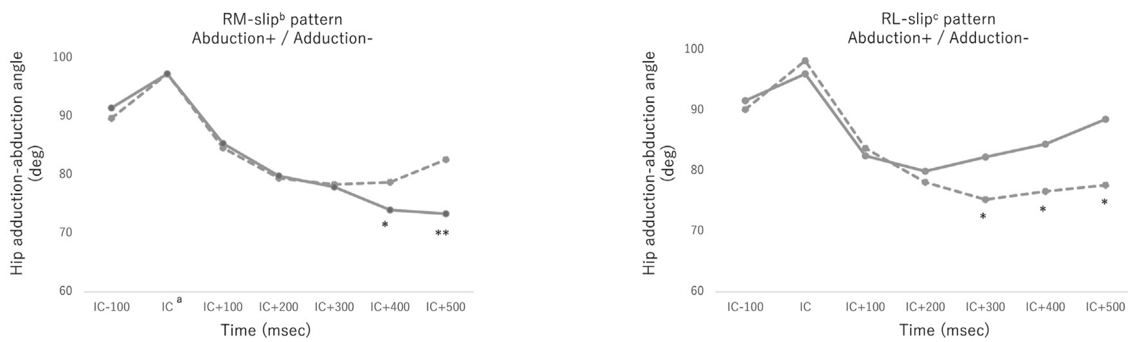
Fig. 3. For examples of slip error. This figure shows RM-slip (left) and RL-slip (right) patterns. We visually confirmed the heel sliding. RM-slip, rearfoot medial-slip; RL-slip, rearfoot lateral-slip.



Time	IC-100	IC	IC+100	IC+200	IC+300	IC+400	IC+500
Successful trials	-0.8 ± 5.7	-2.7 ± 6.4	-2.0 ± 8.0	-2.4 ± 9.4	-1.6 ± 11.3	-3.6 ± 12.6	-5.7 ± 13.9
Failed trials	-1.3 ± 5.8	-2.5 ± 7.1	-2.4 ± 10.1	-1.4 ± 12.4	2.9 ± 13.3	9.1 ± 13.9	13.6 ± 14.3

Time	IC-100	IC	IC+100	IC+200	IC+300	IC+400	IC+500
Successful trials	-0.2 ± 5.5	-1.3 ± 8.2	-1.2 ± 9.3	-0.4 ± 11.2	1.6 ± 12.1	1.4 ± 13.3	2.2 ± 14.4
Failed trials	-2.9 ± 5.9	-5.5 ± 7.0	-4.5 ± 8.7	-6.3 ± 9.5	-10.4 ± 9.9	-15.2 ± 11.1	-22.9 ± 10.0

Fig. 4. The changing of trunk side lean angle for successful trials (dot line) and failed trials (solid line) during single-leg lateral jump-landing. a: IC, initial contact. b: RM-slip, rearfoot medial-slip. c: RL-slip, rearfoot lateral-slip. Statistical significance comparing successful trials and failed trials is deg, noted by *p < 0.05, **P < 0.01.



Time	IC-100	IC	IC+100	IC+200	IC+300	IC+400	IC+500
Successful trials	89.7 ± 5.0	97.3 ± 4.1	84.6 ± 7.1	79.4 ± 6.8	78.3 ± 7.1	78.7 ± 8.1	82.6 ± 7.1
Failed trials	91.5 ± 5.0	97.2 ± 2.9	85.4 ± 6.1	79.8 ± 6.0	77.9 ± 6.9	74.0 ± 7.3	73.3 ± 7.0

Time	IC-100	IC	IC+100	IC+200	IC+300	IC+400	IC+500
Successful trials	90.1 ± 3.7	98.2 ± 3.3	83.7 ± 5.9	78.1 ± 5.7	75.2 ± 7.5	76.6 ± 9.1	77.6 ± 9.7
Failed trials	91.6 ± 4.6	96.0 ± 2.9	82.5 ± 5.7	79.9 ± 5.9	82.3 ± 6.7	84.4 ± 6.8	88.5 ± 7.3

Fig. 5. The changing of HAA angle for successful trials (dot line) and failed trials (solid line) during single-leg lateral jump-landing. a: IC, initial contact. b: RM-slip, rearfootmedial-slip. c: RL-slip, rearfootlateral-slip. Statistical significance comparing successful trials and failed trials is denoted by *p < 0.05, **P < 0.01.

the forefoot does not move, foot adduction and supination are predicted to have occurred in the ankle. When many failures are observed as a result of RL-slip during lateral jump-landing, the possible reason could be that the pivoting internal rotational motion might tend to habitually occur, thus creating an internal risk for ankle inversion sprains. During toe-in landing, the knee valgus and internal rotation movements were larger during IC up to 50 msec after IC than during landing with neutral foot alignment.[32,33] Therefore, toe-in landing was reported to be a risk factor for ACL injury. However, this differed from the results of the present study, which indicated that toe-in landing occurred as a result of lateral slip of the rearfoot after landing, because these reports analyzed landing movements during which toe-in landing occurred from the IC. Therefore, it is unlikely that the same kinetics and kinematics were observed in these and in the present study.

Several studies have shown that hip adduction and trunk lean movement during landing for sports movements are associated with sports injuries.[34–36] For cutting motions, the trunk lateral lean angle from IC to the direction of transition is related to the knee valgus moment during movement.[16,37,38] Many studies analyzed frontal body movement, which occurs at IC during motion tasks and from IC to within 100 msec later.[36,39] However, the hip adduction movement and trunk lean movement observed during this study occurred from 400 msec after IC. Therefore, it is difficult to link the results of previous studies with the results of the present study.

During this study, we analyzed failed trials that are usually excluded from sports movement biomechanical research. During failed trials of single-leg lateral drop jump-landing, we captured the characteristics of vGRF and frontal body movement during slip failure as the rearfoot moved medially or laterally after landing. Many sports injuries such as non-contact ACL injuries and ankle sprains occur within 100 msec after IC. It is difficult to measure the landing impact and biomechanical load without a force plate or three-dimensional analysis device. However, if we can relate the biomechanics to visible movement and estimate the load during landing, then the information can assist in the coaching of an athlete on the playing field, where there are no measuring instruments. Therefore, we think analyzing failed trials of sports movements is meaningful for understanding the relationship between the decline in performance of jump landings and the risk factors for sports injuries.

There were potential limitations to the current investigation that should be considered if these results are to be applied to clinical settings. First, we could not measure rearfoot displacement during landing because accuracy decreases during two-dimensional measurements. Second, it was unclear how the actual mechanical stress on the knee and ankle was changed by rearfoot movement. Third, although it was reported that the kinematics and kinetics of ankle and hip joints relate several sports injuries, we could not capture it in our current research. Forth, we have not yet been able to analyze the results separately for dominant or non-dominant legs. It has already been reported that the landing ability of a single leg landing differs between dominant and non-dominant legs.[27,40] In this study, we only compared successful and unsuccessful trials, but stratified analysis based on dominance is necessary in the future. Finally, it has been reported that there are sex-related differences in vertical GRF maximum values during jump-landing.[25,41] However, because our results were for both men and women, the impact of sex was unknown.

The results of the current investigation indicated that athletes who failed during single-leg lateral drop jump-landing with a high frequency have poor skills absorbing jump-landing impact, which is related to various sports injuries. It is possible to identify the risk factors for sports injuries by analyzing failure patterns. Additional studies that focus on the failed trials of sports biomechanics are needed. In the assessment of single-leg jump-landings in clinical settings, data on the frequency and pattern of failed trials could be used to monitor athletes' skills and screen for the risk of developing injuries.

Declaration of competing interest

The authors have no conflicts of interest relevant to this article.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.asmart.2021.07.004.

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