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Subsequent jumping increases the knee and hip abduction moment, trunk lateral tilt and trunk rotation motion during single-leg landing in female individuals

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Running Title: The effects of subsequent jumping

Abstract

Single-leg landings with or without subsequent jumping are frequently used to evaluate landing biomechanics. The purpose of this study was to investigate the effects of subsequent jumping on the external knee abduction moment and trunk and hip biomechanics during single-leg landing. Thirty young-adult female participants performed a single-leg drop vertical jumping (SDVJ; landing with subsequent jumping) and single-leg drop landing (SDL; landing without subsequent jumping). Trunk, hip and knee biomechanics were evaluated using a three-dimensional motion analysis system. The peak knee abduction moment was significantly larger during SDVJ than during SDL (SDVJ 0.08 ± 0.10 $Nm \cdot kg^{-1} \cdot m^{-1}$, SDL 0.05 ± 0.10 $Nm \cdot kg^{-1} \cdot m^{-1}$, p = .002). The trunk lateral tilt and rotation angles toward the support-leg side and external hip abduction moment were significantly larger during SDVJ than during SDL ($p < .05$). The difference in the peak hip abduction moment between SDVJ and SDL predicted the difference in the peak knee abduction moment (p = .003, R^2 = .252). Landing tasks with subsequent jumping would have advantages for evaluating trunk and hip control as well as knee abduction moment. In particular, evaluating hip abduction moment may be important because of its association with the knee abduction moment.

Keywords: anterior cruciate ligament, risk factor, injury prevention, core, unilateral landing

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Introduction

An anterior cruciate ligament (ACL) injury is a serious athletic injury that requires surgical reconstruction and extensive rehabilitation[1,2]. The majority of ACL injuries occur in noncontact situations, such as jump-landing or cutting maneuvers[3,4]. Cadaveric landing simulation studies have shown that the knee abduction moment contributes to ACL injuries[5–7]. A large knee abduction moment during landing is found to be a predictor of ACL injuries in female athletes[8]. Therefore, the knee abduction moment during landing has been considered a biomechanical risk factor for ACL injuries and should be reduced to prevent ACL injuries. Furthermore, female athletes demonstrate a larger knee abduction moment during landing than male athletes[9] and are more likely to have ACL injuries than male athletes[10]. Therefore, the knee abduction moment during landing tasks should be evaluated and reduced to minimize the risk of ACL injuries, especially in female athletes.

Double-/single-leg drop landing and drop vertical jumping are common landing tasks used to evaluate the knee abduction moment[8,11–14]. The presence or absence of a subsequent jump after landing leads to differences between the two landing tasks. A subsequent jump after landing is common in jump-landing sports, such as basketball, and has been shown to increase the knee abduction moment during double-leg landing[14,15]. On the other hand, another study reported no difference in the knee abduction moment between double-leg drop vertical jumping and double-leg drop landing[16]. The aforementioned studies investigated double-leg landings[14–16]; however, ACL injuries frequently occur during single-leg landing[4,17]. Only one study by Hovey *et al.*[13] reported that the subsequent jump did not increase the knee abduction moment during single-leg landing in 11 female and 14 male athletes. However, because the effects of a subsequent jump on knee biomechanics differ between males and females during double-leg landing[14], such effects during single-leg landing tasks should be investigated separately for male and female participants, especially as females have a greater risk of ACL injury. Hovey's study included 11 female athletes, and this sample size did not allow a medium effect size (less than *dz* of 0.94) with a power of 0.80 and an alpha of 0.05. Further studies are needed to clarify the effect of subsequent jumping in females.

Trunk and hip biomechanics in the frontal and transverse planes have been considered to influence the knee abduction moment. Trunk lateral tilt and rotation toward the support-leg side are associated with the knee abduction moment during athletic movements[11,18–25]. In addition, trunk lateral tilt toward the support-leg side has been observed in ACL injuries in females[26–29]. Furthermore, the hip adduction angle and abduction moment are positively associated with the knee abduction moment during drop vertical jumping and cutting tasks[21,24]. Therefore, the importance of controlling trunk and hip biomechanics in the frontal and transverse planes to decrease the knee abduction moment has been emphasized for ACL injury prevention[11,30,31]. While a previous study reported a trend, although not statistically significant, for the hip abduction moment to increase with a subsequent jump following single-leg landing[13], no study has investigated the effect of subsequent jumping on trunk lateral tilt and rotation motions in the frontal and transverse planes.

Trunk and hip biomechanics are associated with the knee abduction moment during landings[11,18–25]. The effects of subsequent jumping after landing on the knee abduction moment and on trunk and hip biomechanics during single-leg landing tasks in females are unclear. It is possible that the change in the knee abduction moment caused by subsequent jumping is associated with changes in trunk and hip biomechanics. Understanding the relationships between the change in the knee abduction moment and those in other biomechanics caused by a subsequent jump may be helpful for clinicians to reduce the knee abduction moment during a single-leg drop vertical jump. Therefore, the primary purpose of the present study was to investigate the effect of subsequent jumping on the knee abduction moment and on trunk and hip biomechanics during single-leg landing tasks in female participants. The secondary purpose was to identify the kinetic and kinematic factors associated with the change in the knee abduction moment due to subsequent jumping. The hypotheses were that a subsequent jump would increase the knee abduction moment, trunk lateral tilt and trunk rotation angles and that the change in the knee abduction moment caused by a subsequent jump would be associated with those in the trunk and hip biomechanics.

Methods

Participants: Thirty female participants (mean ± SD: age 21.7 ± 1.7 years; height 159.5 ± 5.7 cm; weight 52.5 ± 5.0 kg) volunteered for this study. A priori power analyses in a pilot study with 9 participants showed that 17 participants were necessary to achieve a statistical power (1 - β) of 0.8 with an alpha level (α) of .05 and an effect size (*dz*) of .74 in a paired t test for the knee abduction moment. In addition, a priori power analyses in the pilot study showed that 25 participants were necessary to achieve a statistical power (1 - β) of 0.8 with an alpha level (α) of .05 and a coefficient of determination of .26 in a univariate linear regression using the difference in the knee abduction moment between the single-leg drop vertical jumping and single-leg drop landing as a dependent variable and that in the hip abduction moment as an independent variable. The exclusion criteria included a history of musculoskeletal injuries in the previous 6 months, as well as surgeries or fractures in the lower extremities or trunk. All participants had previous experience with regular sports activities (11 tennis, 9 track and field, 4 volleyball, 3 badminton, 2 each basketball, handball, sepak takraw, softball, table tennis, karate and ballet, and 1 each soccer, kendo and kickboxing). Some participants had previous experience with multiple sports activities. The dominant leg (the side used for kicking a ball), which was the right leg in all participants, was tested and analyzed. Informed consent was obtained from all participants prior to participation in the study. This research was approved by the Institutional Review Board of the Faculty of Health Sciences, Hokkaido University (approval number: 16-97).

Procedures: The participants warmed up on a stationary bicycle for 5 minutes. Then, the marker coordinate data from each participant were collected during a static standing trial to create each participant's model during data processing. After the static standing trial data were collected, the participants performed single-leg landing tasks with or without a subsequent jump in a random order. All participants were barefoot to exclude the effects of shoes on lower extremity kinematics and kinetics[32]. Single-leg drop landing (SDL) was used as the landing task without a subsequent jump (Figure 1a). The participants stood on a 30-cm-high box on their dominant leg, then jumped just enough to clear the box before dropping and landing on their dominant leg and landed with their dominant leg on a force plate in the SDL task[11,33,34]. Participants were asked to hold the landing posture for a minimum of 3 seconds. Single-leg drop vertical jumping (SDVJ) was used as the landing task with a subsequent jump[11,12] (Figure 1b). The participants performed the SDVJ task in a similar manner to the SDL task; however, they were asked to jump with their dominant leg as high and fast as possible immediately after landing. During the two landing tasks, the participants were asked to look forward and to keep their hands at ear level to avoid marker occlusion[11]. The participants were allowed to perform practice trials until they became familiar with each landing task. Data for three successful trials for each SDL and SDVJ were collected after practice trials[11,12,33,34]. The participants were allowed to rest after each trial, as needed. Failed trials were defined as those in which the nondominant leg touched the ground or the participant lost her balance during the test and were excluded from the analysis. The means of three trials for both the SDL and SDVJ tasks were used in the statistical analyses.

Data collection: The marker coordinate data were collected with Cortex 5.0.1 (Motion Analysis Corporation, Santa Rosa, CA, USA) and seven high-speed cameras (Hawk cameras; Motion Analysis Corporation). The ground reaction force data were synchronously collected with a force plate (Type 9286, Kistler AG, Winterthur, Switzerland). The sampling rates were set to 200 Hz for the marker coordinate data and 1,000 Hz for the force plate data. A total of 41 retroreflective markers were placed on the thigh and shank of the dominant leg, the 7th cervical and 10th thoracic spinous process, the sacrum and both iliac crests, the acromions, the anterosuperior iliac spines, the greater trochanters, the medial and lateral femoral condyles, the medial and lateral malleoli, the heels and the second and fifth metatarsal heads.

Data analysis: The marker coordinate data and ground reaction force data were low-pass filtered using a zero-lag fourth-order Butterworth filter. The marker coordinate data were low-pass filtered at 12 Hz[15,33], while the ground reaction force was low-pass filtered at 50 Hz to evaluate the impulsive knee abduction moment immediately after initial contact[35]. The trunk, hip and knee angles and external moments were calculated in Visual3D software (version 6, C-Motion Inc., Germantown, MD, USA) using joint coordinate systems and inverse dynamics. The hip and knee angles were calculated with the Cardan *X-Y-Z* sequence (i.e., flexion/extension, abd-/adduction and internal/external rotation). Positive values indicated knee flexion, abduction and internal rotation as well as hip flexion, adduction and internal rotation. The trunk angles were calculated as the thorax segment angles in the global coordinate system. For the trunk angles, the rotation sequence was changed to *Z-Y-X* (i.e., axial rotation, lateral tilt and anterior/posterior tilt)[36]. Positive values indicated trunk lateral tilt and rotation toward the support-leg side. The segment anthropometric properties used to determine the external moments were based on a previous report[37]. The external joint moment was the torque caused by an external load. The external knee abduction moment would be resisted by the internal knee adduction moment[38]. Positive external moments indicated knee and hip flexion, abduction and internal rotation. In addition, the vertical ground reaction force was calculated considering the possible association with the knee abduction moment[24]. All angles measured during the static standing trial were set to 0°. The angle and moment data were extracted from the landing phase, which was defined as the time between the initial contact and the maximum knee flexion during both landing tasks. The first landing was analyzed in the SDVJ task. The initial contact was defined as when the vertical ground reaction force first exceeded 10 N[39]. Peak values of the trunk lateral tilt and rotation; hip flexion, adduction and internal rotation; and knee flexion, abduction and internal rotation angles were calculated during the landing phase. The peak knee and hip flexion, abduction and internal rotation moments and peak vertical ground reaction force during the landing phase were computed.

Statistical analysis: The normality of all values was evaluated using a Shapiro–Wilk test. A paired t test or Wilcoxon signed-rank test was used to investigate the influence of subsequent jumping on the kinematic and kinetic data depending on normality. Univariate regression analysis was performed using the differences in trunk, hip, and knee biomechanics and the vertical ground reaction force between the SDVJ and SDL tasks as independent variables and the difference in the peak knee abduction moment as a dependent variable. The statistical analyses were performed using IBM SPSS Statistics, version 26 (IBM, Armonk, NY, USA). The level of significance was set to $p < .05$. In addition, effect sizes were calculated for each pairwise comparison with Cohen's *dz* using G*Power 3.1.9.2 (Institute of Experimental Psychology, Hein-rich Heine University, Dusseldorf, Germany). The effect sizes were interpreted as follows: $dz \geq .80$ indicated a large effect, $.50 \leq dz < .80$ indicated a medium effect, and $.20 \leq dz < .50$ indicated a small effect[40].

Results

The peak knee abduction moment was significantly larger during SDVJ than during SDL, with a large effect size ($p = .002$, $dz = .624$) (Table 1). In addition, participants exhibited significantly larger peak knee and hip flexion and peak hip abduction moments during SDVJ than during SDL ($p < .001$, $dz = .819$; $p = .001$, $dz = .642$; $p = .008$, $dz = .517$, respectively)

(Table 1). There was no other difference in the knee or hip joint moments or the peak vertical ground reaction force.

In the kinematic analyses, the peak trunk lateral tilt and rotation angles toward the support-leg side were significantly larger during SDVJ than during SDL ($p < .001$, $dz = .743$; $p = .031$, $dz = .413$, respectively) (Table 2). Moreover, the peak knee and hip internal rotation angles were significantly larger during SDVJ than during SDL ($p = .005$, $dz = .553$; $p = .027$, $dz = .460$, respectively) (Table 2). There was no other difference in the trunk, hip and knee kinematics.

Univariate regression analysis showed that the difference in the peak knee abduction moment between SDVJ and SDL was predicted by the difference in the peak hip abduction moment ($p = .003$, $R^2 = .252$) (Figure 2). The standard regression coefficient (β) was .527. There were no other significant predictors for the difference in the peak knee abduction moment between SDVJ and SDL.

Discussion

This study revealed that the peak knee and hip abduction moments, the peak trunk lateral tilt and rotation angles toward the support-leg side were significantly larger during SDVJ than during SDL and that the increase in the peak knee abduction moment caused by subsequent jumping was significantly associated with the increase in the peak hip abduction moment. These findings supported the a priori hypotheses.

In the present study, the peak knee abduction moment was significantly larger during SDVJ than during SDL, which is consistent with a previous study on double-leg DVJ and DL[14,15]. On the other hand, a previous study of a single-leg landing task did not find a significant difference in the knee abduction moment between SDVJ and SDL, although the knee abduction moment during SDVJ was larger than that during SDL[13]. This previous study included 14 male and 11 female participants, whereas this study included only female participants. Female athletes have a larger knee abduction moment, normalized for body weight and height, during landing than male athletes[9]. The present study was able to detect the difference in the knee abduction moment between the two landing tasks because a sufficient sample size of only female participants were included. Since the effects of a subsequent jump on knee biomechanics differed between males and females during double-leg landing tasks[14], future studies should investigate sex differences in the effects of a subsequent jump following a single-leg landing on the knee abduction moment, taking sample size into account. Furthermore, while the participants in the present study had previous experience with regular sports activities regardless of jumping and landing activities, those in the previous study[13] seemed to be recreational athletes participating in jumping and landing sports activities at the time of the study. The difference in participants' characteristics between studies may lead to different result in knee abduction moment between the studies.

The difference in the peak knee abduction moment during SDVJ and SDL was significantly predicted by the difference in the peak hip abduction moment. In addition, the peak knee and hip abduction moments were larger during SDVJ than during SDL. These results suggest that the increase in the knee abduction moment caused by a subsequent jump is associated with the increase in the hip abduction moment and support previous studies on lateral reactive jumping and cutting tasks[21,25]. Pertinently, the external hip abduction moment is balanced by the internal hip adductor torque. An increase in the trunk lateral tilt toward the support-leg side can generate an external load on the knee abduction moment via the reactive hip adductor torque as a result of the increase in the hip abduction moment[41]. The peak trunk lateral tilt angle during the SDVJ task was also significantly larger than that during the SDL task in the present study, which may have contributed to the increase in the hip abduction moment. However, a causal relationship among these variables cannot be established based on the present study.

Although the difference in the peak hip abduction moment during SDVJ and SDL explained 25% of the variance in the difference in the peak knee abduction moment, the remaining 75% was not explained. Knee abduction moment is associated with lower gluteus medius force during landing[24]. In addition, gluteus medius and minimus and soleus muscle force can resist the knee abduction moment[42]. Moreover, large knee abduction moment during single-leg landing is associated with large adductor longus to gluteus medius activity ratio[43]. Muscle force and activity analysis may be required for better prediction, as net moment analysis does not provide individual muscle force or activity.

To the best of our knowledge, the present study is the first to show larger peak trunk lateral tilt and rotation angles toward the support-leg side during SDVJ than during SDL. The increase in the trunk lateral tilt and rotation angle toward the support-leg side may be needed to position the center of mass closer to the support-leg or to balance the body in preparation for the subsequent jump at maximum height. On the other hand, trunk lateral tilt and rotation toward the support-side leg side are reported as signs of weak hip abduction and extension strength[44], and the increase in those motions during SDVJ may be a response to the large demand on hip abduction muscle strength to prepare for subsequent jumping[45]. Although a large trunk lateral tilt and rotation toward the support-leg side are typically associated with a larger knee abduction moment during landing and side cutting tasks[11,19–23], linear relationships between the difference in the peak knee abduction moment caused by subsequent jumping and the differences in the trunk lateral tilt and rotation angles were not detected. Trunk lateral tilt toward the support-leg side is also a biomechanical feature in ACL injury situations determined by video analysis studies[26–29]. Single-leg landing tasks with a subsequent jump, such as SDVJ, are similar to ACL injury situations and can be used to evaluate frontal plane trunk control. On the other hand, although trunk rotation away from the support-leg side is observed in ACL injury situations[26,28,29], large trunk rotation toward the support-leg side is associated with larger knee abduction moments[19,21]. Thus, further research is needed to investigate the relationship between ACL injury and large trunk rotation toward the support-leg side during single-leg landing tasks with a subsequent jump.

The present study did not find a difference in the knee abduction angle between the SDVJ and SDL tasks. This result contradicts prior research, which found that the knee abduction angle is larger during landing with a subsequent jump than during landing without a subsequent jump[13,14]. In this study, the peak knee and hip internal rotation angles and flexion moments were significantly larger during SDVJ than during SDL. A previous study reported that larger knee and hip internal rotation angle excursions and smaller knee abduction moment were associated with smaller peak knee abduction angles [46]. In addition, a larger knee flexion moment is associated with a larger quadriceps force[34], and quadriceps contraction could be used to resist knee valgus moments[47]. Moreover, the hip flexion moment (internal hip extension moment) is important for modified landing stiffness and is required for soft-landing strategies that are associated with a small knee abduction angle[48,49]. These findings suggest that the increase in the knee and hip internal rotation angles and flexion moments and in the knee abduction moment caused by a subsequent jump might be attributed to no change in the knee abduction angle caused by a subsequent jump.

The present study did not find a difference in the vertical ground reaction force between the two landing tasks. The peak vertical ground reaction forces were comparable between the first and second landings during a double-leg drop vertical jump[15], in which the mid-flight maximum height of center of mass was equivalent between the two landings in a previous study. On the other hand, the peak vertical reaction force during SDVJ was smaller than that during SDL despite the same landing height between the two landings[13]. Additionally, the vertical ground reaction force during the landing phase is not correlated with jumping height in the drop vertical jump task[50]. The peak vertical ground reaction force is usually observed within 63.5 ms after initial contact during single-leg landing[34] and is not associated with subsequent jumping after landing.

The present study had some limitations. First, this study included only female participants. Previous studies have reported sex differences in the effects of subsequent jumps on knee biomechanics[13,14]. Therefore, future studies should investigate sex differences in the effects of subsequent jumps after single-leg landings on knee biomechanics while considering sample size. Second, only single-leg landings were examined. The kinematic and kinetic factors associated with an increase in the knee abduction moment caused by subsequent jumps during single-leg landings may differ from those associated with double-leg landings. Third, this study included participants of different levels and types of previous sports activities. The level and type of sports activities may affect biomechanics during landing[51,52]. Fourth, participants were asked to keep their hands at ear level during the two landing tasks. Therefore, the effects of the subsequent jump on the landing biomechanics may be different in actual sports situations. Fifth, multiple statistical tests were conducted without alpha adjustment in this study. Previous studies used similar statistical comparisons of lower extremity kinetics and kinematics with a similar study design[53,54]. However, we should acknowledge that test repetition increases the probability of a studywise type I error rate. Finally, causal relationships among the knee, hip and trunk biomechanics could not be established based on the associations in this study. The effects of intervention on the knee abduction moment should be investigated based on the findings in the present study.

The present study showed that a subsequent jump after a single-leg landing led to a significant increase in the knee abduction moment. Moreover, subsequent jumping after a single-leg landing significantly increased the trunk lateral tilt and rotation angles toward the support-leg side and hip abduction moment. The knee abduction moment and trunk lateral tilt angle toward the support-leg side were predictive factors of ACL injuries[8,55]. A qualitative assessment tool of single-leg loading included trunk lateral tilt as one of the checklists[56]. Thus, clinicians should use the SDVJ task to evaluate the knee abduction moment, the trunk lateral tilt and rotation angle. Landing instructions focused on the pelvic and trunk lateral tilt are effective in reducing the trunk lateral tilt and knee abduction moment during SDVJ[11]. Furthermore, the change in the peak hip abduction moment caused by a subsequent jump predicted the change in the peak knee abduction moment in this study. Therefore, controlling the hip abduction moment (internal hip adductor torque) may be important for decreasing the knee abduction moment during single-leg landings followed by a subsequent jump. These findings suggest that landing tasks with a subsequent jump, such as SDVJ, would be more advantageous for evaluating the knee abduction moment, trunk lateral tilt and rotation angles and hip abduction moment than landing tasks without subsequent jumping.

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Table 1. Comparison of the peak knee and hip joint moments and the peak vertical ground reaction force between SDVJ and SDL.

	SDVJ	SDL	*p* value	*dz*
Peak moment, Nm·kg^{-1}·m^{-1}				
Hip flexion	2.16 (0.48)	1.91 (0.53)	**.001**	**.642**
Hip abduction	0.14 (0.12)	0.09 (0.15)	**.008**	**.517**
Hip internal rotation[a]	0.04 (0.06)	0.05 (0.06)	.213	.202
Knee flexion	2.02 (0.31)	1.81 (0.24)	< **.001**	**.819**
Knee abduction[a]	0.08 (0.10)	0.05 (0.10)	**.002**	**.624**
Knee internal rotation[a]	0.13 (0.08)	0.13 (0.07)	.349	.137
Peak vertical ground reaction force, N/kg	40.1 (4.7)	40.6 (5.0)	.563	.107

SDVJ: single-leg drop vertical jumping, SDL: single-leg drop landing.
The data are presented as the mean (SD).
Knee and hip moments are calculated as external joint moments.
[a]non-parametric data.

Table 2. Comparison of the peak knee, hip and trunk kinematics between SDVJ and SDL.

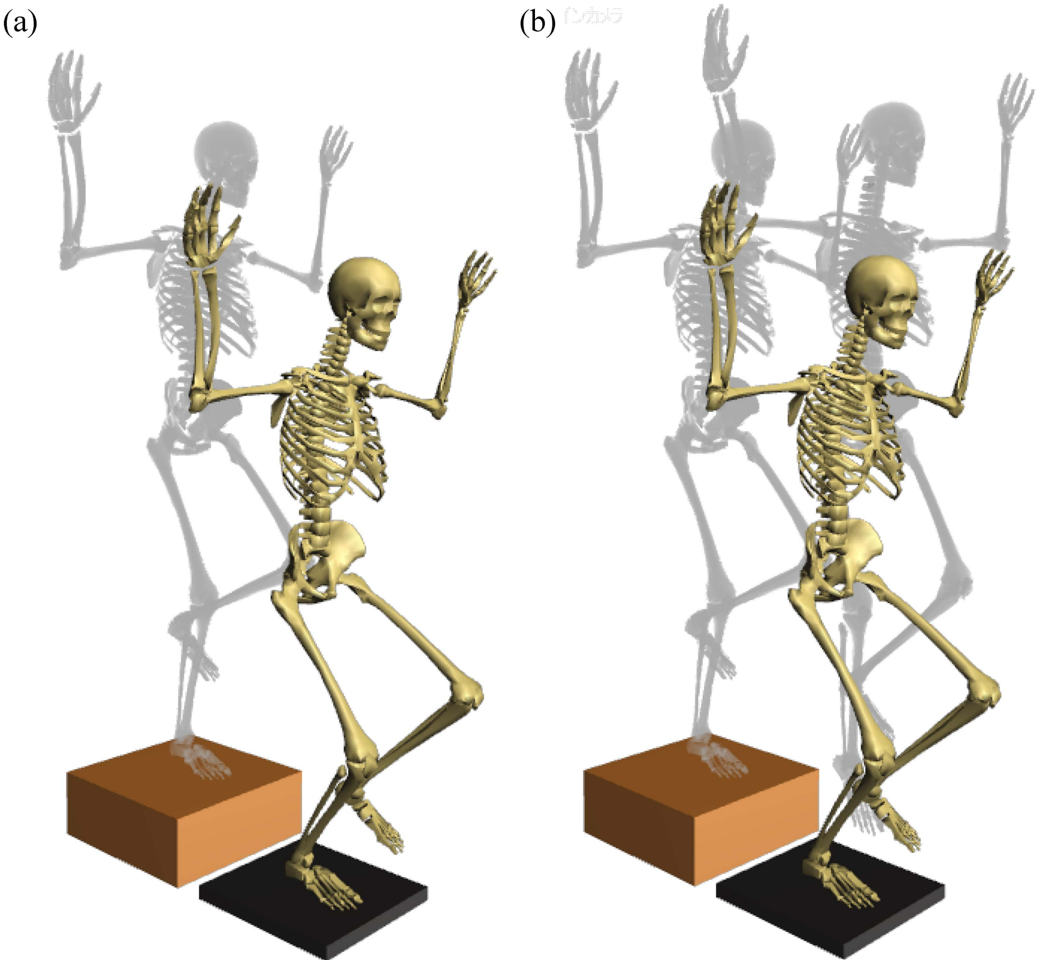
	SDVJ	SDL	*p* value	*dz*
Peak angle, degree				
Trunk lateral tilt	5.7 (3.2)	4.3 (2.6)	**< .001**	**.743**
Trunk rotation	4.9 (3.8)	3.6 (4.3)	**.031**	**.413**
Hip flexion	34.5 (6.4)	36.3 (6.3)	.053	.369
Hip adduction	9.4 (4.2)	9.1 (3.6)	.596	.098
Hip internal rotation[a]	7.4 (5.6)	6.3 (4.7)	**.027**	**.460**
Knee flexion	59.2 (6.6)	59.2 (7.1)	.940	.014
Knee abduction	0.3 (4.2)	-0.2 (3.2)	.143	.275
Knee internal rotation	7.8 (5.3)	6.8 (5.9)	**.001**	**.553**

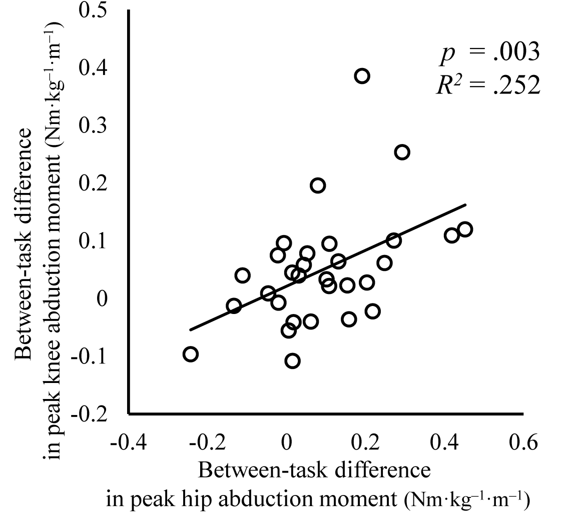
SDVJ: single-leg drop vertical jumping, SDL: single-leg drop landing.
The data are presented as the mean (SD).
Bold font indicates a significant difference ($p < .05$).
Positive angles indicated trunk lateral tilt and rotation toward the support-leg side.
[a]non-parametric data.

Figure Captions

Figure 1. Landing tasks with and without a subsequent jump. Single-leg drop landing (SDL): the participants stood on a 30-cm-high box on their dominant leg, then jumped just enough to clear the box before dropping and landing on their dominant leg and landed on a force plate (a). Single-leg drop vertical jumping (SDVJ): the participants stood on a 30-cm-high box on their dominant leg, then jumped just enough to clear the box before dropping and landing on their dominant leg, landed on a force plate, and executed a maximum single-leg vertical jump immediately after landing (b).

Figure 2. Scatter plot of the association of the between-task difference in the peak knee abduction moment with the between-task difference in the peak hip abduction moment. The between-task difference was determined by subtracting the SDL value from the SDVJ value. Knee and hip abduction moments are calculated as external joint moments.


(a)
(b)


p = .003
R2 = .252
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.4
-0.2
0
0.2
0.4
0.6
Between-task difference
in peak knee abduction moment (Nm·kg−1·m−1)
Between-task difference
in peak hip abduction moment (Nm·kg−1·m−1)