Title	Larger hip external rotation motion is associated with larger knee abduction and internal rotation motions during a drop vertical jump
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Citation	Sports biomechanics https://doi.org/10.1080/14763141.2021.1881151
Issue Date	2021-03-04
Doc URL	http://hdl.handle.net/2115/84301
Rights	This is an Accepted Manuscript of an article published by Taylor & Francis in Sports biomechanics on 04 Mar 2021, available online: http://www.tandfonline.com/10.1080/14763141.2021.1881151.
Type	article (author version)
File Information	Sports Biomech_HUSCAP.pdf

Larger hip external rotation motion is associated with larger knee abduction and internal rotation motions during a drop vertical jump

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Larger hip external rotation motion is associated with larger knee abduction and internal rotation motions during a drop vertical jump

Abstract

Associations among hip motions, knee abduction and internal rotation motion during a drop vertical jump (DVJ), which increases the risk of anterior cruciate ligament (ACL) injury, remain unclear. The purpose of this study was to examine associations among knee abduction, internal rotation and hip joint motions during a DVJ. Fifty-seven young female participants performed a DVJ from a 30-cm height. Hip and knee kinematics and kinetics were analysed using a three-dimensional motion analysis system and force plates. Multiple regression analysis showed that peak knee abduction angle was negatively associated with knee internal rotation and hip internal rotation excursions from initial contact (IC) to peak knee flexion, and positively associated with peak knee abduction moment ($R^2 = 0.465$, $P < 0.001$). Peak knee internal rotation angle was negatively associated with the hip flexion excursion from IC to peak knee flexion and peak hip adduction moment ($R^2 = 0.194$, $P = 0.001$). In addition, hip internal rotation excursion was negatively associated with knee abduction and internal rotation excursion from IC to 50 ms after IC. To avoid a large knee abduction and internal rotation motion during jump-landing training, it might be beneficial to provide landing instructions to avoid a large hip external rotation motion.

Keywords: anterior cruciate ligament (ACL); prevention; knee valgus; hip kinematics; landing

Introduction

Anterior cruciate ligament (ACL) injuries are severe sports injuries. Individuals cannot return to sports for more than 6 months after ACL reconstruction (Barber-Westin & Noyes, 2011). Furthermore, only two-thirds of athletes who underwent ACL reconstruction returned to their preinjury level of sports after surgery, and one-fifth of athletes suffered a second ACL injury after returning to sports (Ardern et al., 2014; Wiggins et al., 2016). Female athletes are more likely to sustain primary and secondary ACL injuries than male athletes (Agel et al., 2016; Paterno et al., 2017). Although some prevention programmes targeting female athletes have shown preventive effects (LaBella et al., 2011; Omi et al., 2018; Waldén et al., 2012), the overall number of ACL injuries among female athletes has not decreased (Agel et al., 2016). Therefore, prevention programmes and rehabilitation after ACL reconstruction for female athletes should be improved to reduce the risk of ACL injury in female athletes.

Most ACL injuries occur during noncontact deceleration, and jump landing is one of the most frequent situations leading to injury (Shimokochi & Shultz, 2008). In cadaveric landing simulations, high external knee abduction moments induced high ACL strains (Bates et al., 2019; Kiapour et al., 2016; Navacchia et al., 2019; Ueno, Navacchia, Bates, et al., 2020). A large knee abduction moment is a key mechanism of ACL injuries occurring during simulated landing (Navacchia et al., 2019; Ueno, Navacchia, Bates, et al., 2020). A previously proposed ACL injury mechanism is compression on the lateral compartment of the knee with knee abduction due to a large knee abduction moment, inducing anterior tibial translation and knee internal rotation due to the posterior slope of the tibia (Koga et al., 2010; Matsumoto, 1990; Navacchia et al., 2019; Ueno, Navacchia, Bates, et al., 2020). In fact, in noncontact ACL injuries, rapid knee abduction motion and knee internal rotation with relatively low knee flexion angle occurred immediately after initial contact (IC) with the ground (Koga et al., 2010). In addition, the peak knee abduction angle and knee abduction excursion during the first landing in a drop vertical jump predicted primary and secondary ACL injuries in female athletes (Hewett et al., 2005; Paterno et al., 2010). A small knee flexion angle during a drop vertical jump was also a risk factor for ACL injury (Hewett et al., 2005; Leppänen et al., 2017). Therefore, a large knee abduction and internal rotation motion and a small knee flexion angle, as well as a large knee abduction and knee internal rotation moment, should be avoided to reduce the risk of ACL injury (Bates et al., 2019; Hewett et al., 2005; Kiapour et al., 2016; Koga et al., 2010; Leppänen et al., 2017; Navacchia et al., 2019; Paterno et al., 2010; Ueno, Navacchia, Bates, et al., 2020).

Previous researchers have suggested that hip and ankle motions during landing are important for reducing the risk of ACL injury because knee kinematics are affected by adjacent joints due to the kinematic chain (Hewett et al., 2005; Hogg et al., 2019; Howard et al., 2011; Ishida et al., 2015; Malloy et al., 2015, 2016; Nguyen et al., 2015; Paterno et al., 2010; Ueno, Navacchia, DiCesare, et al., 2020). Recent studies have shown that limited hip motions are indicated as risk factors for ACL injuries (Beaulieu et al., 2014; Bedi et al., 2016; Koga et al., 2018). In previous *in vitro* studies, models with restricted femoral internal rotation demonstrated larger ACL strain during simulated landing than models without restricted femur motion (Beaulieu et al., 2014; Bedi et al., 2016). Furthermore, the restriction of femoral internal rotation increased the magnitude of anterior tibial translation during simulated landing (Beaulieu et al., 2015). Moreover, a video analysis showed that the hip internal rotation angle, as well as the hip flexion and adduction angles, did not change during the early landing phase of jumps leading to ACL injuries (Koga et al., 2018). These studies indicated that smaller hip motions during landing might increase the risk of ACL injuries (Beaulieu et al., 2014, 2015; Bedi et al., 2016; Koga et al., 2018). However, the application of these *in vitro* findings may be limited because hip internal rotation was restricted by a hard stop, such as femoroacetabular impingement, in these *in vitro* studies (Beaulieu et al., 2014, 2015; Bedi et al., 2016). During *in vivo* landing, the peak knee abduction angle was associated with the peak hip adduction angle but not the peak hip internal rotation angle (Hogg et al., 2019). On the other hand, another recent study has shown that the knee abduction and internal rotation angle was increased with ipsilateral trunk rotation to the knee during a double leg landing, and the authors suggested that femur external rotation is a possible mechanism underlying these findings (Critchley et al., 2020). The relationships between hip and knee joint motions during *in vivo* landing remains uncertain. In addition, which knee and hip joint motions and moments have the largest effect on the peak knee joint angles and excursions including abduction, internal rotation and flexion, it is unknown. Understanding the associations among knee and hip joint motions and external joint moment during a drop vertical jump, could help improve jump-landing training and optimise hip joint motions, thereby reducing the peak knee abduction and internal rotation angle and increasing the peak knee flexion angle.

The purpose of the present study was to examine the association of the peak knee joint angles (knee abduction, internal rotation and flexion) with hip joint motions and the external moment of the knee and hip joints during the first landing in a drop vertical jump. In addition, the associations of knee joint angle excursions (knee abduction, internal rotation and flexion) with hip flexion, adduction and internal rotation excursions were examined to identify the kinematic relationships. The hypotheses were that a larger peak angle and excursion for knee abduction and internal rotation and a smaller peak angle and excursion for knee flexion are associated with smaller hip internal rotation excursion or larger hip external rotation, as well as smaller hip adduction and flexion excursions.

Methods

Participants

Based on a previous study (Hogg et al., 2019), a medium effect size was estimated for an independent variable. To achieve a significance level (α), statistical power ($1 - \beta$) and effect size (f^2) of 0.05, 0.8 and 0.15 in the regression model, respectively, 55 participants were needed. Considering the possibility of data deficiency, 57 healthy female participants (mean ± SD: age 21.1 ± 1.3 years, height 160.6 ± 6.5 cm, mass 52.9 ± 6.9 kg) participated in this study. Individuals were excluded if they reported a history of musculoskeletal injuries or disorders within the last 6 months, severe injuries of the lower extremities or trunk, knee injuries, or participation in an ACL injury prevention programme. All participants had experience with regular sports, such as basketball, handball or soccer. The right leg was tested and analysed because the dominant side of all participants was the right side. The dominant leg was defined as the side preferable for kicking a ball. Prior to participation, the participants were provided information regarding this study and were required to sign informed consent forms. The present study was approved by the review board of the Faculty of Health Sciences, Hokkaido University (11-55).

Procedures and data collection

The participants warmed up on a stationary bicycle for 5 min and then performed a standardised static standing trial, followed by landing trials. A drop vertical jump task was used to evaluate the landing kinematics. The participants were instructed to drop from a 30-cm-high box and then land on two force plates (Type 9286, Kistler AG, Winterthur, Switzerland) with one foot on each plate and perform a maximum vertical jump immediately thereafter. Practice trials were permitted to allow the participants to become familiar with the landing task. Three successful trials of drop vertical jumps were collected.

Synchronised marker coordinates and force data were recorded using EVaRT 4.4 (Motion Analysis Corp., Santa Rosa, CA, USA) with six digital cameras (Hawk cameras, Motion Analysis Corp.) and the force plates. The two force plates were positioned 5.5 cm apart and 10 cm in front of the box to land on a different force plate with each foot (Ishida et al., 2015; Nguyen et al., 2015). The sampling rate was 200 Hz for the marker coordinate data and 1,000 Hz for the force plate data. In total, 39 retroreflective markers were placed on the bony landmarks of the pelvis and lower extremities (the sacrum, right iliac crest and medial knee, both shoulders, anterosuperior iliac spines (ASIS), greater trochanters, lateral knees, medial and lateral ankles, heels, and second and fifth metatarsal heads), and 10 and 6 cluster markers were placed on the right thigh and shank, respectively.

Data processing and reduction

The first landing in the drop vertical jump task was analysed because the knee abduction angle and moment during the first landing have been shown to predict ACL injuries (Hewett et al., 2005; Paterno et al., 2010). In addition, the first landing yielded larger knee abduction motion and moment than the second landing and a drop landing without a subsequent jump (Bates et al., 2013; Ishida et al., 2018). Three-dimensional knee and hip kinematics were estimated using a rigid-body skeletal model with a joint coordinate system using SIMM 6.0.2 software (MusculoGraphics Inc., Santa Rosa, CA, USA) (Delp et al., 1990). The marker trajectory data were low-pass filtered using a fourth order Butterworth filter with a 12-Hz cutoff frequency. The ground reaction force data were low-pass filtered using a generalised cross validation spline with a 25-Hz cutoff frequency. The joint angles were calculated using the Cardan sequence (flexion/extension, abduction/adduction, and then internal/external rotation), and those during the static standing trial were set to zero and served as references for the drop vertical jump trials. The positive angles indicate knee flexion, abduction and internal rotation; and hip flexion, adduction and internal rotation. The analysed landing phase was defined as the phase from the initial contact (IC) to the peak knee flexion. IC was defined as when the vertical ground reaction force first exceeded 10 N (Ford et al., 2007). The peak knee flexion, abduction and internal rotation angles during the landing phase were derived. Angular excursions of the knee and hip joints were calculated from IC to 50 ms after IC. This time range was chosen for the analysis since it is the time range during which ACL injuries have been shown to occur (Koga et al., 2010; Ueno, Navacchia, Bates, et al., 2020). In addition, angular excursions of the knee and hip joints from IC to peak knee flexion were calculated to examine the association between the peak knee joint angles (flexion, abduction and internal rotation) and knee and hip joint motion during the landing phase. The external moments at the joints were also estimated using inverse dynamics with SIMM software. The segment inertial parameters were selected based on a previous report (de Leva, 1996). The peak moments of the knee and hip joints were derived and normalised to the body mass and height (Nm/kg/m). The positive moments indicate knee flexion, abduction and internal rotation; and hip flexion, adduction and internal rotation.

Statistical analysis

A stepwise multiple regression analysis was conducted to determine which kinetic and kinematic variables of the hip and knee joints predict the peak knee flexion, abduction and internal rotation angles and the excursion of knee flexion, abduction and internal rotation excursions from IC to 50 ms after IC. The independent variables were the excursions of the knee and hip joints from IC to peak knee flexion or 50 ms after IC, the peak external moments of the knee and hip joints, and the peak vertical ground reaction force. The criterion for a dependent variable to be included was $P < 0.05$, and the criterion to exclude a dependent variable was $P > 0.10$. The statistical analyses were performed using the IBM SPSS Statistics 22 software program (IBM Corporation, Armonk, NY, USA). and the level of significance was set to $P < 0.05$.

Results

The knee flexion angle increased from 23.9 ± 6.7° at IC to 51.9 ± 5.8° at 50 ms after IC and 83.0 ± 10.9° at the peak (Fig. 1A). The hip flexion, hip adduction and knee abduction angles showed an increasing tendency from IC to the peak knee flexion (Fig. 1B, D and E). In contrast, the knee internal rotation angle reached its peak at 50.6 ± 16.7 ms after IC, and then the knee rotated externally (Fig. 1C). Regarding the hip rotation motion, the average curve displayed small external rotation motion because two motion patterns were observed among the participants (Fig. 1F). Twenty-five participants demonstrated hip internal rotation motion (increased internal rotation or decreased external rotation), while the other 32 participants demonstrated hip external rotation motion (Fig. 2).

The multiple regression analysis revealed that the knee internal rotation and hip internal rotation from IC to peak knee flexion and the peak knee abduction moment predicted the peak knee abduction angle ($R^2 = 0.465$, $P < 0.001$) (Table 1). Negative associations were found with the knee internal rotation excursion and hip internal rotation excursion (Fig. 3A), while a positive association was found with the peak knee abduction moment. From IC to 50 ms after IC, the hip internal rotation excursion, knee internal rotation excursion and the peak knee abduction moment predicted the knee abduction excursion ($R^2 = 0.292$, $P < 0.001$) (Table 2). The peak knee abduction moment was positively associated, while the hip internal rotation excursion (Fig. 4A) and knee internal rotation excursion were negatively associated with the knee abduction excursion from IC to 50 ms after IC.

The peak knee internal rotation angle was predicted by the hip flexion excursion from IC to peak knee flexion and the peak hip adduction moment ($R^2 = 0.194$, $P = 0.003$) (Table 1). Negative associations were found with the hip flexion excursion (Fig. 3B) and peak hip adduction moment. The knee internal rotation excursion from IC to 50 ms after IC was predicted by the hip internal rotation and knee abduction excursions from IC to 50 ms after IC and the peak knee flexion moment ($R^2 = 0.302$, $P < 0.001$) (Table 2). Negative associations were found with the hip internal rotation excursion (Fig. 4B) and knee abduction excursion.

The hip flexion excursion from IC to peak knee flexion and the peak vertical ground reaction force were included in the regression model of the peak knee flexion angle ($R^2 = 0.636$, $P < 0.001$) (Table 1). The hip flexion excursion was positively associated with the knee flexion excursion, while the peak vertical ground reaction force was negatively associated with the knee flexion excursion. The knee flexion excursion from IC to 50 ms after IC was explained by the hip flexion excursion from IC to 50 ms after IC and the peak knee abduction moment ($R^2 = 0.641$, $P < 0.001$) (Table 2).

Discussion and implications

The purpose of the present study was to identify the associations of the peak knee joint angles and excursions (knee abduction, internal rotation and flexion) with hip joint motions and external moments of the knee and hip joints during the first landing in a drop vertical jump task. A main finding of the present study is that a smaller hip internal or a larger hip external rotation excursion from IC to peak knee flexion was associated with a larger peak knee abduction angle. A smaller internal or a larger external hip rotation excursion was also associated with a larger knee abduction and internal rotation excursion during the 50 ms after IC. In addition, a smaller hip flexion excursion was associated with a smaller peak knee flexion and a larger peak knee internal rotation angle. These findings partially support the *a priori* hypothesis that a smaller hip internal rotation excursion or a larger hip external rotation, as well as smaller hip adduction and flexion excursions are associated with larger peak angles and excursions for knee abduction and internal rotation and a smaller peak angle and excursion for knee flexion.

The present study showed that hip internal rotation excursion was a predictor in the regression models that predicted the peak knee abduction angle, the knee abduction excursion, and the knee internal rotation excursion from IC to 50 ms after IC. A smaller internal or a larger external hip rotation motion was associated with a larger peak knee abduction angle and a larger knee abduction excursion from IC to 50 ms after IC. Even among the participants with larger knee abduction moments, the peak knee abduction angle and the knee abduction excursion tended to be smaller when the participants showed hip internal rotation patterns or smaller hip external rotation excursions. Previous studies reported that a larger femoral anteversion was associated with a larger knee abduction excursion during single-leg and double-leg landings (Howard et al., 2011; Nguyen et al., 2015). Although these studies suggested the possibility that a large hip internal rotation motion could be associated with a large knee abduction during single-leg and double-leg landings, the present study showed that the kinematic relationship between knee abduction and hip rotation motion during a double-leg landing was the opposite. On the other hand, another study showed that a large knee abduction angle was associated with a large hip adduction angle but not a hip internal rotation angle during a single-leg landing (Hogg et al., 2019). Therefore, the kinematic relationship between the knee and hip may differ between double-leg and single-leg landings. When the external knee abduction moment is applied, knee abduction motion accompanied by hip internal rotation might be the natural kinematic relationship, which is known as the dynamic valgus alignment of the lower extremity (Hewett et al., 2010; Olson et al., 2011). Although hip internal rotation motion can be associated with lower extremity dynamic valgus alignment (Hewett et al., 2010; Olson et al., 2011), the results of the present study showed that a large hip internal rotation was not associated with a large knee abduction during a landing. When the medial tilt of the tibia occurs with the hip internal rotation at the knee flexed position with the foot in contact with the ground, the motion directions of both the tibia and femur could face the same direction, and knee abduction might be diminished (Fig. 5A). In contrast, hip external rotation motion would cause the femur to face the opposite direction to the medial tilt of the tibia and could increase knee abduction motion (Fig. 5B). Ipsilateral trunk rotation motion to the knee, which could be associated with femur external rotation, increased the knee abduction angle during a double leg landing (Critchley et al., 2020), which is consistent with the present findings. However, the lack of a cause-effect relationship is acknowledged in the present study. Additional studies are necessary to examine the effect of instruction to avoid a large hip external rotation motion on knee abduction motion during a double-leg landing.

A smaller internal or larger external hip rotation excursion was also associated with a larger knee internal excursion during the 50 ms after IC. Previous *in vitro* studies have shown that a restriction of the hip internal rotation increases the ACL strain compared to no restrictions due to increases in anterior tibial translation and knee internal rotation in a simulated landing task (Beaulieu et al., 2014, 2015; Bedi et al., 2016). Although hip internal rotation was restricted by a hard stop, such as bony impingement, in these *in vitro* studies, the present *in vivo* study supports the previous hypothesis that hip internal rotation can decrease knee internal rotation during the early landing phase (Beaulieu et al., 2014; Bedi et al., 2016). In addition, ipsilateral trunk rotation, which could be associated with the femur external rotation to the pelvis, increased the knee internal rotation angle during a double-leg landing (Critchley et al., 2020). The present findings also suggest the possibility that hip external rotation motion might increase knee internal rotation during a landing, although the cause-effect relationship between hip rotation and knee rotation motion is uncertain based on the present study. Further studies are necessary to reveal the mechanism underlying these kinematic relationships.

A smaller hip flexion excursion was associated with a larger peak knee internal rotation and a smaller peak knee flexion angle and knee flexion excursion from IC to 50 ms after IC. These associations seem to be similar to previous video analysis studies that showed a rapid knee internal rotation immediately after landing in cases of ACL injury (Koga et al., 2010), while the hip flexion angle did not change (Koga et al., 2018). A smaller total of hip flexion and knee flexion during landing was associated with a larger knee abduction angle and moment during a drop vertical jump (Pollard et al., 2010). A landing pattern that relies on passive restraints to decelerate the body centre of mass, instead of knee and hip flexion, is referred to as the ‘ligament dominance’ strategy, which is considered indicative of poor neuromuscular control associated with ACL injury (Pollard et al., 2010). Although the mechanism underlying the relationship between the peak knee internal rotation angle and hip flexion excursion was not found in this study, the present findings could indicate a ‘ligament dominance’ strategy in female participants. A small peak knee flexion angle during a drop vertical jump was also reported to be a risk factor of ACL injury (Hewett et al., 2005; Leppänen et al., 2017). Small knee flexion angles are associated with high ACL strain (Markolf et al., 1995). Therefore, the hip flexion motion would be important in relation to knee flexion motion.

The regression analysis showed that the hip internal rotation excursion was negatively associated with the peak knee abduction angle, the knee abduction excursion, and knee internal rotation excursion from IC to 50 ms. Hence, the regression analysis also showed that the knee internal rotation excursion from IC to peak knee flexion was negatively associated with the peak knee abduction angle and that the knee internal rotation excursion was negatively associated with the knee abduction excursion from IC to 50 ms after IC. These results initially seem contradictory but are not surprising because the regression model includes adjustments for other variables, such as hip internal rotation excursion. Among healthy participants in the quasi-static lunge position, dynamic knee valgus alignment was associated with increasing knee abduction and external rotation angles (Ishida et al., 2014). The coupling of knee abduction with knee internal rotation was one of the occurring mechanisms of ACL injuries (Koga et al., 2010; Matsumoto, 1990; Navacchia et al., 2019; Ueno, Navacchia, Bates, et al., 2020). Therefore, the negative association between knee abduction and knee internal rotation observed in the present *in vivo* study could be a natural motion pattern to avoid ACL injury.

Concerning its application, the present study showed that hip internal rotation motion, rather than external rotation, was associated with a smaller peak knee abduction angle and smaller excursion to knee abduction and internal rotation during the early landing phase in a drop vertical jump task. To reduce knee abduction and internal rotation motion in jump-landing training, it might be beneficial to provide instructions to avoid a large hip external rotation motion during a double-leg landing. However, the present study did not address the cause-effect relationship between hip internal rotation and knee abduction and internal rotation. Additional studies are needed to reveal whether landing instructions to avoid a large hip external rotation motion could reduce knee abduction and internal rotation during a double-leg landing. Although the relationship between the passive range of motion (ROM) and hip rotation motion during a landing is unclear, a sufficient ROM to allow for hip internal rotation motion would be important. Previous studies have also shown that patients with ACL tears have a significantly smaller internal rotation ROM in the hip than control participants (Bedi et al., 2016; Ellera Gomes et al., 2008; Tainaka et al., 2014). To control hip rotation motion during a landing, muscular function would also be important. The hip external rotator strength is a predictor of ACL injuries (Khayambashi et al., 2016), and hip targeted ACL injury prevention programmes decreased ACL injury risk (LaBella et al., 2011; Omi et al., 2018; Waldén et al., 2012). The eccentric contraction of the hip external rotators would be necessary for a controlled hip internal rotation motion (Malloy et al., 2016). However, this study lacked information regarding muscle strength and activation during landing. Hip internal rotators might also be important to avoid a large hip external rotation motion during landing. Therefore, future studies are needed to clarify the role of hip internal rotators and hip external rotators during a double-leg landing. Hip flexion excursion was positively associated with the peak knee flexion angle but negatively associated with the peak knee internal rotation angle in the present study. Instructions to increase hip flexion motion during a landing might induce an increase in the knee flexion motion and a decrease in the peak knee internal rotation angle. As used in previous studies, instruction to emphasise hip flexion motion during landing in jump-landing training could be important to prevent ACL injury (LaBella et al., 2011; Omi et al., 2018; Pollard et al., 2010).

There are some limitations that should be acknowledged. First, the association between knee abduction motion and hip internal rotation motion in other tasks, such as single-leg landing and jump-cutting tasks with a change in direction, might differ from the findings reported in the present study investigating double-leg landing. The pelvis might rotate more on the transverse plane in single-leg landing than double-leg landing. In addition, the hip rotation motion would be larger during the movement of directional change after landing than during the drop vertical jump task used in the present study. Additional studies should be conducted to investigate this association in single-leg landing and jump-cutting tasks with a change in direction. Second, whether an intervention to avoid hip external rotation motion reduces the knee abduction and internal rotation angles during landing is unclear. Additional studies should be conducted to investigate the effects of jump-landing training focusing on hip rotational motions. Third, this study investigated only female participants. Therefore, the kinematic relationships observed in the present study might not apply to male participants. Finally, the effects of skin movement on frontal- and transverse-plane hip and knee joint motions should be acknowledged. Skin artefacts might have impacted the results of the present study.

Conclusion

The present study examined the associations of the peak knee joint angles and knee joint angular excursions with hip joint motions during a drop vertical jump. The multiple regression analysis showed that a smaller hip internal rotation or a larger hip external rotation excursion was associated with a larger peak knee abduction angle and a larger excursion to knee abduction and knee internal rotation from IC to 50 ms after IC. In addition, a smaller hip flexion excursion was associated with smaller peak knee flexion and a larger peak knee internal rotation angle. Therefore, jump-landing training to avoid a large knee abduction and internal rotation motion might be beneficial for avoiding a large hip external rotation, in addition to increasing hip flexion motion during a double-leg landing.

Acknowledgments

We thank American Journal Experts (https://www.aje.com/) for editing a draft of this manuscript.

Disclosure statement

No potential conflicts of interest were reported by the author(s).

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Table 1 Multiple regression models to determine the associations of the peak knee joint angles with hip and knee joint angle excursions and moments

	Partial correlation	*β*	*P*
Peak knee flexion angle (°)			
Hip flexion excursion (°) [a]	0.760	0.714	< 0.001
Peak vertical ground reaction force (Nm/kg) [b]	-0.362	-0.237	0.006
Peak knee abduction angle (°)			
Knee internal rotation excursion (°) [a]	-0.534	-0.488	< 0.001
Hip internal rotation excursion (°) [a]	-0.539	-0.475	< 0.001
Peak knee abduction moment (Nm/kg/m) [c]	0.286	0.221	0.035
Peak knee internal rotation angle (°)			
Hip flexion excursion (°) [a]	-0.421	-0.434	0.001
Peak hip adduction moment (Nm/kg/m) [c]	-0.272	-0.264	0.043

Model for the peak knee flexion angle: $R^2 = 0.636$, $P < 0.001$; Model for the peak knee abduction angle: $R^2 = 0.465$, $P < 0.001$; Model for the peak internal rotation angle: $R^2 = 0.194$, $P = 0.003$

[a] excursion from initial contact (IC) to peak knee flexion

[b] normalised to body mass

[c] normalised to body mass and height

Table 2 Multiple regression models to determine the associations of the knee joint excursions during the 50 ms after initial contact with hip and knee joint angle excursions and moments

	Partial correlation	*β*	*P*
Knee flexion excursion (°) [a]			
Hip flexion excursion (°) [a]	0.798	0.794	< 0.001
Peak knee abduction moment (Nm/kg/m) [b]	-0.272	-0.170	0.042
Knee abduction excursion (°) [a]			
Hip internal rotation excursion (°) [a]	-0.452	-0.466	0.001
Peak knee abduction moment (Nm/kg/m) [b]	0.281	0.253	0.037
Knee internal rotation excursion (°) [a]	-0.276	-0.268	0.042
Knee internal rotation excursion (°) [a]			
Hip internal rotation excursion (°) [a]	-0.544	-0.513	< 0.001
Knee abduction excursion (°) [a]	-0.284	-0.297	0.027
Peak knee flexion moment (Nm/kg/m) [b]	0.263	0.292	0.031

Model for the knee flexion excursion: $R^2 = 0.641$, $P < 0.001$; Model for the knee abduction excursion: $R^2 = 0.292$, $P < 0.001$; Model for the knee rotation excursion: $R^2 = 0.302$, $P < 0.001$

[a] excursion from initial contact (IC) to 50 ms after IC

[b] normalised to body mass and height

Figure captions

Fig. 1 Average curves of the knee flexion (A), knee abduction (B), knee internal rotation (C), hip flexion (D), hip adduction (E) and hip internal rotation (F) angles. Positive values indicate knee flexion, abduction and internal rotation; and hip flexion, adduction and internal rotation. Error bars indicate ± one standard deviation. The landing phase from initial contact to peak knee flexion was normalised to 101 data points.

Fig. 2 The two pattens of hip rotation motion. Twenty-five participants demonstrated hip internal rotation motion (solid black line), while 32 participants demonstrated hip external rotation motion (grey dashed line). Error bars indicate ± one standard deviation. The landing phase from initial contact to peak knee flexion was normalised to 101 data points.

Fig. 3 The associations between the peak knee abduction angle and the hip internal rotation excursion from initial contact (IC) to peak knee flexion (A) and the association between the peak knee internal rotation angle and the hip flexion excursion from IC to peak knee flexion (B). The positive values indicate knee abduction, knee internal rotation, hip internal rotation, and hip flexion.

Fig. 4 The associations of between knee abduction and hip internal rotation excursions (A) and between knee internal rotation and hip internal rotation excursions (B) from initial contact (IC) to 50 ms after IC. The positive values indicate knee abduction, knee internal rotation and hip internal rotation.

Fig. 5 Schematic of the hypothesis about the association between knee abduction motion and hip rotation motion during a landing. When the medial tilt of the tibia occurs with hip internal rotation at the knee flexed position, the motion directions of both the tibia and femur would face in the same direction. Thus, the knee abduction motion might be diminished (A). When the medial tilt of tibia occurs with hip external rotation at the knee flexed position, the femur faces in the opposite direction to the medial tilt of the tibia. Thus, the knee abduction motion might be increased (B).

Fig.1

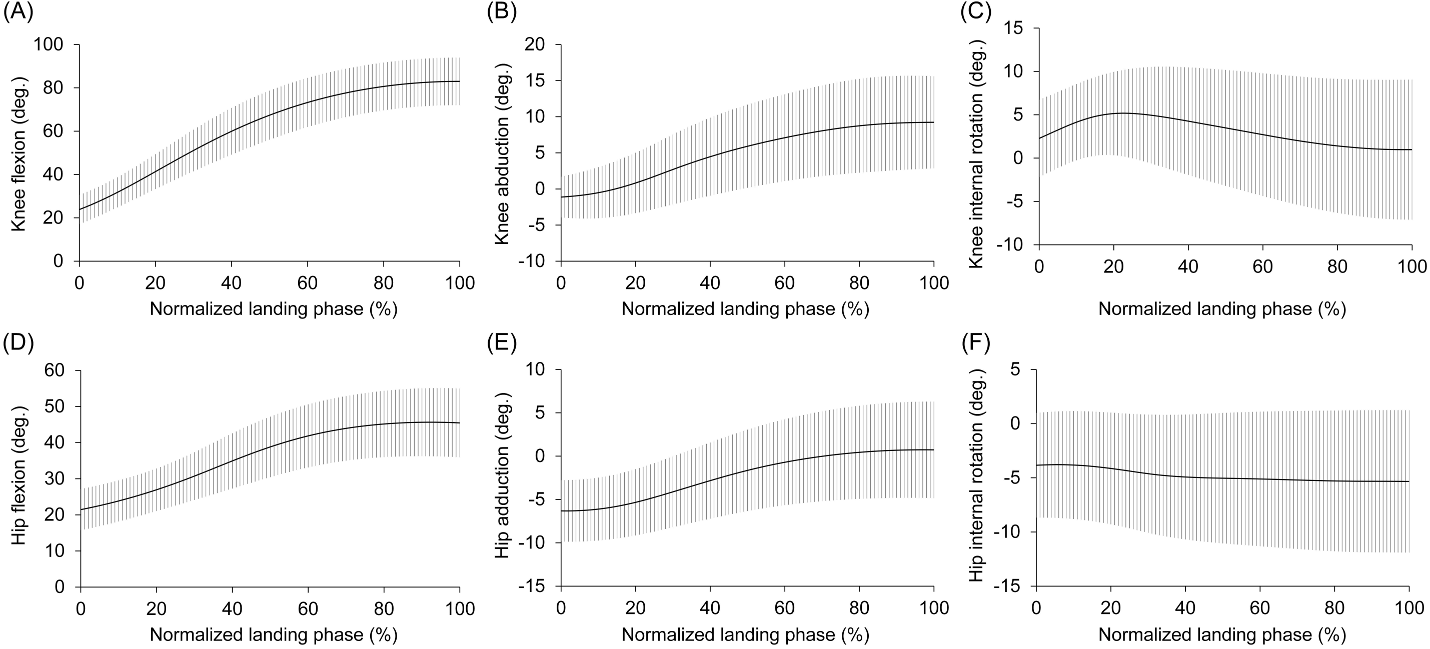
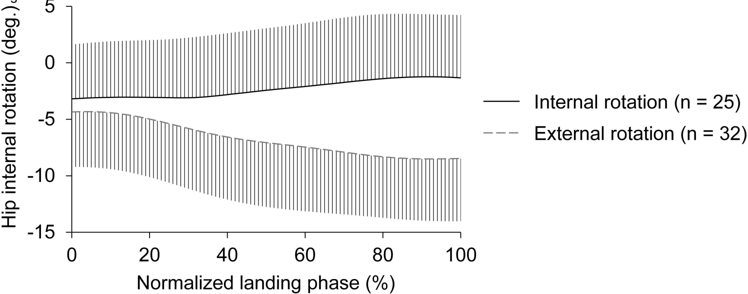

(A)
Knee flexion (deg.)
100
80
60
40
20
0
0
20
40
60
80
100
Normalized landing phase (%)
(B)
Knee abduction (deg.)
20
15
10
5
0
-5
-10
0
20
40
60
80
100
Normalized landing phase (%)
(C)
Knee internal rotation (deg.)
15
10
5
0
-5
-10
0
20
40
60
80
100
Normalized landing phase (%)
(D)
Hip flexion (deg.)
60
50
40
30
20
10
0
0
20
40
60
80
100
Normalized landing phase (%)
(E)
Hip adduction (deg.)
10
5
0
-5
-10
-15
0
20
40
60
80
100
Normalized landing phase (%)
(F)
Hip internal rotation (deg.)
5
0
-5
-10
-15
0
20
40
60
80
100
Normalized landing phase (%)

Fig.2



5
0
-5
-10
-15
Hip internal rotation (deg.)
0
20
40
60
80
100
Normalized landing phase (%)
Internal rotation (n = 25)
External rotation (n = 32)

Fig.3

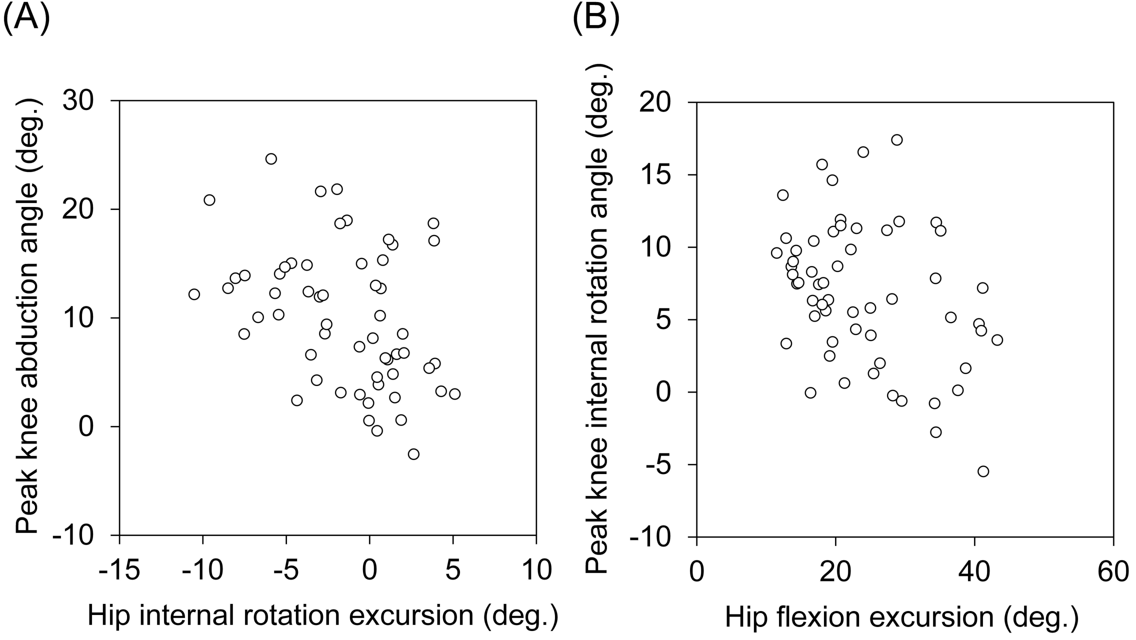

(A)
30
20
10
0
-10
Peak knee abduction angle (deg.)
-15
-10
-5
0
5
10
Hip internal rotation excursion (deg.)
(B)
20
15
10
5
0
-5
-10
Peak knee internal rotation angle (deg.)
0
20
40
60
Hip flexion excursion (deg.)

Fig.4

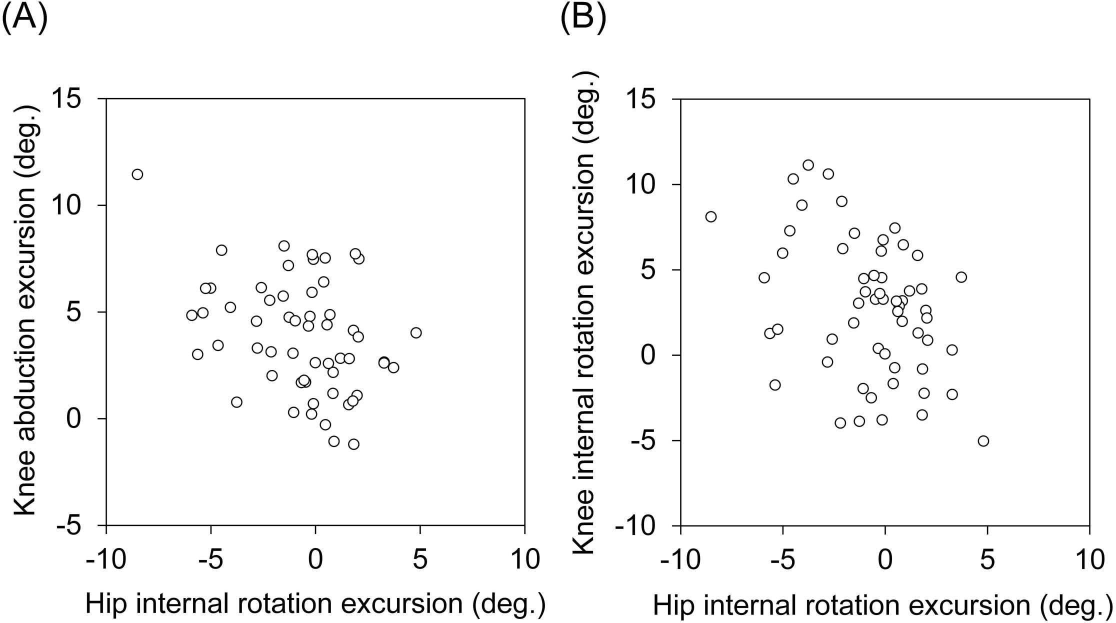
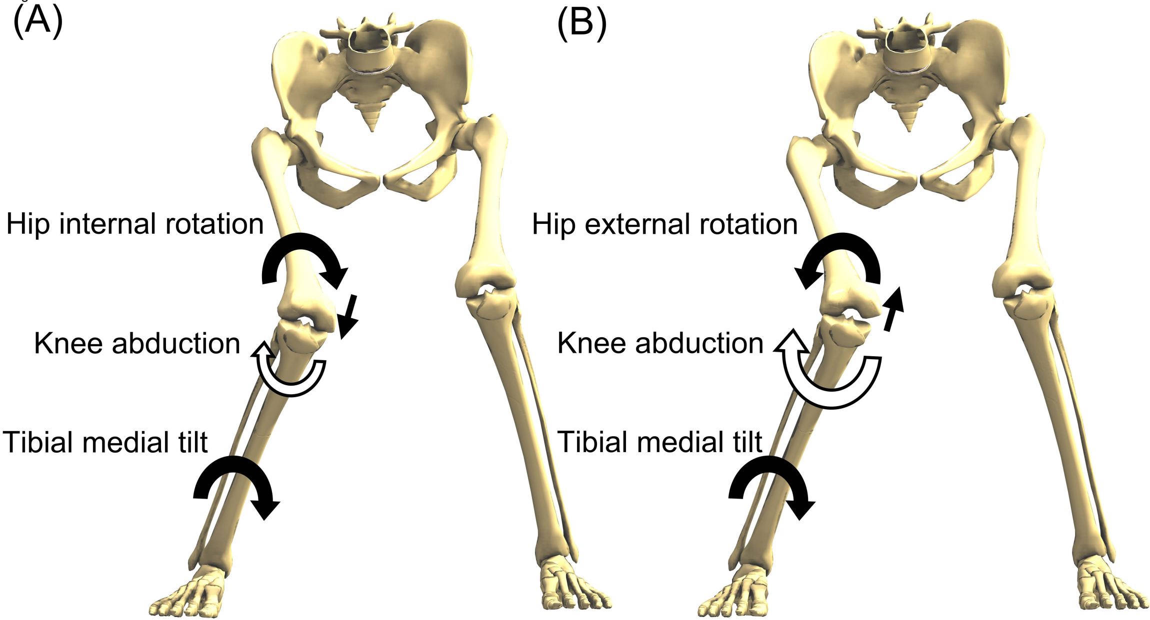

(A)
Knee abduction excursion (deg.)
15
10
5
0
-5
-10
-5
0
5
10
Hip internal rotation excursion (deg.)
(B)
Knee internal rotation excursion (deg.)
15
10
5
0
-5
-10
-10
-5
0
5
10
Hip internal rotation excursion (deg.)

Fig.5


(A)
Hip internal rotation
Knee abduction
Tibial medial tilt
(B)
Hip external rotation
Knee abduction
Tibial medial tilt