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ORIGINAL ARTICLE

Side-to-side differences in lower extremity biomechanics during multi-directional jump landing in volleyball athletes

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Abstract
Side-to-side differences of lower extremities may influence the likelihood of injury. Moreover, adding the complexity of jump-landing direction would help to explain lower extremity control during sport activities. The aim was to determine the effects of limb dominance and jump-landing direction on lower extremity biomechanics. Nineteen female volleyball athletes participated. Both dominant limbs (DLs) and non-dominant limbs (NLs) were examined in single-leg jump-landing tests in four directions, including forward (0°), diagonal (30° and 60°), and lateral (90°) directions. Kinematic marker trajectories and ground reaction forces were collected using a 10 camera Vicon system and an AMTI force plate. Repeated measures ANOVA (2 × 4, limb × direction) was used to analyse. The finding showed that, at peak vertical GRF, a significant interaction of limb dominance and direction effects was found in the hip flexion angle and lower extremity joint kinetics ($p < .05$). NLs and DLs exhibited significantly different strategies while landing in various directions. Significantly higher increase of ankle dorsiflexion angle was observed in lateral direction compared to other directions for both DLs and NLs ($p < .05$). Increasingly using ankle dorsiflexion was observed from the forward to the lateral direction for both DLs and NLs. However, NLs and DLs preferentially used different strategies of joint moment organization to respond to similar VGRFs in various directions. The response pattern of DLs might not be effective and may expose DLs to a higher injury risk, especially with regard to landing with awkward posture compared with NLs.

Keywords: *Limb dominance, jump landing, volleyball athletes, joint kinetics, joint kinematics*

Highlights

- Neuromuscular studies of lower extremities during jump landing are essential for understanding the risk of lower extremity injury and for guiding preventive, pre-operative, and post-operative training.
- Non-dominant and dominant limbs showed significantly different strategies during jump landing, especially at peak vertical ground reaction force. Different lower extremity biomechanics exist in different sides and jump-landing directions.
- The response pattern of dominant limb might not be as effective as that of non-dominant limb, and therefore dominant limb may be exposed to a higher risk of knee injury, especially by landing with awkward posture or poor balance, compared with non-dominant limb.
- High lower extremity flexion, especially in the hip and knee joints, should be used while landing in lateral and diagonal directions of jump landing. Moreover, dominant limb should be trained for effective function during landing in a manner similar to non-dominant limb, which are habituated to landing or stance activities.

Introduction

Neuromuscular studies of lower extremities during jump landing are essential for understanding the risk of lower extremity injury and for guiding preventive, pre-operative, and post-operative training (Brown, Palmieri-Smith, & McLean, 2009; Kernozek, Torry, & Iwasaki, 2008). The dynamic neuromuscular response of landing requires the function of the peripheral and central nervous systems to process, regulate, and respond to the situation and environment (Hewett, Paterno, & Myer, 2002). Coordination failure and a combination of high velocity and impaired muscle protection are the important factors of non-contact anterior cruciate ligament (ACL) injury (Beck & Wildermuth, 1985). Biomechanics of lower extremity joints were the important factor of the ACL injury risk including valgus and internal rotation moments (Shin, Chaudhari, & Andriacchi,

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2011), knee valgus angle and a combination of knee flexion and femoral internal rotation (Hewett et al., 2005), and knee flexion angle (Fukuda et al., 2003). Effective training for ACL injury prevention is the result of a good understanding the mechanical aetiology and the risk factors, especially neuromuscular control which could be trained and improved (Dai, Herman, Liu, Garrett, & Yu, 2012). A higher rate of ACL injury has been reported in female athletes than in male athletes (Beynnon et al., 2014). Less lower extremity flexion, higher ground reaction forces (GRFs), greater variation in leg dominance, greater knee valgus, and less total lower limb energy absorption are the contributing factors of knee injury and have been found in female athletes during landing (Ford, Myer, & Hewett, 2003; Salci, Kentel, Heycan, Akin, & Korkusuz, 2004; Schmitz, Kulas, Perrin, Riemann, & Shultz, 2007).

Side-to-side differences in the strength, structure, neuromuscular control, and gait pattern of lower extremities may influence the likelihood of lower limb injury (Zhang, Derrick, Evans, & Yu, 2008). Limb dominance affects lower extremity biomechanics during landing (van der Harst, Gokeler, & Hof, 2007; Niu, Wang, He, Fan, & Zhao, 2011). However, inconsistent results were observed in dynamic landing (Borotikar, Newcomer, Koppes, & McLean, 2008; Ford et al., 2003; van der Harst et al., 2007). No important kinetic or kinematic differences were observed in the previous studies (Ernst, Saliba, Diduch, Hurwitz, & Ball, 2000; van der Harst et al., 2007). Limb dominance might be associated with knee injury in soccer (Ross, Guskiewicz, Prentice, Schneider, & Yu, 2004; Soderman, Alfredson, Pietila, & Werner, 2001). In volleyball, a higher risk of ACL injury was exhibited in the right leg during two landing techniques, including a bilateral stick landing and a right step back from the net (Zahradnik, Jandacka, Uchytil, Farana, & Hamill, 2015). However, the association between ACL injury and limb differences is not yet clear.

To prevent injury, restoring the strength and performance of the affected side is suggested to improve the symmetry of the lower extremities. Frequently, the contralateral limb has been taken as the referential limb in the clinic or laboratory. van der Harst et al. (2007) suggested that the unaffected limb can be used as the compared limb for an ACL-reconstructed limb. By contrast, Hewett et al. (2002) stated that the contralateral limb may not be used as the comparative side in athletes with ACL deficiency or reconstruction. Therefore, information on normal inter-limb differences would help the health professional understand neuromuscular control in healthy athletes. Little research has evaluated side-to-side differences in functional movements (Soderman et al., 2001; Wikstrom, Tillman, Kline, & Borsa, 2006). Adding the complexity of jump-landing direction would help to explain lower extremity control in a manner that closely resembles actual participation in sports. Different responses between lower limbs might be observed during jump landing in various directions. In male athletes, an ankle strategy, including an increase of net plantarflexor moment and dorsiflexion angle, was preferred during multi-directional jump landings (Sinsurin, Vachalathiti, Jalayondeja, & Limroongreungrat, 2013b).

In this study, we studied the main effects of limb dominance and jump-landing direction during single-leg landing in female athletes. The first purpose was to determine the effects of limb dominance on lower extremity biomechanics in female athletes. The second purpose was to compare lower extremity biomechanics among different jump-landing directions. We hypothesized that different lower extremity biomechanics would be observed for the different sides and jump-landing directions. We also hypothesized that dominant limb might show higher risk of knee injury during landing than non-dominant limb.

Methods

Subjects

A total of 21 volleyball female athletes participated in the current study. This number of subjects was required to provide a statistical power of 85% and an effect size of 0.3 calculating from the pilot study of 5 volleyball athletes. However, the data of 3 subjects were incomplete for processing, the data of 19 subjects were analysed. The female volleyball athletes ($n = 19$) included 5 setters, 4 middle blockers, and 10 outside hitters. The athletes' average age and experience were 19.7 ± 1.4 yrs and 9.6 ± 2.0 yrs, respectively. All participants were right-leg-dominant. All participants had been participating in an organized university team and had no reported musculoskeletal problems on either leg in the three months before data collection. Subjects were excluded if they had a serious injury or an operation on the lower extremities, such as ankle sprain, ACL injury, fracture, or patellar dislocation. Testing procedures were explained to all subjects. Each participant read and signed an informed consent form, which was approved by the Committee on Human Rights Related to Human Experimentation of Mahidol University (COA No. 2013/045.1705).

The anthropometric data of each subject was measured, including height, body weight, leg length, knee width, ankle width, elbow width, wrist width, and hand thickness. These data were entered into Plug-in-Gait model in Vicon Nexus software for estimating joint kinematics and kinetics. The dominant limb was defined by the single-leg hop for distance protocol, which determines the longest hop distance for the dominant side (van der Harst et al., 2007).

Jump-landing tests

Multi-directional jump landing tests were collected in the Motion Analysis Laboratory and were conducted with a Vicon™ Nexus system (Oxford Metrics, Oxford, UK). The GRFs and kinematics data were collected with an AMTI force plate (1000 Hz) and ten video cameras (100 Hz).

Based on the full body model of Plug-in-Gait, 35 reflective markers were placed bilaterally on the subject's bony prominences, including 4 markers of the head, the spinous process of the 7th cervical vertebra, the jugular notch, the xiphoid process, the right scapula, the spinous process of the 10th thoracic vertebra, the acromioclavicular joint, the lateral epicondyle of the humerus, the thumb side of the wrist bar, the pinkie side of the wrist bar, the head of the second metacarpal bone, the anterior superior iliac spine, the posterior superior iliac spine, the thigh, the lateral condyles of the femur, the shank, the lateral malleolus, the heel, and the head of the second metatarsal bone. Both dominant limbs (DLs) and non-dominant limbs (NLs) were examined following the research setting depicted in Figure 1. A 30-cm-height wooden platform was placed 70 cm from the centre of the force plate (Sinsurin, Vachalathiti, Jalayondeja, & Limroongreungrat, 2013a). Before the jump-landing tests, the subject was allowed to practice jump landing in each direction 3–5 times to become accustomed with the testing procedure. The order of the limbs and jump directions was selected randomly. The participants stood on the platform on the leg to be tested and flexed the other knee approximately 90° with a neutral hip rotation. To eliminate variability in jumping mechanics due to arm-swing, the subjects were asked to place both hands on their waist. Each subject was instructed to carefully jump off the wooden platform without an upward jump action. The subjects jumped and landed with the tested leg while always facing and looking forward during the jump-landing tests. A successful trial was collected if the subject was able to land on the centre of the force plate, maintain unilateral balance, and maintain their hands on their waist. Unsuccessful trials were excluded, and in those cases, the jump-landing test was performed again. The participants were allowed to rest for 5 minutes between directional sessions and for at least 30 seconds between jumping trials.

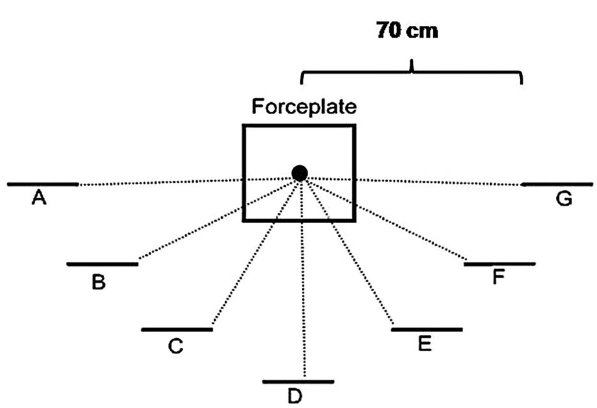

Figure 1. Starting point of jump-landing tests and the research setting in the laboratory. A, lateral (90°) jump landing for the right lower limb; B, 60° diagonal jump landing for the right lower limb; C, 30° diagonal jump landing for the right lower limb; D, forward (0°) jump landing for the right and left lower limbs; E, 30° diagonal jump landing for the left lower limb; F, 60° diagonal jump landing for the left lower limb; and G, lateral (90°) jump landing for the left lower limb.

Data acquisition and statistical analysis

The 35 marker coordinates and GRFs were filtered by a fourth-order zero-lag Butterworth digital filter at cut-off frequencies of 6 and 40 Hz, respectively. The cut-off frequency was determined by the residual analysis technique (Winter, 2005). A three-dimensional model was constructed by the Plug-in-Gait software. The average of three successful trials of each limb was analysed in each direction. Joint kinetics and kinematics were determined at the initial contact phase and at the peak vertical GRF (VGRF) phase. The peak VGRF, time to peak VGRF, net joint moments, and joint angles were reported and compared between limbs and also between jump-landing directions. The net joint moment in this study is the internal moment representing joint mechanical demand between agonist and antagonist muscle groups. Normalized net joint moment by body weight was reported.

Statistical computation was performed using SPSS version 17. Repeated-measure ANOVA (2×4, limb × jump-landing direction) was used to analyse the effect of limb dominance and jump-landing direction. An alpha level of $p \leq .05$ was set as statistical significance.

Results

The results of three planes of lower extremity movements, peak VGRF, and time to peak VGRF are shown in Tables I and II.

Table I. Mean ± SD of the joint angles of lower extremities at initial contact during jump landings in forward (0°), 30° diagonal, 60° diagonal, and lateral (90°) directions.

	Non-dominant				Dominant				*p*-Values		
Dependent variables	0°	30°	60°	90°	0°	30°	60°	90°	Dominant	Direction	Interaction
Hip angle (°)											
Flexion (+) /extension (−)	33.5 ± 6.2[b,c]	34.1 ± 6.0[b,c]	32.5 ± 6.0[c]	29.2 ± 6.1	31.5 ± 6.7[c]	31.8 ± 7.1[c]	31.2 ± 7.2[c]	28.1 ± 6.2	.096	**<.001**	.175
Adduction (+)/abduction (−)	−7.5 ± 4.2[a,b,c]	−11.5 ± 5.0[b,c]	−14.8 ± 4.6[c]	−15.5 ± 4.3	−7.2 ± 3.4[a,b,c]	−11.4 ± 2.8[b,c]	−15.3 ± 2.8[c]	−16.6 ± 2.9	.814	**<.001**	.139
Internal (+)/external (−) rotation	−3.8 ± 21.3	−4.1 ± 22.9[c]	−4.9 ± 23.2[c]	−1.1 ± 24	−12.6 ± 26.9	−13.1 ± 27.5[c]	−14.1 ± 28.2[c]	−10.9 ± 29.1	.073	**.002**	.902
Knee angle (°)											
Flexion (+)/extension (−)	12.3 ± 5.6[a,b,c]	13.3 ± 5.7[c]	14.1 ± 6.2[c]	16.4 ± 6.6	10.8 ± 5.2[b,c]	11.4 ± 5.5[c]	12.3 ± 6.1[c]	14.7 ± 6.1	.090	**<.001**	.965
Varus (+)/valgus (−)	−1.2 ± 4.3[a,b]	−1.9 ± 4.6	−2.5 ± 5.4	−1.8 ± 6.0	−2.2 ± 4.3[a,b,c]	−3.3 ± 4.5	−3.8 ± 5.3	−4.0 ± 6.4	.179	**.026**	.159
Internal (+)/external (−) rotation	−3.4 ± 11.5[a,b,c,d]	−1.5 ± 11.5[b,d]	−0.3 ± 11.9[c,d]	−1.9 ± 12.1[d]	3.7 ± 12.9[a,b]	5.4 ± 13.6	6.0 ± 14.2[c]	4.7 ± 14.4	**.028**	**<.001**	.647
Ankle angle (°)											
Dorsiflexion (+)/plantarflexion (−)	−21.5 ± 5.6[c]	−21.4 ± 5.7[c]	−20.6 ± 5.7	−20.1 ± 5.7	−20.7 ± 8.5[c]	−20.8 ± 8.3	−20.8 ± 7.9	−19.3 ± 8.5	.717	**.009**	.649
Inversion (+)/eversion (−)	−0.7 ± 2.7[b,c]	−0.7 ± 2.7[b,c]	−0.3 ± 2.7[c]	0.5 ± 2.9	−1.1 ± 3.2[b,c]	−1.0 ± 3.5[b,c]	−0.7 ± 3.6[c]	0.1 ± 3.5	.590	**<.001**	.936
Internal (+)/external (−) rotation	0.8 ± 13.0[b,c]	1.0 ± 13.0[b,c]	−1.4 ± 13.2[c]	−5.0 ± 14.0	1.2 ± 14.6[b,c]	1.0 ± 15.5[b,c]	−0.8 ± 16.3[c]	−4.9 ± 16.9	.945	**<.001**	.937

[a]Statistically significant difference compared with 30° diagonal direction (<.05).
[b]Statistically significant difference compared with 60° diagonal direction (<.05).
[c]Statistically significant difference compared with lateral direction (<.05).
[d]Statistically significant difference compared with dominant limb (<.05).

Table II. Mean ± SD of the peak vertical ground reaction force (VGRF), the time to peak VGRF, and the joint angles and net joint moment of lower extremities at peak VGRF during jump landings in forward (0°), 30° diagonal, 60° diagonal, and lateral (90°) directions.

Dependent variables	Non-dominant				Dominant				*p*-Values		
	0°	30°	60°	90°	0°	30°	60°	90°	Dominant	Direction	Interaction
Peak VGRF (N)	2331.8 ± 369.9	2393.2 ± 333.5	2416.1 ± 317.4	2417.2 ± 332.5	2350.5 ± 269.5	2389.1 ± 302.0	2392.1 ± 294.6	2352.4 ± 287.0	.756	.092	.375
Time to peak VGRF (ms)	49 ± 8[b,c]	50 ± 7[b,c]	53 ± 6	65 ± 7	45 ± 5[b,c]	46 ± 6[b,c]	52 ± 7[c]	64 ± 8	.073	**<.001**	.065
Hip angle (°)											
Flexion (+)/ extension (−)	39.1 ± 6.9[b,c]	39.4 ± 6.6[b,c]	37.3 ± 5.8[c]	34.9 ± 6.4	37.1 ± 7.0[c]	37.2 ± 6.9[c]	36.9 ± 6.9[c]	34.2 ± 6.7	.213	**<.001**	**.035**
Adduction (+)/ abduction (−)	−5.7 ± 4.3[a,b,c]	−9.1 ± 5.[b,c]	−12.4 ± 4.6	−11.9 ± 4.3	−5.8 ± 3.5[a,b,c]	−9.9 ± 3.4[b,c]	−13.3 ± 3.2	−13.3 ± 3.5	.524	**<.001**	.370
Internal (+)/ external (−) rotation	7.3 ± 22.3[a,b,c,d]	9.0 ± 23.0[b,d]	8.8 ± 23.0[d]	10.1 ± 23.3[d]	−3.4 ± 28.6[c]	−2.1 ± 28.8[c]	−2.0 ± 29.6[c]	−0.4 ± 29.6	**.030**	**.001**	.940
Knee angle (°)											
Flexion (+)/ extension (−)	28.8 ± 6.5	29.5 ± 7.2	29.1 ± 6.4	30.0 ± 7.2	26.1 ± 6.6[b,c]	26.7 ± 7.4[c]	27.7 ± 8.3	28.8 ± 9.0	.180	**<.001**	.226
Varus (+)/ valgus (−)	4.4 ± 9.5[d]	4.2 ± 9.9[d]	3.9 ± 10.6[d]	4.5 ± 10.7[d]	−0.6 ± 10.4	−0.9 ± 10.8	−1.2 ± 11.5	−0.3 ± 12.3	**.012**	.283	.949
Internal (+)/ external (−) rotation	4.3 ± 11.5[d]	4.7 ± 11.7[d]	4.6 ± 12.3[d]	4.5 ± 11.8[d]	11.7 ± 14.2	12.6 ± 15.9	12.1 ± 15.8	11.2 ± 15.6	**.014**	.210	.504
Ankle angle (°)											
Dorsiflexion (+)/ plantarflexion (−)	2.0 ± 3.3[a,b,c]	3.7 ± 2.7[b,c]	6.4 ± 2.6[c]	13.3 ± 3.1	1.2 ± 2.3[a,b,c]	2.7 ± 2.9[b,c]	6.6 ± 3.6[c]	14.3 ± 3.7	.812	**<.001**	.082
Inversion (+)/ eversion (−)	2.4 ± 2.7	2.2 ± 2.7	2.4 ± 2.7	2.5 ± 2.9	1.8 ± 3.5	1.7 ± 4.1	1.5 ± 4.5	1.7 ± 4.5	.379	.320	.557
Internal (+)/ external (−) rotation	−14.8 ± 13.7	−13.9 ± 13.4	−14.5 ± 13.2	−14.9 ± 13.7	−13.3 ± 16.4	−12.7 ± 18.4	−11.8 ± 19.8	−13.3 ± 20.0	.624	.246	.618
Hip net joint moment (Nm/kg)											
Extensor (+)/ flexor (−)	1.49 ± 1.02[b,c]	1.24 ± 1.07[c,d]	1.06 ± 1.09[c,d]	0.58 ± 1.08[d]	1.71 ± 0.88[b,c]	1.72 ± 0.81[b,c]	−1.45 ± 0.36	−0.56 ± 1.33	**<.001**	**<.001**	**<.001**
Adductor (+)/ abductor (−)	1.13 ± 0.70	1.33 ± 076	1.37 ± 0.82	1.46 ± 0.65	1.57 ± 0.38	1.52 ± 0.49	1.23 ± 0.80	1.02 ± 0.92	.949	.537	**.002**
Internal (+)/ external (−) rotator	−0.27 ± 0.10[a,b,d]	−0.34 ± 0.15[d]	−0.33 ± 0.1[d]	−0.29 ± 0.1[d]	0.14 ± 0.11[a,b]	0.31 ± 0.09[c]	0.29 ± 0.13[c]	0.16 ± 0.18	**<.001**	**.006**	**<.001**
Knee net joint moment (Nm/kg)											
Extensor (+)/ flexor (−)	−0.10 ± 0.53[c]	0.13 ± 0.62[d]	0.07 ± 0.60[c,d]	0.31 ± 0.44[d]	−0.30 ± 0.55[b,c]	−0.20 ± 0.48[b,c]	0.94 ± 0.26	0.77 ± 0.63	**.026**	**<.001**	**<.001**

(*Continued*)

Table II. Continued.

Dependent variables	Non-dominant				Dominant				*p*-Values		
	0°	30°	60°	90°	0°	30°	60°	90°	Dominant	Direction	Interaction
Varus (+)/ valgus (−)	0.70 ± 0.28[a,b,c]	0.95 ± 0.36	0.98 ± 0.35[d]	1.07 ± 0.29[d]	0.76 ± 0.25[a,b,c]	0.94 ± 0.34[b,c]	−0.07 ± 0.53	0.19 ± 0.28	**<.001**	**.001**	**<.001**
Internal (+)/ external (−) rotator	0.08 ± 0.07[a,b,c,d]	0.16 ± 0.08[b,c,d]	0.19 ± 0.08[c,d]	0.28 ± 0.10[d]	−0.01 ± 0.08[a,c]	0.03 ± 0.07[c]	−0.01 ± 0.13[c]	−0.11 ± 0.13	**<.001**	**<.001**	**<.001**
Ankle net joint moment (Nm/kg)											
Plantarflexor (+)/ dorsiflexor (−)	1.82 ± 0.37[b,c]	1.89 ± 0.39[b,c]	2.02 ± 0.27[c,d]	2.26 ± 0.31[d]	1.87 ± 0.45[b,c]	1.94 ± 0.38[b,c]	0.03 ± 0.32[c]	1.11 ± 1.06	**<.001**	**<.001**	**<.001**
Adductor (+)/ abductor (−)	0.002 ± 0.11[a,b,c]	0.15 ± 0.11[b,c,d]	0.24 ± 0.12[c,d]	0.31 ± 0.11[d]	0.02 ± 0.19[b,c]	−0.09 ± 0.36[b,c]	2.02 ± 0.55[c]	1.18 ± 0.89	**<.001**	**<.001**	**<.001**
Internal (+)/ external (−) rotator	0.03 ± 0.10[a,b,c,d]	0.11 ± 0.10[b,c,d]	0.14 ± 0.08[c,d]	0.26 ± 0.09[d]	−0.03 ± 0.05[a,b,c]	0.19 ± 0.09[b,c]	0.37 ± 0.10[c]	0.51 ± 0.11	**<.001**	**<.001**	**<.001**

[a]Statistically significant difference compared with 30° diagonal direction (<.05).
[b]Statistically significant difference compared with 60° diagonal direction (<.05).
[c]Statistically significant difference compared with lateral direction (<.05).
[d]Statistically significant difference compared with dominant limb (<.05).

The results of the current study indicated that at initial contact (Table I), there was no significant difference in the interaction between limb dominance and directional effects on the lower extremity joint angles. The direction of jump landing significantly affected the hip, knee, and ankle angles at initial contact ($p < .05$). However, the effect of limb dominance did not significantly influence the lower extremity angles except for the knee rotation angle ($F(1, 18) = 5.73$, $p = .028$). Slight differences in knee rotation angle were observed between NLs and DLs. At initial contact, NLs landed in an external knee rotation position, but a position of internal knee rotation was noted in DLs.

At peak VGRF (Table II), a significant interaction between limb dominance and jump-landing direction effects was found in hip flexion angle and the net joint moments of the hip, knee, and ankle. Higher knee internal rotation, less internal knee varus moment, and knee valgus position were observed in DLs. Knee flexion and ankle dorsiflexion angles showed an increasing trend in NLs and DLs. A decreasing trend of hip flexion angle was observed from forward to lateral direction. Besides, there was no significant difference in the peak VGRF between different limbs and across different jump-landing directions. Jump-landing direction significantly ($F(3, 54) = 257.14$, $p < .001$) influenced the time to peak VGRF. We observed an increase in the time to peak VGRF during jump landing from the forward, diagonal, and lateral directions.

Discussion

The results of the current study revealed that the NLs and DLs showed significantly different strategies during jump landing, especially at peak VGRF. These data support the study's hypothesis that different lower extremity biomechanics exist in different sides and jump-landing directions. At peak VGRF (Table II), an interaction between the effects of limb dominance and jump-landing direction significantly affected the hip flexion angle and all kinetic parameters. Moreover, main limb dominance and direction significantly influenced all joint kinetics except for hip adductor moment. At initial contact (Table I), the combined effects of limb dominance and jump-landing direction did not significantly influence the lower extremity angles. NLs landed in an external knee rotation position, but internal rotation of the knees during landing was noted in DLs.

Information on differences between lower limbs will help health professionals to understand neuromuscular control in healthy athletes during jump landing. The likelihood of lower limb injury on each side may be influenced by side-to-side differences in strength, structure, neuromuscular control, and gait pattern (Zhang et al., 2008). Ross et al. (2004) showed different biomechanics between lower limbs in knee muscle strengths and VGRF, time to peak VGRF, and knee kinematics during landing. However, some studies found that there were no limb differences in dynamic postural stability, VGRF, and time to peak VGRF during landing (Wikstrom et al., 2006), and in lower limb joint excursion and VGRF during hop test (van der Harst et al., 2007). The current study demonstrated that, at peak VGRF, limb dominance and jump-landing direction had significant combined effects on all joint kinetics. Moreover, limb dominance and jump-landing direction significantly influenced all joint kinetics except for hip adductor moment. No significant difference in the peak VGRF and the time to peak VGRF was noted between NLs and DLs. The current results for peak VGRF and time to peak VGRF were consistent with previous studies (Niu et al., 2011; Ross et al., 2004; Wikstrom et al., 2006). However, Ross et al. (2004) reported differences in the time to peak VGRF during single-leg landing in soccer athletes. They showed that the kicking limb or DL demonstrated higher strength and reached the time to peak VGRF (89 ms) slower than the NL (84 ms). By contrast, no significant differences in the peak VGRF or time to peak VGRF were reported in Wikstrom's study (Wikstrom et al., 2006). The participants in each study have different sport-specific skills. Healthy subjects were included in Niu's and Wikstrom's studies. However, Ross et al. (2004) examined limb differences in soccer athletes and suggested that limb dominance might be associated with knee injury. Therefore, participant experience and sport-specific skills could be the reasons underlying the inconsistent results between NLs and DLs during landing.

In volleyball, lower extremity injuries typically occur during landing after jumping to hit or block the ball (Eerkes, 2012). Zahradnik et al. (2015) examined lower extremity mechanics during two landing techniques in male athletes and stated that a greater risk of ACL injury may be found in the right lower extremity than in the left lower extremity while performing a right step-back landing. However, they did not report data on limb dominance.

An increasing time to peak VGRF may be associated with a decreased peak VGRF, which reduces the risk of knee injury (Devita & Skelly, 1992). In our study, jump-landing direction significantly influenced the time to peak VGRF. We observed an increase in the time to peak VGRF during jump landing from the forward, 30° diagonal, 60° diagonal, and lateral directions. The NLs of volleyball athletes landed with the longer time to peak VGRF across jump landings in all directions. This might reflect a strategy of NLs of volleyball athletes to prevent excessive high-impact force while landing in various directions. However, there was no significant effect of limb dominance on the time to peak VGRF.

A difference of strength of less than 10–15% is acceptable as a normal range between NLs and DLs to avoid injury (Bennell et al., 1998). At peak VGRF (Table II), significant differences in three plane moments of the hip, knee, and ankle joints were observed between NLs and DLs, with the exception of hip abductor moment. Moreover, limb dominance significantly influenced the knee valgus angle and the rotation angle of the hip and knee joints. Our study indicated that NLs and DLs preferentially used different strategies with different mechanical demands of lower extremities to respond to similar magnitudes of VGRF while landing in various directions. We think that more differences between NLs and DLs during jump landing could be observed from net joint moment data instead of joint angles. However, further studies should include strength measurements to confirm the strength differences between NLs and DLs.

Tillman, Hass, Brunt, and Bennett (2004) investigated the frequency of unilateral landing after spiking the ball and reported that 35% unilateral landing with left foot was observed compared with 10% unilateral landing with right foot in volleyball games. Right-handed players were the majority of the participants. They suggested that landing with left foot may relate to right-hand spiking. All athletes in the present study have right hand and leg dominances. Typically, while hitting a ball with the right hand, the body's centre of mass shifts to the left due to left lateral trunk flexion. This movement could result in landing on the left lower limb. The NL is frequently preferred as the landing limb and therefore it habituates the landing task. Muscular adaptation in strength and function can be affected by sport training and competition (Fousekis, Tsepis, & Vagenas, 2010). A more effective strategy of the ankle joint of the NL was found in Niu's et al. (2011) study. They also suggested that higher injury risk is found in the ankle of the DL during landing tasks and that the NL may effectively function in postural stabilization during landing tasks. Therefore, after rehabilitation, better performance of the NL might be expected during landing in volleyball athletes with injuries.

At peak VGRF, the combined effect of limb dominance and jump-landing direction significantly influenced all lower extremity moments. Lower extremity moments of the NLs trended towards an increase or decrease during landing from the forward to the lateral direction, but this did not occur for DLs. Moreover, during 60° diagonal and lateral jump landings, greater knee extensor and hip flexor loading was noted in DLs than in NLs at peak VGRF. It is possible that the response pattern of DLs might not be as effective as that of NLs, and therefore DLs may be exposed to a higher risk of knee injury, especially by landing with awkward posture or poor balance, compared with NLs.

Higher hip and knee flexions during landing are associated with less injury risk (Laughlin et al., 2011). Lower peak VGRF and an increasing time to peak VGRF were found during landing with a higher lower extremity flexion pattern (Cronin, Bressel, & Finn, 2008; Onate, Guskiewicz, & Sullivan, 2001). The results of the current study showed that different directions of jump landing significantly affected the lower extremity angles in three planes at the initial contact (Table I). High hip and knee flexion during landing is defined as soft-style landing, which is suggested to prevent injury (Favre, Clancy, Dowling, & Andriacchi, 2016; Laughlin et al., 2011). Moreover, high knee flexion at initial contact is recommended to prevent high impact forces (Dufek & Bates, 1990). An increase in the knee flexion angle at initial contact and ankle dorsiflexion at peak VGRF was found during jump landing from the forward, diagonal, and lateral directions.

The finding of the current study supported Sinsurin's studies (Sinsurin et al., 2013a, 2013b), which investigated the effect of jump-landing direction on lower extremity biomechanics of DLs. Male athletes were examined with the same testing protocol as the current study. Our study showed, similar to Sinsurin's study, that ankle dorsiflexion significantly increased from the forward to the lateral direction. This seems like stiff-style landing, with less hip and knee flexion and high ankle dorsiflexion (Devita & Skelly, 1992). Moreover, Sinsurin's studies showed that higher peak knee valgus and ankle moment occurred during landing in a lateral direction than in the 60° diagonal, 30° diagonal, and forward directions. Therefore, the diagonal and lateral directions of jump landing have higher injury risks than the forward direction. We found an increase in the knee flexion angle at initial contact during landing from the forward (15.5° ± 4.2°), 30° diagonal (17.1° ± 4.0°), 60° diagonal (17.3° ± 5.9°), and lateral (19.8° ± 6.0°) directions. This indicated that at initial contact, both male and female athletes preferred a strategy of increasing knee flexion to respond during landing from the forward to the lateral directions. However, male athletes landed with slightly higher knee flexion than female athletes.

Higher potential injury of ACL was observed as a result of multi-planar loading (Markolf et al., 1995). The present study exhibited that, at initial contact, DLs landed with higher knee valgus than NLs in all directions. Besides, significant angle of knee internal rotation was noted in DLs while NLs landed with external rotation posture. Additional internal tibial rotation was suggested as a risk factor of ACL strain (Berns, Hull, & Patterson, 1992; Nagano, Ida, Akai, & Fukubayashi, 2007). Therefore, combination of higher knee valgus and internal rotation, and less knee flexion might be the higher risk of knee injury of DLs than NLs, especially in extreme player who performs an extreme trunk lateral flexion while hitting a ball and, then, lands with awkward posture.

At peak VGRF, higher knee internal rotation and knee valgus positions were significantly observed in DLs. Combination of high knee valgus angle and lower internal moment of knee varus would tend to increase knee injury risk (Kernozek, Torry, Van Hoof, Cowley, & Tanner, 2005). This would imply that, in the present study, single-leg landing with DLs may have the higher risk of knee injury than NLs, especially jump landing in 60° diagonal and lateral directions.

More adaptive and safer landing techniques might be trained by learning corrected control strategies (Myer, Ford, & Hewett, 2004). Training athletes to perform landing safely might instil movement adaptations, promoting readiness for unanticipated movements, and increase the field of play. High injury risk has been noted in unanticipated tasks (Borotikar et al., 2008). In the current study, NLs landed with higher knee flexion than DLs in all directions of jump landing. It seems that NLs might perform landing more safely than DL. We recommend that high lower extremity flexion, especially in the hip and knee joints, should be used while landing in lateral and diagonal directions. Moreover, in female volleyball athletes, DLs should be trained for effective function during landing in a manner similar to NLs, which are habituated to landing or stance activities. For future studies, it would be interesting to study these effects in a wider variety of different sport types. Differences in movement control between NLs and DLs might be observed in different types of sports.

The limitations of the study were, firstly, the height of wooden platform was 30 cm which may too low comparing to jumping height in the sports and this height was not normalized for each participant's leg length. However, drop landing from 30 cm-height-platform is widely used to study lower extremity biomechanics. This height may be the minimal level for biomechanical study compromising between safety and lower limb joint loading. Secondly, the finding of this study could be applied to other sports carefully. Only female volleyball athletes were included in the study. Thirdly, comparing joint rotation in frontal and horizontal planes should be interpreted carefully between protocols in gait analysis. Ferrari et al. (2008) compared five worldwide protocols in gait analysis and found that a good consistency was observed for lower extremity joint flexion-extensions but it was less consistency in knee and ankle rotations in frontal and horizontal planes.

Conclusion

In volleyball athletes, NLs and DLs preferentially used different strategies with different mechanical joint demand on the lower extremities to respond to similar magnitudes of VGRF during single-leg landing. DLs showed the higher knee internal rotation, less internal knee varus moment, and knee valgus position at peak VGRF. The response pattern of DLs might not be as effective and may therefore expose the DL to a higher risk of knee injury, especially when landing with awkward posture or poor balance, compared with NL. In female volleyball athletes, DLs should be trained for effective function during landing in a manner similar to NLs, which are habituated to landing or stance activities. Jump-landing direction significantly affected lower extremity biomechanics. An increase in stiff-style landing, increasing ankle dorsiflexion and decreasing hip flexion, was noted from the forward, diagonal, and lateral directions. High lower extremity flexion, especially in the hip and knee joints, should be used while landing in the diagonal and lateral directions.

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References

Beck, J. L., & Wildermuth, B. P. (1985). The female athlete's knee. *Clinics in Sports Medicine*, *4*(2), 345–366.

Bennell, K., Wajswelner, H., Lew, P., Schall-Riaucour, A., Leslie, S., Plant, D., & Cirone, J. (1998). Isokinetic strength testing does not predict hamstring injury in Australian rules footballers. *British Journal of Sports Medicine*, *32*(4), 309–314.

Berns, G. S., Hull, M. L., & Patterson, H. A. (1992). Strain in the anteromedial bundle of the anterior cruciate ligament under combination loading. *Journal of Orthopaedic Research*, *10*(2), 167–176. doi:10.1002/jor.1100100203

Beynnon, B. D., Vacek, P. M., Newell, M. K., Tourville, T. W., Smith, H. C., Shultz, S. J., … Johnson, R. J. (2014). The effects of level of competition, sport, and sex on the incidence of first-time noncontact anterior cruciate ligament injury. *The American Journal of Sports Medicine*, *42*(8), 1806–1812. doi:10.1177/0363546514540862

Borotikar, B. S., Newcomer, R., Koppes, R., & McLean, S. G. (2008). Combined effects of fatigue and decision making on female lower limb landing postures: Central and peripheral contributions to ACL injury risk. *Clinical Biomechanics (Bristol, Avon)*, *23*(1), 81–92. doi:10.1016/j.clinbiomech.2007.08.008

Brown, T. N., Palmieri-Smith, R. M., & McLean, S. G. (2009). Sex and limb differences in hip and knee kinematics and kinetics during anticipated and unanticipated jump landings: Implications for anterior cruciate ligament injury. *British Journal of Sports Medicine*, *43*(13), 1049–1056. doi:10.1136/bjsm.2008.055954

Cronin, J. B., Bressel, E., & Finn, L. (2008). Augmented feedback reduces ground reaction forces in the landing phase of the volleyball spike jump. *Journal of Sport Rehabilitation*, *17*(2), 148–159.

Dai, B., Herman, D., Liu, H., Garrett, W. E., & Yu, B. (2012). Prevention of ACL injury, part I: Injury characteristics, risk factors, and loading mechanism. *Research in Sports Medicine*, *20*(3–4), 180–197. doi:10.1080/15438627.2012.680990

Devita, P., & Skelly, W. A. (1992). Effect of landing stiffness on joint kinetics and energetics in the lower extremity. *Medicine and Science in Sports and Exercise*, *24*(1), 108–115.

Dufek, J. S., & Bates, B. T. (1990). The evaluation and prediction of impact forces during landings. *Medicine and Science in Sports and Exercise*, *22*(3), 370–377.

Eerkes, K. (2012). Volleyball injuries. *Current Sports Medicine Reports*, *11*(5), 251–256. doi:10.1249/JSR.0b013e3182699037

Ernst, G. P., Saliba, E., Diduch, D. R., Hurwitz, S. R., & Ball, D. W. (2000). Lower extremity compensations following anterior cruciate ligament reconstruction. *Physical Therapy*, *80*(3), 251–260.

Favre, J., Clancy, C., Dowling, A. V., & Andriacchi, T. P. (2016). Modification of knee flexion angle has patient-specific effects on anterior cruciate ligament injury risk factors during jump landing. *The American Journal of Sports Medicine*. doi:10.1177/0363546516634000

Ferrari, A., Benedetti, M. G., Pavan, E., Frigo, C., Bettinelli, D., Rabuffetti, M., … Leardini, A. (2008). Quantitative comparison of five current protocols in gait analysis. *Gait and Posture*, *28*(2), 207–216. doi:10.1016/j.gaitpost.2007.11.009

Ford, K. R., Myer, G. D., & Hewett, T. E. (2003). Valgus knee motion during landing in high school female and male basketball players. *Medicine and Science in Sports and Exercise*, *35*(10), 1745–1750. doi:10.1249/01.MSS.0000089346.85744.D9

Fousekis, K., Tsepis, E., & Vagenas, G. (2010). Lower limb strength in professional soccer players: Profile, asymmetry, and training age. *Journal of Sports Science & Medicine*, *9*(3), 364–373.

Fukuda, Y., Woo, S. L., Loh, J. C., Tsuda, E., Tang, P., McMahon, P. J., & Debski, R. E. (2003). A quantitative analysis of valgus torque on the ACL: A human cadaveric study. *Journal of Orthopaedic Research*, *21*(6), 1107–1112. doi:10.1016/S0736-0266(03)00084-6

Hewett, T. E., Myer, G. D., Ford, K. R., Heidt, R. S.J., Colosimo, A. J., McLean, S. G., & Succop, P. (2005). Biomechanical measures of neuromuscular control and valgus loading of the knee predict anterior cruciate ligament injury risk in female athletes: A prospective study. *The American Journal of Sports Medicine*, *33*(4), 492–501. doi:10.1177/0363546504269591

Hewett, T. E., Paterno, M. V., & Myer, G. D. (2002). Strategies for enhancing proprioception and neuromuscular control of the knee. *Clinical Orthopaedics and Related Research*, *402*, 76–94.

Kernozek, T. W., Torry, M. R., & Iwasaki, M. (2008). Gender differences in lower extremity landing mechanics caused by neuromuscular fatigue. *The American Journal of Sports Medicine*, *36*(3), 554–565. doi:10.1177/0363546507308934

Kernozek, T. W., Torry, M. R., Van Hoof, H., Cowley, H., & Tanner, S. (2005). Gender differences in frontal and sagittal plane biomechanics during drop landings. *Medicine and Science in Sports and Exercise*, *37*(6), 1003–1012. discussion 1013.

Laughlin, W. A., Weinhandl, J. T., Kernozek, T. W., Cobb, S. C., Keenan, K. G., & O'Connor, K. M. (2011). The effects of single-leg landing technique on ACL loading. *Journal of Biomechanics*, *44*(10), 1845–1851. doi:10.1016/j.jbiomech.2011.04.010

Markolf, K. L., Burchfield, D. M., Shapiro, M. M., Shepard, M. F., Finerman, G. A., & Slauterbeck, J. L. (1995). Combined knee loading states that generate high anterior cruciate ligament forces. *Journal of Orthopaedic Research*, *13*, 930–935. doi:10.1002/jor.1100130618

Myer, G. D., Ford, K. R., & Hewett, T. E. (2004). Methodological approaches and rationale for training to prevent anterior cruciate ligament injuries in female athletes. *Scandinavian Journal of Medicine & Science in Sports*, *14*(5), 275–285. doi:10.1111/j.1600-0838.2004.00410.x

Nagano, Y., Ida, H., Akai, M., & Fukubayashi, T. (2007). Gender differences in knee kinematics and muscle activity during single limb drop landing. *The Knee*, *14*(3), 218–223. doi:10.1016/j.knee.2006.11.008

Niu, W., Wang, Y., He, Y., Fan, Y., & Zhao, Q. (2011). Kinematics, kinetics, and electromyogram of ankle during drop landing: A comparison between dominant and non-dominant limb. *Human Movement Science*, *30*(3), 614–623. doi:10.1016/j.humov.2010.10.010

Onate, J. A., Guskiewicz, K. M., & Sullivan, R. J. (2001). Augmented feedback reduces jump landing forces. *The Journal of Orthopaedic and Sports Physical Therapy*, *31*(9), 511–517. doi:10.2519/jospt.2001.31.9.511

Ross, S., Guskiewicz, K., Prentice, W., Schneider, R., & Yu, B. (2004). Comparison of biomechanical factors between the kicking and stance limbs. *Journal of Sport Rehabilitation*, *13*, 135–150.

Salci, Y., Kentel, B. B., Heycan, C., Akin, S., & Korkusuz, F. (2004). Comparison of landing maneuvers between male and female college volleyball players. *Clinical Biomechanics (Bristol, Avon)*, *19*(6), 622–628. doi:10.1016/j.clinbiomech.2004.03.006

Schmitz, R. J., Kulas, A. S., Perrin, D. H., Riemann, B. L., & Shultz, S. J. (2007). Sex differences in lower extremity biomechanics during single leg landings. *Clinical Biomechanics (Bristol, Avon)*, *22*(6), 681–688. doi:10.1016/j.clinbiomech.2007.03.001

Shin, C. S., Chaudhari, A. M., & Andriacchi, T. P. (2011). Valgus plus internal rotation moments increase anterior cruciate ligament strain more than either alone. *Medicine and Science in Sports and Exercise*, *43*(8), 1484–1491.

Sinsurin, K., Vachalathiti, R., Jalayondeja, W., & Limroongreungrat, W. (2013a). Altered peak knee valgus during jump-landing among various directions in basketball and volleyball athletes. *Asian Journal of Sports Medicine*, *4*(3), 195–200.

Sinsurin, K., Vachalathiti, R., Jalayondeja, W., & Limroongreungrat, W. (2013b). Different sagittal angles and moments of lower extremity joints during single-leg jump landing among various directions in basketball and volleyball athletes. *Journal of Physical Therapy Science*, *25*(9), 1109–1113. doi:10.1589/jpts.25.1109

Soderman, K., Alfredson, H., Pietila, T., & Werner, S. (2001). Risk factors for leg injuries in female soccer players: A prospective investigation during one out-door season. *Knee Surgery, Sports Traumatology, Arthroscopy*, *9*(5), 313–321. doi:10.1007/s001670100228

Tillman, M. D., Hass, C. J., Brunt, D., & Bennett, G. R. (2004). Jumping and landing techniques in elite women's volleyball. *Journal of Sports Science & Medicine*, *3*(1), 30–36.

van der Harst, J. J., Gokeler, A., & Hof, A. L. (2007). Leg kinematics and kinetics in landing from a single-leg hop for distance: A comparison between dominant and non-dominant leg. *Clinical biomechanics (Bristol, Avon)*, *22*(6), 674–680. doi:10.1016/j.clinbiomech.2007.02.007

Wikstrom, E. A., Tillman, M. D., Kline, K. J., & Borsa, P. A. (2006). Gender and limb differences in dynamic postural stability during landing. *Clinical Journal of Sport Medicine*, *16*(4), 311–315.

Winter, D. A. (2005). *Biomechanics and motor control of human movement* (3rd ed.). Waterloo: John Wiley & Sons.

Zahradnik, D., Jandacka, D., Uchytil, J., Farana, R., & Hamill, J. (2015). Lower extremity mechanics during landing after a volleyball block as a risk factor for anterior cruciate ligament injury. *Physical Therapy in Sport*, *16*(1), 53–58. doi:10.1016/j.ptsp.2014.04.003

Zhang, S., Derrick, T. R., Evans, W., & Yu, Y. J. (2008). Shock and impact reduction in moderate and strenuous landing activities. *Sports Biomechanics / International Society of Biomechanics in Sports*, *7*(2), 296–309. doi:10.1080/14763140701841936