Article

Knee joint coordination during single-leg landing in different directions

Sinsurin, Komsak, Vachalathiti, Roongtiwa, Srisangboriboon, Sarun and Richards, James

Sinsurin, Komsak, Vachalathiti, Roongtiwa, Srisangboriboon, Sarun and Richards, James ORCID: 0000-0002-4004-3115 (2018) Knee joint coordination during single-leg landing in different directions. Sports Biomechanics . ISSN 1476-3141

Title Page

Knee Joint Coordination during Single-leg Landing in Different Directions

Komsak Sinsurin[a], Roongtiwa Vachalathiti[a], Sarun Srisangboriboon[a], Jim Richards[b]

[a]*Biomechanics and Sports Research unit, Faculty of Physical Therapy, Mahidol University, Thailand*

[b]*Allied Health Research unit, University of Central Lancashire, UK*

Corresponding Author:

Associate Professor Roongtiwa Vachalathiti, PT, PhD

Faculty of Physical Therapy, Mahidol University, 999 Phuttamonthon 4 Road, Salaya, Thailand.

E-mail: roongtiwa.vac@mahidol.ac.th

Tel: +6624415450 #20401 Fax: +6624415454

Word count: 2845 words

Acknowledgements

The authors would like to thank all the athletes for participation in this study.

Funding

This research project is supported by Mahidol University.

Abstract

Knee joint coordination during jump landing in different directions is an important consideration for injury prevention. The aim of the current study was to investigate knee and hip kinematics on the non-dominant and dominant limbs during landing. Nineteen female volleyball athletes performed single-leg jump landing tests in four directions; forward (0°), diagonal (30° and 60°), and lateral (90°) directions. Kinematic and ground reaction force (GRF) data were collected using a 10-camera Vicon system and an AMTI force plate. Knee and hip joint angles, and knee angular velocities were calculated using a lower extremity model in Visual3D. A two factor repeated measures ANOVA was performed to explore limb dominance and jump direction. Significant differences were seen between the jump directions for; angular velocity at initial contact ($p < 0.001$), angular velocity at peak VGRF ($p < 0.001$), and knee flexion excursion ($p = 0.016$). Knee coordination was observed to be poorer in the early phase of velocity-angle plot during landing in lateral direction compared to forward and diagonal directions. The non-dominant limb seemed to have better coordination than the dominant limb during multi-direction jump landing. Therefore, dominant limbs appear to be at a higher injury risk than non-dominant limbs.

Keywords: knee stability, knee angular velocity, single-leg landing, volleyball athletes

Introduction

Landing from jumps can induce moderate strain forces to the structures of the knee due to the complex and aggressive nature of such tasks (Boden, Dean, Feagin, & Garrentt, 2000; Kirkendall & Garrett, 2000). These can lead to knee injuries such as anterior cruciate ligament (ACL) injury, which have been frequently reported during landing (Hootman, Dick, & Aqel, 2007). A ‘soft-style landing’ with greater knee and hip flexion, has been shown to reduce ground reaction forces (Devita & Skelly, 1992), which in turn has been shown to decrease loading of the ACL (Yu, Lin, & Garrett, 2006).

Joint coordination may be described as the ability of the muscles to control a joint during dynamic tasks such as landing. Measures of joint coordination may provide a greater insight into the motor control by the central nervous system (Scholz, 1990). Coordination may also be described as the ability to reduce joint loading during movement through improved dynamic stability (William, Chmielewski, Rudolph, Buchanan, & Snyder-Mackler, 2001). William et al. proposed that dynamic knee stability depends on articular geometry, soft tissue restraints, and joint loading from both weight bearing and muscle forces. Therefore, any increases in knee stability during landing may be as a result of improved coordination, and any fluctuation of movement variability may represent poor coordination. However, in contrast, previous study reported that atypically increases or decreases in variability may be the cause of injury (Robertson, Caldwell, Hamill, Kamen, Whittlesey, 2014). This supported Kurz and Stergious (2004), who suggested that abnormal movement patterns during movement perturbations could be observed in an unhealthy system, indicating an inability to adapt or control movement in multiple degrees of freedom.

Previously angle-angle plots and velocity-angle plots (phase plane plot) have been used to measure lower limb and joint coordination (Bartlett & Bussey, 2012). The use of angle-angle diagram was first proposed by Grieve (1986) as a simple technique for analysing the interaction of the angle data from two joints. These plots allow a representation of movement coordination of two joints and how they ‘co-vary’ which can be used to compare coordination patterns between conditions, and to focus on how the joint changes with respect to an adjacent joint. Phase plane plots offer a representation of the interaction between joint velocity and angle. These may be used to identify changes in joint control and coordination characteristics (Robertson, Caldwell, Hamill, Kamen, Whittlesey, 2014). Excessive variation of movement pattern or poor coordination has been associated with instabilities which are the result of neuromuscular impairment (Clark and Phillips, 1993), such as in gait of people with Parkinson disease. Heidersciet et al. (2002) demonstrated that the coordination variability of the thigh/leg movement was different between individuals with and without patellofemoral pain, with reduced variability representation movement compensation due to pain.

Various directions of landing can be observed in different sporting activities. Previous studies have shown differences in lower limb biomechanics during multi-directional landing (Sinsurin, Srisangboriboon, & Vachalathiti, 2017; Sinsurin et al., 2013; Sinsurin, Vachalathiti, Jalayondeja, & Limroongreungrat, 2016). However, assessment of differences in knee and hip coordination during jump landing in different directions has not been reported to date. This should provide a greater understanding of the knee coordination when performing different directions of jump which could highlight important considerations for injury prevention. Therefore, the aim of the current study was to investigate knee coordination during landing in various directions, and to compare landing on the non-dominant knees and dominant knees. We hypothesised that differences in knee and hip kinematics exist between jump-landing direction and between dominant and non-dominant limbs.

Methods

Participants

Twenty-one female volleyball athletes were recruited. All had participated in the university team and had no report of musculoskeletal problems on either leg in the three months prior to testing. Exclusion criteria included any serious injury or surgery to the lower extremities, such as ankle sprain, ACL injury, fracture, or patellar dislocation. Testing procedures were explained to all participants. 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).

A power calculation identified that 21 participants were required to provide a statistical power of 85% and an effect size of 0.3 calculated from pilot data of 5 volleyball athletes. However, data was incomplete for 2 participants, therefore data from only 19 participants was reported. The athletes' average age and experience were 19.7 ± 1.4 years and 9.6 ± 2.0 years, respectively, and all participants were right-leg dominant. The dominant limb was defined by the single-leg hop for distance protocol, which determined the longest hop distance for the dominant side (van der Harst, Gokeler, & Hof, 2007). In addition, height, body weight, leg length, knee width, and ankle width were recorded.

Jump-Landing Tests

Multi-directional jump landing tests were collected in a Motion Analysis Laboratory. Kinematic data were recorded using a 10 camera Vicon™ Nexus system (Oxford Metrics, Oxford, UK) at 100 Hz, and force data were collected using an AMTI force plate (Advanced Mechanical Technology, Massachusetts, USA) at 1,000 Hz. The force plate was used to define the events of an initial contact and peak vertical ground reaction force (VGRF). Sixteen reflective markers were placed bilaterally on the lower-limb bony prominences of participants including; anterior superior iliac spines, posterior superior iliac spines, thighs, lateral condyles of the femurs, shanks, lateral malleoli, heels, and the head of the 2nd metatarsal bones. A 30-cm-height wooden platform was placed 70 cm from the centre of the force plate.

Tillman et al. (2004) reported that unilateral landing was 50% approximately in volleyball. This supports the use of unilateral jump-landing test as an appropriate assessment of the risk of lower extremity landing injuries (Sinsurin et al., 2013; Sinsurin et al., 2017; Tamura, Akasaka, Otsudo, Schiozawa, Toda, & Yamada, 2017). Therefore, this study examined jump-landing test with one leg. 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 participants were asked to place both hands on their waist. Each participant was instructed to carefully jump off the wooden platform without an upward jump action in order to standardised the jump height between jump-landing tests in four directions. Four randomised directions were used; forward (0°), diagonal (30° and 60°), and lateral (90°) (Figure 1). These have been previously used by Sinsurin et al. (2013), who showed that jump-landing direction influenced lower extremity biomechanics. The participants 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 participant 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 the jump-landing test was repeated. The participants were allowed up to five practice jumps landing in each direction before the recorded trials. Participants were allowed to rest for five minutes between test directions and for at least thirty seconds between individual jumping trials.

Data Acquisition and Statistical Analysis

The kinematic and force plate data were filtered using a fourth-order zero-lag Butterworth digital filter at cut-off frequencies of 6 Hz and 40 Hz, respectively. The cut-off frequency was determined by the residual analysis technique (Winter, 2005). A three-dimensional model was constructed using Visual3D version 6 (C-Motion Inc., USA). The average of three successful trials in each direction for each limb was analysed. The landing phase was identified from the initial contact to 300 ms after initial contact. Knee and hip joint kinematics were calculated based on the cardan sequence of XYZ, equivalent to the joint coordinate system proposed by Grood and Suntay (1983). Knee-hip angle-angle plots, knee velocity-angle plots, knee flexion excursion, and knee angular velocity at initial contact and at peak VGRF were reported. Knee flexion excursion was calculated from an angular displacement from an initial contact to peak knee flexion during landing phase.

Statistical analysis was performed using SPSS version 17. Repeated-measure ANOVA (2 × 4, side × jump-landing direction) were used to determine the effect of limb jump-landing direction and knee side. In addition, post hoc pairwise comparisons were performed to compare the landing directions. The statistical significance was set at an alpha level of 0.05.

Results

No significant interactions were seen between limb and direction of landing and no significant differences were seen between the dominant and non-dominant limbs. However, the direction of jump landing significantly affected knee angular velocity at initial contact with the greatest velocity seen during the 0 degree jump and the lowest at 90 degrees ($F (1.388, 24.986) = 64.447$, $p < 0.001$). Conversely the greatest knee angular velocity at peak VGRF was seen during the 90 degrees jump and the lowest at 0 and 30 degrees ($F (2.007, 36.127) = 16.583$, $p < 0.001$).

Whereas knee flexion excursion showed the lowest value during the 90 degrees jump (F (3, 54) = 3.750, p = 0.016). Further analysis of the patterns of knee flexion angle, knee angular velocity, hip-knee angle-angle plot, and knee velocity-angle plots showed similar patterns for the non-dominant and dominant limbs. However, non-dominant and dominant limbs revealed different movement strategies between the different jump directions, Figures 2-6.

Discussion and Implications

The purpose of this study was to examine how knee joint coordination on the non-dominant and dominant limbs respond during landing in various directions. Sagittal plane knee kinematics included knee angular velocity at initial contact and at peak VGRF, and knee flexion excursion. Moreover, differences in coordination during landing of the hip-knee angle-angle and knee velocity-angle plots were explored.

Greater flexion of the knee and hip joints has been shown to help to reduce GRF during landing (Onate, Guskiewicz, & Sullivan, 2001; Cronin, Bressel, & Fkinn, 2008). A key finding of this study was that that jump-landing direction significantly influenced flexion excursion and angular velocity of the knee. The difference of knee flexion excursion between directions was small, albeit significant, with less excursion of knee flexion noted in lateral direction for both limbs compared to other directions (Figure 2). However, a maximum difference of 2.4 degrees between landing directions could not be considered as clinical important (Table 1).

At initial contact, significant differences were seen between landing directions with a trend of decreasing knee angular velocity observed from forward, diagonal, and lateral direction, respectively (Table 1). In addition, on average the knee angular velocity on the non-dominant limb was lower than the dominant, although no significant differences were seen between limbs. Previous studies (Sinsurin et al., 2013; Sinsurin et al., 2017) exhibited that lateral jump landing needed higher knee flexion at initial contact than forward and diagonal directions. They suggested that lateral jump landing has the higher risk of knee injury compared to forward and diagonal directions. Indicating that athletes preferred a strategy of increased knee flexion at initial contact to prevent knee injury. Therefore, the increased knee flexion and decreased knee angular velocity at initial contact would be the preferred strategy of normal knee control responding jump landing in forward, 30° diagonal, 60° diagonal, and lateral directions, respectively.

Previously, it has been reported that an increase of lower limb flexion during a soft-style landing helps to control body downward motion more effectively (Laughlin et al., 2011; Favre, Clancy, Dowling, & Andriacchi, 2016). Our data shows that, after foot contact, knee flexion progressively increased (Figure 2) while angular velocity showed a trend of decrease in all directions except with lateral direction (Figure 3). At peak VGRF, a significant greater knee angular velocity of both limbs was noted in lateral direction compared to other directions (Table 1). This finding would indicate that the better control of the knee during landing was noted in forward direction followed by the diagonal and lateral directions. Even though athletes have the strategy to prevent knee injury with increased flexion angle and decreased angular velocity at initial contact, greater angular velocity during landing phase was observed in lateral jump landing (Figure 3). This could be the result from poor control of eccentric contraction of knee extensor muscles in lateral jump landing compared to other directions (Figure 3). This was the phenomenon of knee control in healthy volleyball athletes, and it could be that the risk of knee injury might be higher in athletes who have asymptomatic musculoskeletal problems, especially when landing in lateral direction.

Hip-knee angle-angle diagrams offer a representation of the movement coordination which was compared qualitatively between conditions (Bartlett & Bussey, 2012). In addition, the smoothness of movement may also be observed during movements in such angle-angle plots (Richards, 2008). The current study focused on how the knee flexion changed with a change in the hip flexion and how these ‘co-vary’ during landing, Figure 4. A linear relationship was observed as ‘in-phase’ coordination. Increased knee flexion was observed while hip flexion increased during landing for all jump-landing directions and sides. Comparing between directions, all plots showed a smooth trend of increase for both sides. However, hip and knee muscular coordination responded differently in jump-landing direction constraint, with the coordinative response in lateral direction appearing to be different from the other directions. In particular, less hip-knee flexion-flexion angle was noted during the lateral jump landing (Figure 4), which would indicate a greater stiffness of the lower limb through the landing phase. Previous studies have reported an increased risk of lower limb injuries with a higher joint stiffness, indicating poorer energy dissipation during landing (Zhang, Bates, & Dufek, 2000). Moreover, in lateral direction, displacement of knee flexion was greater than hip flexion compared to other directions for both limbs in the late phase of landing. This might indicate that athletes need to keep lower center of mass position to maintain body stability in lateral direction compared to other directions.

The knee coordination during landing phase was reported in terms of knee velocity-angle or phase plane plot. Comparing patterns between directions in Figure 5, the knee velocity-angle plot in the lateral direction was notably different from other directions. In lateral direction, knee angular velocity progressively increased from initial contact to 35° knee flexion during landing, whereas forward and diagonal demonstrated a progressive decrease of knee angular velocity indicating that knee extensor muscle worked eccentrically with difficulty to control dynamic knee flexion during lateral jump landing. With greater the control difficulty there is a higher risk of knee injury, which would be exacerbated if athletes landed awkwardly or had a poor balance during landing in lateral direction. Comparing patterns of knee velocity-angle plot between the non-dominant and dominant limbs, Figure 6, knee angular velocity-angle plots exhibited a similar pattern in each of the jump directions. Although a higher angular velocity was observed in the dominant compared to the non-dominant limbs for all directions of jump landing. Previous studies suggested that non-dominant limbs get used to weight-bearing and therefore have the less risk of knee injury than dominant limbs (Ross, Guskiewicz, Prentice, Schneider, & Yu, 2004). In addition, the findings from this current study are supported by Sinsurin et al., (2017) who reported that non-dominant limbs seem land with more control than dominant limbs in volleyball athletes. This would suggest a greater level of joint control, through a decrease of the number of functional degrees of freedom allowed by the neuromuscular system. It has also been reported that after performing preventive training, the knee coordinative response would be expected to change. In task constraint when the direction of jump landing is changed, the pattern of angle-angle and angle-velocity plots in lateral jump landing should have a similarity to the forward direction. Soft-landing style, more flexion of hip and knee joints, which has been suggested to reduce the risk of lower injury during landing in various direction (Sinsurin et al., 2017; Sinsurin et al., 2013). Further work to investigate the effect of soft-landing styles on knee coordinate may provide a greater understanding of the effect of training techniques to reduce injury mechanisms.

The findings of this study are specific to volleyball athletes, application of these findings to other sports should be made with caution. Further studies are required to explore the coronal and transverse plane hip and knee kinematics, and other athletic groups should be included to determine if the patterns of knee and hip coordination are similar. Further factors that should be considered include, gender differences, athletes with ACL insufficiency, recovering from ankle injury and athletes with patellofemoral pain syndrome. Multi-direction jump landing could also be utilised to investigate the effectiveness of lower limb rehabilitation and risk of re-injury.

Conclusion

The current study determined that direction of jump landing significantly influenced knee flexion excursion and knee angular velocity during landing. In volleyball athletes, poor knee coordination was observed in the early phase of lateral landing compared to forward and diagonal directions. The non-dominant limb seems to land with better coordination than the dominant limb during multi-direction jump landing. It may be possible to improve the control of the dominant limb with training such as weight-bearing tasks to reduce risk of injury. Injury risk awareness should be most concerned with lateral jump landing tasks in both limbs.

Acknowledgements

The authors would like to thank all the athletes for participation in this study.

Disclosure statement

No conflict of interest

Funding

This research project is supported by Mahidol University.

References

Bartlett, R. & Bussey, M. (2012). *Sports biomechanics: Reducing injury risk and improving sports performance* (pp. 229-243). New York: Routledge.

Boden, B.P., Dean, G.S., Feagin, J.A., & Garrentt, W.E. (2000). Mechanism of anterior cruciate ligament injury. *Orthopedics*, 23, 573-578.

Clack, J.E., & Phillips, S.J. (1993). A longitudinal study of intralimb coordination in the first year of independent walking: A dynamical system analysis. *Child Development*, 64, 1143-1157.

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

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, 108-115.

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*, 44, 1540-1546.

Grieve, D.W. (1986). Gait patterns and the speed of walking. *Biomedical Engineering*, 3, 119-122.

Grood, E.S. & Suntay, W.J. (1983). A joint coordinate system for the clinical description of three-dimensional motion: application to the knee. *Journal of Biomechanical Engineering*, 105, 136-144.

Heiderscheit, B.C. (2002). Variability of stride characteristics and joint coordination among individuals with unilateral patellofemoral pain. *Journal of Applied Biomechanics*, 18, 110-121.

Hootman, J.M., Dick, R., & Aqel, J. (2007). Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. *Journal of Athletic Training*, 42, 311-319.

Kirkendall, D.T., & Garrett, W.E. (2000). The anterior cruciate ligament enigma. Injury mechanisms and prevention. *Clinical Orthopaedics and Related Research*, 372, 64-68.

Kurz, M.J., & Stergiou, N. (2004). Applied dynamic system theory for the analysis of movement. In N. Stergiou (Eds.), *Innovative analyses of human movement* (pp. 93-119). Illinois: Human Kinetics.

Laughlin, W.A., Weinhandl, J.T., Kernozek, T.W., Cobb, S.C., Keennan, K.G., & O'Connor, K.M. (2011). The effects of single-leg landing technique on ACL loading. *Journal of Biomechanics*, 44, 1845-1851.

Onate, J.A., Guskiewicz, K.M., & Sullivan, R.J. (2001). Augmented feedback reduces jump landing forces. *The Journal of Orthopaedic & Sports Physical Therapy*, 31, 511-7.

Richards, J. (2008). *Biomechanics in clinical and research* (pp. 64-65). Churchill Livingstone Elsevier.

Robertson, G., Caldwell, G., Hamill, J., Kamen, G., & Whittlesey, S. (2014). *Research Methods in Biomechanics* (pp. 291-297). Illinois: Human kinetics.

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.

Scholz, J.P. (1990). Dynamic pattern theory: some implications for therapeutics. *Physical Therapy*, 70, 827-843.

Sinsurin, K., Srisangboriboon, S., & Vachalathiti, R. (2017). Side-to-side differences in lower extremity biomechanics during multi-directional jump landing in volleyball athletes. *European Journal of Sport Sciences*, 17, 699-709.

Sinsurin, K., Vachalathiti, R., Jalayondeja, W. & Limroongreungrat, W. (2016). Knee muscular control during jump landing in multidirections. *Asian Journal of Sports Medicine*, 7, e31248.

Sinsurin, K., Vachalathiti, R., Jalayondeja, W. & Limroongreungrat, W. (2013). 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, 1109-1113.

Tamura, A., Akasaka, K., Otsudo, T., Schiozawa, J., Toda, Y. & Yamada, K. (2017). Dynamic knee valgus alignment influences impact attenuation in the lower extremity during the deceleration phase of a single-leg landing. *PLoS One*, 12, e0179810.

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, 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*, 22, 674–680.

William, G.N., Chmielewski, T., Rudolph, K., Buchanan, T.S., & Snyder-Mackler, L. (2001). Dynamic knee stability: current theory and implications for clinicians and scientists. *The Journal of Orthopaedic and Sports Physical Therapy*, 31, 5466-5466.

Winter, D. A. (2005). *Biomechanics and motor control of human movement* (pp. 49-50). Waterloo: John Wiley & Sons.

Yu, B., Lin, C.F., & Garrett, W.E. (2007). Mechanisms of non-contact ACL injuries. *British Journal of Sports Medicine*, 41, 147-151.

Zhang, S.N., Bates, B.T., & Dufek, J.S. (2000). Contributions of lower extremity joints to energy dissipation during landings. *Medicine and Science in Sports and Exercise*, 32, 812-819.

Table 1. Mean ± SD of the knee kinematics 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**
Angular velocity at initial contact (degrees/sec)	235.3 ± 104.4 [a,b,c]	202.4 ± 100.1 [b,c]	160.5 ± 108.3 [c]	90.8 ± 68.6	238.0 ± 94.6 [a,b,c]	205.3 ± 108.2 [b,c]	183.2 ± 83.3 [c]	104.7 ± 49.6	0.649	**< 0.001**	0.331
Angular velocity at peak VGRF (degrees/sec)	165.5 ± 181.6 [b,c]	161.3 ± 218.1 [b,c]	266.4 ± 221.0 [c]	366.9 ± 243.7	188.9 ± 220.6 [c]	174.5 ± 357.9 [c]	192.2 ± 269.1 [c]	412.8 ± 324.8	0.963	**< 0.001**	0.212
Flexion excursion (degrees)	38.9 ± 6.2	39.0 ± 5.4 [c]	38.9 ± 5.7	37.2 ± 4.9	40.3 ± 6.3	40.0 ± 5.4 [c]	40.0 ± 4.9 [c]	37.9 ± 4.8	0.398	**0.016**	0.926

[a] Statistically significant difference compared with 30° diagonal direction (<0.05), [b] Statistically significant difference compared with 60° diagonal direction (<0.05), [c] Statistically significant difference compared with lateral direction (<0.05), [d] Statistically significant difference compared with dominant limb (<0.05)

Figure 1. Research setting in the laboratory (modified from Sinsurin et al., 2017). 70cm is the distance from the starting point of jump-landing tests to the center of force plate. 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; G, lateral (90°) jump landing for the left lower limb.

Figure 2. Knee flexion angle during landing of non-dominant knee (a) and dominant knee (b). The y-axis is knee flexion angle (degrees). The x-axis is the time during landing phase (300ms) which is normalised to 100% (%normalised landing phase).

Figure 3. Knee angular velocity during landing of non-dominant knee (a) and dominant knee (b). The y-axis is knee angular velocity (degrees/sec). The x-axis is the time during landing phase (300ms) which is normalised to 100% (%normalised landing phase).

Figure 4. Hip-knee angle-angle plot during landing of non-dominant knee (a) and dominant knee (b). The y-axis is hip flexion angle (degrees). The x-axis is knee flexion angle (degrees).

Figure 5. Comparing pattern of knee velocity-angle plot between directions of non-dominant knee (a) and dominant knee (b). The y-axis is knee angular velocity (degrees/sec). The x-axis is knee flexion angle (degrees).

Figure 6. Comparing pattern of knee velocity-angle plot between non-dominant and dominant limbs in various directions (a) at forward (0 degree) direction (b) at 30 degrees diagonal (c) at 60 degrees diagonal (d) at lateral (90 degrees) direction. The y-axis is knee angular velocity (degrees/sec). The x-axis is knee flexion angle (degrees).