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Original Article

Lower limb biomechanics during drop vertical jump at different heights among university athletes

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Abstract:
Poor technique during landing might lead to increased risk of non-contact lower limb injuries. The purpose of the study was to evaluate the effects of landing heights and gender on the lower limb mechanics during drop vertical jump among athletes. Thirty university athletes between the ages of 19 and 25, with healthy weight, screened for a normal range of dynamic knee valgus and train regularly three times weekly were recruited as participants for the study. The lower limbs joint angles and moments were compared across gender and landing heights (30 cm vs 45 cm) at three landing time-points (initial contact, maximum vertical ground reaction force, and maximum knee flexion). The findings indicated that no significant differences were observed in lower limb joint angles and moments at the sagittal and frontal planes across gender and landing heights. Meanwhile, a significant difference existed for knee extensor moment during maximum knee flexion ($F(1.618,90.629) = 4.096$, $p = 0.027$) across landing heights. landing heights and gender may not affect lower limb mechanics except for knee extensor moments during maximum knee flexion. Females with normal range of dynamic knee valgus may exhibit a safe landing technique hence a screening test is crucial to identify its presence among female athletes.
Key Words: **biomechanics, collegiate athletes, dynamic knee valgus, injury prevention, sports medicine**

Introduction

Landing maneuvers are one of the fundamental tasks in high-risk sports activities such as volleyball, handball, and basketball (Dufek & Bates, 1991). The landing technique and height may affect the ground reaction force (GRF) and lower limb kinematics (Pappas et al., 2007; Lephart et al., 2002; Seegmiller & McCaw, 2003). Thus, poor landing mechanics with inadequate movement at the hip and knee joints will not only reduce shock absorption but also increase the risk of lower limb injury (Yeow et al., 2009). An example of poor landing technique is excessive dynamic knee valgus (DKV) which is characterized as knee valgus, contralateral pelvic drop, hip internal rotation, and a shift in the center of mass away from the stance leg. DKV is mainly caused by the weakness of the hip abductor (Powers, 2010), which lead to non-contact injuries such as patellofemoral pain syndrome and anterior cruciate ligament (ACL) injury (Noyes et al., 2005).

Stiff landing, characterized by a more extended knee position or less knee flexion at ground contact (i.e., erect posture), is also another poor landing technique that may lead to non-contact lower limb injuries. This is due to increased ground-reaction forces (GRFs) during stiff landing, which increases loads on the knee that leads to increased risk of ACL injury (Decker et al., 2003; Huston et al., 2001). The knee flexion angles during landing were inversely related to the ACL strain, which means that landing with higher knee flexion will reduce the strain and vice versa (Taylor et al., 2011). Previous literature on non-contact lower limb injury (Pappas et al., 2007; Lephart et al., 2002; Seegmiller & McCaw, 2003; Yeow et al., 2009) confirmed the influence of excessive DKV on landing mechanics. However, to the best of our knowledge, the effects of landing on the lower limb mechanics of those with normal DKV remain unknown.

It was reported that female athletes land with an increased knee valgus and vertical GRF compared to males during unilateral and bilateral landings (Pappas et al., 2007; Ford et al., 2009). Females usually use the ankle musculature more than males for impact attenuation during landing, which causes them to be in a contact position with erect posture (i.e., stiff landing) (Decker et al., 2003). Additionally, male athletes relied mostly on the gluteal and hamstring muscles, while female athletes had greater use of the quadriceps in landing strategy (Cleather et al., 2019). These gender-specific landing techniques probably placed the female athletes at an increased risk of ACL injury (Smith et al., 2012). With increased landing heights, females displayed a higher peak knee adduction moment while males showed a lower peak hip abduction and knee extensor moment (Weinhandl et al., 2015). Furthermore, greater landing heights will also increase the maximum GRF (Peng et al., 2019) and knee loading (Patterson et al., 2004), which will lead to a higher risk of lower limb injury.

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The previous studies (Patterson et al., 2004; Weinhandl et al., 2015; Cleather et al., 2019; Peng et al., 2019) that investigated the lower limb kinematics and/or kinetics across gender and different landing heights did not explicitly exclude those with excessive DKV. Due to this limitation, we did not know whether the landing mechanics and its relationship with non-contact injury also existed among those with normal DKV, which is defined as achieving the knee Frontal Plane Projection Angle (FPPA) between 7° to 13° in female and 3° to 8° and male during drop vertical jump screening test (Munro et al., 2012). Thus, the current study aims to compare the effects of landing from different heights on the lower limb kinematics and kinetics among university-level athletes with normal DKV. It is hypothesized that significant differences exist between landing heights but not between the genders among the athletes with a normal range of DKV.

Material & methods

Participants

The cross-sectional study design and protocol was approved by the ethical research committee of a local university (USM/JEPeM/18020132; USM/JEPeM/18020142). Sample size was calculated by using GPower software (version.3.1.9.2, University of Düsseldorf, Germany). We found that 30 participants are sufficient to obtain 80% power with 0.47 effect size. The effect size was based on the knee adduction angle during initial contact in the study of Yeow et al., (2009). A total of thirty (males = 15; females = 15) university athletes aged between 19 and 25 years, with normal body mass index (BMI) between 18.5-24.9 kg/m^2 and trained regularly at least thrice weekly, volunteered to participate in the study (World Health Organization, 2004). Greater BMI will increase the amount of force and load exerted to the knee mechanics during landing, which lead to a higher risk of lower limb injury (Montgomery et al., 2012). Importantly, we also included those who passed the 30 cm drop vertical jump (DVJ) screening test with the standard knee Frontal Plane Projection Angle (FPPA) between 3° to 8° for male and between 7° to 13° for female (Munro et al., 2012). The procedure of the screening test was based on Munro et al., (2012) and Jamaludin et al., (2020). Briefly, markers were placed at the midpoint of the knee joint, midpoint of the ankle joint, and anterior superior iliac spine (ASIS). Then, participants performed three trials of DVJ with one-minute rest interval between the trials. The jump-landing motions were captured from the frontal plane using a digital camera (SONY, Tokyo, Japan) and were analyzed using Silicon Coach Pro v.8 (The Tarn Group, Dunedin, New Zealand). The two-dimensional (2D) knee FPPA is the intersection of the line created between the ASIS and center of the knee joint and the line between the center of the knee joint and the center of the ankle joint. The knee FPPA values of more than the normal range (> 8° for male and > 13° for female) may suggest that the participant exhibit excessive DKV, thus were excluded from this study.

Study procedure

Prior to the data collection process, each participant was given an informed consent form that includes information on their medical history, medications prescription, and other medicals conditions. Upon obtaining their consent to participate in the study, their body weight, height and percentage of body fat were measured (Shaharudin et al., 2017).

Next, Firstly, the participants underwent warming up session, which involves five minutes of cycling on an ergometer with 50 watts loads at 60 RPM and ballistic jumps for five times. Next, they were required to wear tight-fitted attire for accurate markers' placement. Retroreflective markers were attached to their sacrum, ASIS, iliac crest, greater trochanter, thigh, lateral and medial knee, shank, lateral and medial ankle, heels, and the 2nd metatarsal of both legs. Cluster markers were attached to each of the thigh and shank segments in both limbs.

Then, all the participants practiced landing with both legs on a force plate (Bertec Corporation, Columbus, OH, US) following dropping off a plyometric box. The double-leg landing style was employed to have a better impact on shock absorption (Decker et al., 2003) as this landing style was commonly used in sports such as netball, badminton, and basketball. Participants stood barefooted on a plyometric box with their feet shoulder-width apart, then lean forward and drop from the box with double-leg landing, followed by a maximal vertical jump (i.e., jump as high as they can), and finally performed forefoot landing with both feet. The jump tasks were performed naturally without any influence from arm movement (Yeow et al., 2009). A five-minute rest interval was provided between the tested heights. The landing heights (i.e., 30 cm and 45 cm) were tested randomly across the participants. The data from the three trials were analyzed and averaged for each participant at each landing height.

Data collection and analysis

The biomechanical variables in this study were compared at three landing time points, namely, the initial contact (IC), maximum vertical ground reaction force (MVGRF), and maximum knee flexion (MKF) between the gender and landing heights (30 cm vs 45 cm) on the frontal and sagittal planes. The IC is the point in the trial when the vertical GRF was greater than 10 N [21], while MVGRF represents the first peak associated with the impact during landing, and MKF indicates the timeframe whereby greatest knee flexion was achieved while landing. The reflective markers' motions were collected at 100 Hz and then filtered with a fourth-order, zero-lag Butterworth at a 12 Hz cutoff frequency (Qualisys Track Manager Software, version 2.6.673, Gothenburg, Sweden). For missing trajectories, we used spline estimates to fill the patterns. Then, bone model was created for each trial (Visual 3D software, version 5, C-Motion Inc., Rockville, MD, USA) to analyze the kinematics and kinetics data (Zainuddin et al., 2019).

Statistical analysis

The Statistical Package for the Social Sciences (SPSS version 24.0, IBM Corp., Armonk, New York, USA) software was used to analyze the data quantitatively. The distribution of the data was assessed by using the Shapiro-Wilk test. Next, the effects of landing from different heights on the lower limb kinematics and kinetics at all the landing time-points across gender were analyzed by using a Repeated Measured ANOVA. Kinematics and kinetics of the lower limb joints were compared between different landing heights and gender. For any detected significant differences ($p < 0.05$) between the compared variables, the Least Significant Difference (LSD) post hoc test was applied for further analysis.

Results

The participants were within the normal range of BMI and body fat percentage for their age group. Except for body mass, there were significant differences in all physical characteristics' measurements between the males and females (Table 1).

Table 1. Comparisons of physical characteristics between male and female participants (N=30)

Physical characteristics	**Mean (SD)**		**p value**
	Male (n=15)	**Female (n=15)**	
Height (cm)	163.7 (7.188)	155.80 (4.11)	0.01*
Body mass (kg)	55.56 (9.8)	56.77 (3.68)	0.66
Body Mass Index (BMI) (kg/m^2)	21.98 (1.86)	22.40 (1.40)	0.03*
Body Fat Percentage (%)	10.19 (5.15)	21.12 (3.02)	0.01*

cm = Centimetre; kg = Kilogram; m = Meter; % = Percentage

The kinematics and kinetics of the lower limb joints for the dominant leg on the frontal and sagittal planes are shown in Tables 2 and 3, respectively. When compared between the landing heights (30 cm vs 45 cm) and gender, no statistically significant differences in the lower limb mechanics on the frontal plane were observed. Moreover, no statistically significant differences were observed in the lower limb mechanics on the sagittal plane except for the knee extensor moment during MKF ($F(1.618,90.629) = 4.096$, $p = 0.027$) across landing height.

Table 2. Comparison of kinematics and kinetics of dominant leg in frontal plane at landing phases across landing heights (30 cm and 45 cm) and gender.

Variables	**Landing Phase**	**Gender**		**P value**	**Landing Height**		**P value**
		Male (n=15)	**Female (n=15)**		**30 cm (n=30)**	**45 cm (n=30)**	
Hip Adduction/ Abduction (°)	IC	-2.16 (6.80)	-1.55 (3.14)	0.706	-1.52 (4.85)	-2.19 (5.70)	0.424
	MVGRF	-1.71 (7.15)	-1.20 (3.35)	0.352	-1.19 (5.13)	-1.72 (6.00)	0.435
	MKF	1.85 (7.30)	4.79 (5.79)	0.790	3.65 (6.96)	3.00 (6.52)	0.670
Knee Adduction/ Abduction (°)	IC	0.92 (4.51)	0.27 (5.53)	0.284	1.08 (5.55)	0.11 (4.45)	0.216
	MVGRF	0.84 (6.96)	0.71 (6.31)	0.179	1.45 (7.19)	0.11 (5.97)	0.552
	MKF	2.84 (8.39)	3.47 (6.27)	0.193	3.63 (7.80)	2.68 (6.98)	0.573
Ankle Adduction/ Abduction (°)	IC	-0.21 (10.15)	5.45 (13.64)	0.319	3.60 (14.09)	1.63 (10.26)	0.125
	MVGRF	-4.36 (9.86)	4.80 (20.04)	0.315	1.40 (21.01)	-0.97 (9.90)	0.215
	MKF	-9.78 (12.20)	-1.86 (10.70)	0.244	-7.27 (13.09)	-4.37 (10.96)	0.410
Hip Moment (Nm/kg)	IC	-0.20 (1.79)	0.48 (0.20)	0.192	-0.01 (1.84)	0.29 (0.27)	0.702
	MVGRF	0.06 (0.24)	0.69 (0.54)	0.475	0.38 (0.53)	0.36 (0.52)	0.200
	MKF	0.07 (0.19)	0.39 (0.25)	0.167	0.23 (0.28)	0.23 (0.27)	0.202
Knee Moment (Nm/kg)	IC	0.06 (0.12)	0.41 (0.20)	0.392	0.25 (0.24)	0.23 (0.24)	0.399
	MVGRF	0.09 (0.23)	0.73 (0.58)	0.401	0.41 (0.55)	0.41 (0.55)	0.362

	MKF	0.02 (0.07)	0.17 (0.15)	0.788	0.09 (0.14)	0.09 (0.14)	0.434
Ankle Moment (Nm/kg)	IC	0.03 (0.07)	0.31 (0.27)	0.247	0.17 (0.24)	0.17 (0.24)	0.281
	MVGRF	0.09 (0.22)	0.62 (0.45)	0.220	0.36 (0.45)	0.35 (0.44)	0.343
	MKF	0.06 (0.14)	0.28 (0.25)	0.179	0.17 (0.24)	0.17 (0.23)	0.104

Abbreviations: IC= Initial Contact, MVGRF= Maximum Vertical Ground Reaction Force, and MKF= Maximum Knee Flexion
*Mean difference is significant at p<0.05 level across landing phase
(-) sign indicate hip, knee and ankle abduction
(+) sign indicate hip, knee and ankle adduction

Table 3. Comparison of kinematics and kinetics of dominant leg in sagittal plane at landing phases across landing heights (30 cm and 45 cm) and gender.

Variables	**Landing Phase**	**Gender**		**P value**	**Landing Height**		**P value**
		Male (n=15)	**Female (n=15)**		**30 cm (n=30)**	**45 cm (n=30)**	
Hip Flexion/ Extension (°)	IC	19.13 (6.58)	24.33 (9.89)	0.420	21.71 (7.53)	21.74 (9.92)	0.264
	MVGRF	24.87 (7.78)	33.38 (9.37)	0.715	28.71 (8.79)	29.54 (10.40)	0.093
	MKF	50.22 (12.31)	63.92 (9.050)	0.691	56.15 (13.37)	57.99 (12.24)	0.771
Knee Flexion/ Extension (°)	IC	-27.39 (8.95)	-31.73 (11.20)	0.465	-27.47 (8.30)	-31.65 (11.72)	0.813
	MVGRF	-50.30 (12.04)	-53.46 (8.16)	0.837	-48.92 (9.32)	-54.84 (10.58)	0.330
	MKF	-91.67 (21.71)	-104.25 (12.30)	0.689	-94.60 (19.28)	-101.33 (17.58)	0.696
Ankle Flexion/ Extension (°)	IC	70.55 (9.20)	71.88 (9.47)	0.270	71.90 (9.09)	70.53 (9.57)	0.668
	MVGRF	94.75 (9.26)	96.33 (6.42)	0.162	94.88 (8.35)	96.20 (7.59)	0.696
	MKF	113.31 (13.21)	116.83 (8.06)	0.527	115.55 (10.42)	114.60 (11.69)	0.605
Hip Moment (Nm/kg)	IC	0.12 (0.18)	-0.10 (0.33)	0.647	0.01 (0.24)	0.002 (0.33)	0.054
	MVGRF	0.43 (0.28)	-0.18 (0.51)	0.371	0.07 (0.56)	0.18 (0.45)	0.061
	MKF	0.06 (0.38)	-1.05 (0.51)	0.089	-0.55 (0.78)	-0.44 (0.66)	0.116
Knee Moment (Nm/kg)	IC	-0.17 (0.11)	0.09 (0.34)	0.607	-0.08 (0.22)	0.004 (0.33)	0.802
	MVGRF	0.06 (0.24)	0.75 (0.69)	0.292	0.38 (0.64)	0.44 (0.61)	0.670
	MKF	0.08 (0.38)	1.01 (0.63)	0.117	0.60 (0.73)	0.49 (0.67)	**0.027***
Ankle Moment (Nm/kg)	IC	-0.05 (0.16)	-0.58 (0.34)	0.419	-0.32 (0.40)	-0.31 (0.36)	0.413
	MVGRF	-0.15 (0.38)	-1.15 (0.63)	0.666	-0.64 (0.69)	-0.66 (0.76)	0.138
	MKF	-0.08 (0.20)	-0.94 (0.47)	0.514	-0.54 (0.60)	-0.49 (0.53)	0.455

Abbreviations: IC= Initial Contact, MVGRF= Maximum Vertical Ground Reaction Force, and MKF= Maximum Knee Flexion
*Mean difference is significant at p<0.05 level across landing phase
(-) sign indicate hip, knee and ankle flexion
(+) sign indicate hip, knee and ankle extension

Discussion

We found that there were no significant differences in lower limb kinematics and kinetics on frontal and sagittal planes during all the time-points of landing between both the gender and the landing heights among university athletes with normal DKV. An exception was observed for the knee extensor moment during MKF, which was significantly reduced with increased landing height. Such findings are not in line with the previous studies (Weinhandl et al., 2015; Decker et al., 2003; Yeow et al., 2009; Pappas et al., 2007) as those with excessive DKV were excluded from the current study. The inclusion of only those with normal DKV ranging between 3 ° to 8 ° for males and 7 ° to 13 ° for females had excluded a major biomechanical bias across subjects (Munro et al., 2012).

Decker et al., (2003) reported a more significant knee extension and ankle plantar-flexion angles (i.e., erect posture) at initial ground contact in females than males at 60 cm of landing. On the other hand, Weihandl et al., (2015) observed that females exhibited greater hip abduction during IC at 50 cm of landing height but demonstrated a decrease in their maximum jumping ability (MJA) landings compared to males. However, these previous studies (Weinhandl et al., 2015; Decker et al., 2003) that compared landing mechanics across gender did not screened for excessive DKV, which explained the non-significant differences (Table 2 and 3) across gender in our results. Therefore, we proceed to analyze the lower limb mechanics across landing heights after we had found no statistically significant differences across gender. Furthermore, it has been reported that excessive knee abduction is a critical cause of ACL tear (Jacobs et al., 2005; Jacobs et al., 2007), while excessive ankle abduction may result in bone fractures and severe ligament tears (Funk et al., 2003). Our participants did not show excessive value in ankle and knee abduction angles across gender and landing heights (Table 2). Therefore, the participants from the current study executed a safe landing technique with regards to frontal plane motions.

When landing heights increase (from 30 cm up to MJA), females showed increased peak knee adductor moment increased and decreased peak ankle plantar-flexor moment (Weinhandl et al., 2015). Moreover, females also exhibited a decreased hip abduction during IC, with an increased peak knee extensor and plantar-flexor moments during MJA landing but displayed an increased hip abduction during IC at 50 cm landing (Weinhandl et al., 2015). Moreover, the female athletes in a previous study (Decker et al., 2003) executed a stiff landing technique with increased knee extensor moment during first and second peak of vertical GRF at 60 cm of landing height. We did not observe any of these in our results (Table 2 and Table 3) except for knee extensor moment which was significantly reduced following increased landing heights at MKF time point which is different from the previous study (Weinhandl et al., 2015). From Table 3, both genders perform DVJ test with knee extensor moment reduced as landing heights increases at MKF time point, which indicated that they performed soft landing technique with reduced impact forces across landing heights. The findings show that those with normal DKV exhibited safer landing technique, which emphasizes the importance of DKV screening among athletes.

Both genders executed more than 90º of knee flexion (male: 91.60º while female: 104.25°) (Table 3) which is around the similar range for female athletes in Devita et al. (1992). The soft-landing technique showed by our participants was achieved without any instructions regarding their landing technique. As a major shock absorber (Coventry et al., 2006), soft landing with knee flexion greater than 90° at IC (Devita et al. 1992) may cause a reduction in impact shock, loading rate and vertical ground reaction force during landing that help in lowering the risk of lower limb injury. Hence, informing athletes to flex their knee during IC is a crucial element to train them to execute soft landing technique (Devita et al. 1992).

For impact attenuation, females tend to rely more on their ankle musculature, which caused them to land with erect posture (i.e., increased knee extension and ankle plantar flexion) (Decker et al. 2003). However, our participants did not show any significant differences in sagittal plane joint angles. In fact, they exhibited greater knee flexion (male: 91.60º while female: 104.25°) (Table 3) compared to Decker et al. (2003) (male: 63.4º while female: 75.8°) during MKF across landing heights, which indicated our participants executed landing with higher energy absorption and reduced impact forces in the sagittal plane (Hewett et al., 1999). This indicates that those with normal DKV, regardless of gender, performed safe and soft-landing technique in sagittal plane motions, which reduce the risk of non-contact lower limb injury.

The barefooted condition during the jumps and landing in this study aimed to reduce bias in the lower limb biomechanics that is related to footwear across subjects as the shoes worn by the participants may have a shock absorption effect. Nevertheless, this was achieved at the expense of not accurately representing the jumping mechanics during sporting activities with shoes. Overall, the findings of this study, which involved university athletes with normal DKV, are therefore different from the findings of previous studies. We observed that those with normal DKV were able to land with reduced knee extensor moment at increased landing heights which indicate a safe landing technique.

Conclusions

The study concludes that no significant differences were observed in lower limb joint angles and moments at sagittal and frontal planes across gender and landing heights except for knee extensor moment during MKF which was significantly reduced following increased height. Hence, among those with normal DKV, landing heights and gender may not significantly affect their lower limb mechanics. Our findings implied that training programs aiming to achieve normal DKV are crucial to avoid risks of non-contact injuries. Future studies are recommended to compare the jump landing mechanics among those with and without excessive DKV, with the inclusion of whole-body motion analysis. For coaches and sports team manager, a regular DVJ screening test can be conducted to differentiate athletes with and without excessive DKV. Early and correct detection of DKV will reduce the risks of non-contact injuries among athletes.

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Conflicts of interest - There are no conflicts of interest declared by the authors.

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