ORIGINAL ARTICLE

Comparison of Knee Kinematics during Single Leg Squat across Physically Active Females with and without Dynamic Knee Valgus

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ABSTRACT

Introduction: Introduction: Knee valgus which also known as dynamic knee valgus (DKV), is frequently linked to non-contact lower-limb injuries, especially in females. This retrospective study aims to compare the kinematic variables of lower limb joints in physically active females with normal versus excessive DKV during single leg squat (SLS) at 45° and 60° knee flexion. **Methods:** Based on the outcomes of drop vertical jump screening test, 34 females were recruited and divided into two groups (i.e., normal and excessive DKV). Participants performed SLS at 45° and 60° knee flexion with three-dimensional motion capture and analysis. The kinematic variables of lower limb joints at both knee flexion of SLS were compared across groups using independent T-test. **Results:** During 45° SLS with the dominant limb, the normal DKV group performed significantly greater hip adduction angle (4.49±3.25°, t(32) = 2.371, p= 0.024) than the excessive DKV group (1.426±4.23°). During 60° SLS with the dominant limb, the normal DKV group showed knee adduction (0.223±0.07°, t(16.048) = 10.707, p=0.001) while the excessive DKV group showed knee abduction (-4.478±1.81°). **Conclusion:** Females with excessive DKV showed significantly different lower limb kinematics and motion control strategy compared to females with normal range of DKV. The findings highlighted the importance of DKV screening among physically active females, and the rationale for prescribing individualized exercise intervention to prevent lower limb non-contact injuries.
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INTRODUCTION

Dynamic knee valgus (DKV) is an atypical motion pattern of weight-bearing motion described by an exaggerate medial lower limb collapse (1). DKV motions consisted of a combination of contralateral pelvic drop, hip internal rotation, and tibial rotation or knee valgus are typically caused by weakness of hip abductor (2). Non-contact injuries such as anterior cruciate ligament (ACL) rupture, patellar dislocation, and knee pain have all been associated to abnormal knee joint loading related to DKV (3).

The single leg squat (SLS) was commonly used as a functional test to assess irregular lower limb motions related to the kinetic chain or muscle coordination (4). During SLS, clinicians assessed the motion quality in general, trunk and pelvic alignment, knee and hip joint motions (4). Additionally, SLS is also used to assess knee function and rehabilitation process (5). Clinicians tend to favor this test because it replicates motion for high-intensity activities, for instance jumping and running, as well as having good validity and reliability (4, 6).

Zeller et al. (7) found that compared to male athletes, female athletes had greater knee valgus during SLS, which was related to greater activation of rectus femoris, decreased trunk lateral flexion, increased ankle dorsiflexion and pronation, and increased hip flexion, rotation and adduction (7, 8). However, studies addressing DKV on gender comparisons are more prevalent in the drop vertical jump (DVJ) compared to SLS (9, 10). Furthermore, there are studies that compare SLS on DKV in females only, but primarily between females with and without patellofemoral pain syndrome (PFPS) (11) or among females with PFPS across intervention (12). However, no studies have been conducted regarding the lower limb kinematics at different knee flexion of SLS within the physically active females' population. In order to reduce the occurrence of non-contact injury related to excessive DKV, individualized training programs should be prescribed. Non-contact ACL tear in female athletes is frequently caused by a loss of hip and pelvic control, internal femur rotation, valgus knee, and external tibial rotation on a pronated, externally rotated foot (13). These motions that increased the risks of non-contact ACL tear can be evaluated during SLS test. Therefore, the current study aimed to evaluate the lower limb kinematics across physically active females with and without excessive DKV during SLS test at 45° and 60° knee flexion.

MATERIALS AND METHODS

A priori sample size calculation (GPower, v.3.1.9.2, Dьsseldorf, Germany) of Independent T-test showed that 34 participants (i.e., 17 participants per group) was sufficient to yield 0.72 study power with effect size of 0.9. Effect size was determined using peak knee valgus angle data among female participants (15). From this calculation, in normal DKV and excessive DKV group, 17 participants per group are required to reject null hypothesis.

This cross-sectional retrospective study included 34 volunteered university female athletes (22.35 ± 1.12 years and mean BMI of 21.80 ± 2.31 kg/m^2) who trained at least three times per week in various sports (e.g., handball, volleyball, Frisbee, basketball, netball, and badminton). We recruited those age between 19 and 25 years old, with normal Body Mass Index (BMI), and without back and leg injuries at the time of data collection and six months prior. Participants in the normal group showed normal values of two-dimensional (2D) knee frontal plane projection angle (FPPA) while performing DVJ screening test, which is 7°-13° for females (14). Meanwhile, participants in excessive DKV group showed more than 13° of 2D knee FPPA during DVJ screening test (16). We excluded those who are pregnant, with musculoskeletal injury during data collection, physically inactive (i.e., did not exercise for at least three times per week) (17), have a history of lower limb orthopedic injury, neurological and balance disorders that restrict their level of activity.

Prior to recruitment, participants were provided with study details and requested to sign a consent form. Once agreed, the researcher explained all the study details. The physical characteristics of the participants were then recorded, including their height (m), weight (kg) and body fat percentages utilizing Omron HBF-360 Electronic Body Fat Percentage Analyzer (Omron, Kyoto, Japan) (18). The BMI was categorized by Asian population classification standards (19). The leg length (cm) was measured during standing using a non-stretchable tape measuring from the anterior superior iliac spine (ASIS) to the center of medial malleolus (20). Participants were required to wear tight clothes to facilitate the accuracy of markers' placement and data collection. Furthermore, they have been advised to consume food at least two hours prior to the experimental session and to get adequate sleep (at least six hours) a day before the test. Data collection for each participant was conducted between 9 am and 12 noon at Exercise and Sports Science Lab of Universiti Sains Malaysia. Human Research Ethics Committee of Universiti Sains Malaysia had approved the study procedure (USM/JEPeM/18070316).

Screening Test

Participants warmed up for five minutes by cycling on an ergometer at 50 RPM and 60 watts. After warming up, participants stood shoulder-width apart on a plyometric box with a 30 cm height (TRIDENT, Kuckreja, Malaysia). The markers were attached on both limbs at ASIS, the lateral and medial part of the femoral condyles and malleolus (21). The researchers demonstrated the test which included leaning forward and drop vertically from the box, followed by a subsequent maximal vertical jump, and finally landing on the force platform (16). No specific commands for arm motion (21). Each participant completed three DVJs from standing position, and a one-minute rest period between each jump (9). The jump frontal motions were captured with a digital camera (SONY HDR-CX240, Japan) and analyzed with Kinovea software (www.kinovea.org, version 0.9.4, Lasne, Belgium) (9). The screening test was conducted in accordance with Herrington & Munro's procedure (21). The knee FPPA during DVJ screening test denotes the angle formed via the intersection of ASIS and knee markers with the line formed by the knee and ankle markers (22). Participants were classified according to Munro et al., (16) recommendation whereby knee FPPA between 7°-13° is categorized as normal DKV whereas knee FPPA more than 13° is categorized as excessive DKV. Participants rested for at least one day before resuming the next test.

Single Leg Squat Test

Before the test, participants cycled at 50 RPM and 60 watts for 5 minutes on an ergometer. 35 retroreflective markers were placed at the participant's lower body for both limb: sacrum, ASIS, iliac crest, greater trochanter, heels, second metatarsal as well as medial and lateral parts of the knee and ankle (9). Each thigh and shank segment had four markers (i.e., cluster markers) placed on it. The participants then performed a double leg squat whereas the researchers adjusted the angle of knee flexion (i.e., 60° and 45°) based on a goniometer and then put an adjustable plinth at the level of the ischial tuberosity to indicate the pre-determined squat depth (23).

Participants executed a SLS by standing on a force plate (Bertec Corp., Ohio, USA), keeping their hands to their chests, holding erect trunk while standing on a stance leg, and flexed the other leg. The foot was positioned neutrally (i.e., directed forward) throughout the tests. Then, participants must ensure that their buttocks had touched the plinth to indicate the desired knee flexion while the other leg was extended to the front to avoid contact with the ground (23).

A metronome was preset at 60 beats per minute (bpm) to guide the squatting movement with one minute of rest interval between the trials. The leg that used to kick the ball furthest was referred as the dominant limb (24). Three trials of SLS for each leg and depth squat (i.e., 60° and 45° of knee flexion) were completed by all the participants. After the tests, participants were instructed to stretch their legs to cool down.

The lower limb joints kinematics during SLS tests were captured by Qualisys (version 2.6.673, Gothenburg, Sweden) in three planes (i.e., frontal, sagittal, and transverse). The raw data for the markers' coordinates was low-pass filtered by using a fourth-order, zero-lag Butterworth filter with a cutoff frequency of 12 Hz (9). To fill in the missing trajectories, spline estimations were applied (9). Then, inverse dynamics was applied to build a musculoskeletal model by using Visual 3D (version 5, C-motion, Inc. Rockville, MD, USA) (16).

Statistical Analysis

The Shapiro-Wilk test was performed to evaluate the normality of data distribution for small sample sizes (less than 50 samples) (25). The Independent T-Test was conducted to compare the lower limb kinematics during two different depths of SLS (i.e., 45° and 60° knee flexion) across the normal DKV group and the excessive DKV group. The significance level was set at $p<0.05$. Statistical analysis was conducted using Statistical Package for Social Sciences (IBM Corp., Version 25, Armonk, NY, USA).

RESULTS

Table I showed the comparison of physical characteristics across both groups. The knee FPPA during screening test was significantly larger in those with excessive DKV than the normal group. All participants are within normal range of BMI and body fat percentage for physically active females (19).

The joint kinematics of the dominant and non-dominant limb in all three planes were compared across the two groups (normal versus excessive DKV) during the SLS test at 45° knee flexion (Table II) and 60° knee flexion (Table III).

When the dominant limb squatted at 45° knee flexion, the participants in the normal DKV group performed significantly greater hip adduction angle (4.49±3.25°, $t(32) = 2.371$, $p= 0.024$) than the participants in the excessive DKV group (1.426±4.23°). Furthermore, the participants in the normal DKV group demonstrated knee adduction (1.72±6.14°, $t(32) = 2.291$, $p= 0.029$), whereas the excessive DKV group demonstrated knee

Table I: Comparison of physical characteristics between normal and excessive DKV groups (N=34)

Physical characteristics	Groups (mean ± SD)		P-value
	Normal DKV (n=17)	Excessive DKV (n=17)	
Height (cm)	159.24 ± 4.27	156.71 ± 5.51	0.14
Body weight (kg)	55.15 ± 7.57	53.96 ± 5.77	0.61
Body Mass Index ±BMI) (kg/m^2)	21.63 ± 2.50	21.97 ± 2.17	0.67
Body Fat Percentage (%)	20.21 ± 5.95	22.32 ± 5.17	0.28
Knee FPPA of dominant leg during DVJ test (°)	10.30 ± 1.88	15.95 ± 0.76	**0.00***
Pelvic width (cm)	27.29 ± 2.11	27.25 ± 2.14	0.96

SD=standard deviation; cm=centimetre; kg=kilogram; m=metre; %=percentage; °=degree
* indicates mean difference is significant at p<0.05 across groups

Table II: Comparison of hip, knee and ankle angles of both limbs in frontal, sagittal and transverse planes during SLS at 45° of knee flexion across normal and excessive DKV groups (N = 34)

Variables	Stance Leg	Groups (mean ± SD)		P value
		Normal (n=17)	Excessive DKV (n=17)	
Hip abduction/adduction (°)	Dominant	4.493 ± 3.25	1.426 ± 4.23	**0.024***
	Non-dominant	3.640 ± 4.37	1.168 ± 4.33	0.107
Knee abduction/adduction (°)	Dominant	1.72 ± 6.14	-3.620 ± 7.40	**0.029***
	Non-dominant	0.240 ± 8.54	-3.745 ± 8.60	0.185
Ankle abduction/adduction (°)	Dominant	-5.381 ± 7.96	-3.908 ± 7.34	0.579
	Non-dominant	-4.582 ± 8.05	-3.580 ± 8.37	0.724
Hip flexion/extension (°)	Dominant	19.748 ± 6.89	16.979 ± 6.73	0.245
	Non-dominant	16.245 ± 7.95	16.333 ± 7.57	0.974
Knee flexion/extension (°)	Dominant	-45.169 ± 0.03	-45.146 ± 0.06	0.167
	Non-dominant	-45.263 ± 0.42	-45.263 ± 0.15	0.996
Ankle flexion/extension (°)	Dominant	103.074 ± 5.58	106.150 ± 6.89	0.162
	Non-dominant	101.057 ± 10.74	106.192 ± 7.29	0.113
Hip internal/external rotation (°)	Dominant	2.311 ± 7.61	1.760 ± 9.93	0.857
	Non-dominant	2.093 ± 9.25	-1.847 ± 6.65	0.164
Knee internal/external rotation (°)	Dominant	-5.722 ± 10.24	-3.34 ± 8.32	0.461
	Non-dominant	5.731 ± 9.40	6.754 ± 9.66	0.756
Ankle internal/external rotation (°)	Dominant	-11.586 ± 4.17	-8.472 ± 8.13	0.171
	Non-dominant	14.303 ± 10.82	11.154 ± 9.92	0.383

*Mean difference is significant at p<0.05 level across groups
(+) sign indicate the lower limb joint motion of adduction, extension, internal rotation
(-) sign indicate the lower limb joint motion of abduction, flexion, external rotation

Table III: Comparisons of hip, knee and ankle angles of both limbs in frontal, sagittal and transverse planes during SLS at 60° of knee flexion across normal and excessive DKV groups (N = 34)

Variables	Stance Leg	Groups (mean ± SD)		P value
		Normal (n=17)	Excessive DKV (n=17)	
Hip abduction/adduction (°)	Dominant	3.640 ± 4.37	1.168 ± 4.33	0.107
	Non-dominant	-1.127 ± 0.89	0.635 ± 0.57	**0.000***
Knee abduction/adduction (°)	Dominant	0.223 ± 0.07	-4.478 ± 1.81	**0.000***
	Non-dominant	0.635 ± 0.54	-0.245 ± 0.23	**0.000***
Ankle abduction/adduction (°)	Dominant	-4.582 ± 8.05	-3.580 ± 8.37	0.724
	Non-dominant	0.646 ± 5.78	1.729 ± 8.24	0.660
Hip flexion/extension (°)	Dominant	20.530 ± 8.00	24.543 ± 6.46	0.118
	Non-dominant	20.055 ± 9.40	22.372 ± 7.41	0.431
Knee flexion/extension (°)	Dominant	-60.279 ± 0.15	-60.206 ± 0.14	0.173
	Non-dominant	-60.283 ± 0.18	-60.251 ± 0.17	0.595
Ankle flexion/extension (°)	Dominant	111.198 ± 5.94	112.335 ± 6.36	0.594
	Non-dominant	111.256 ± 6.93	113.777 ± 7.26	0.308
Hip internal/external rotation (°)	Dominant	2.992 ± 7.78	0.884 ± 7.79	0.436
	Non-dominant	-0.006 ± 9.15	-1.458 ± 7.14	0.650
Knee internal/external rotation (°)	Dominant	-4.339 ± 7.65	-4.584 ± 9.86	0.936
	Non-dominant	4.993 ± 10.87	6.649 ± 10.41	0.653
Ankle internal/external rotation (°)	Dominant	-11.516 ± 4.62	-8.329 ± 9.215	0.212
	Non-dominant	13.136 ± 11.21	15.833 ± 9.90	0.462

*Mean difference is significant at p<0.05 level across groups
(+) sign indicate the lower limb joint motion of adduction, extension, internal rotation
(-) sign indicate the lower limb joint motion of abduction, flexion, external rotation

abduction (-3.620±7.40°).

Significant differences in knee kinematics were observed when squatting at 60° knee flexion with the dominant leg, with participants in the normal DKV group showed knee adduction (0.223±0.07°, t(16.048) = 10.707, p=0.001) while participants in the excessive DKV group showed knee abduction (-4.478±1.81°). During squatting at 60° knee flexion with the non-dominant leg, participants in the normal DKV group demonstrated hip abduction (-1.127±0.89°, t(21.410) =-6.863, p=0.001), whereas participants in the excessive DKV group demonstrated hip adduction (0.635±0.57°). Those in the normal DKV group performed knee adduction (0.635±0.54°, t(21.567) = 6.225, p= 0.001) while those in the excessive DKV group performed knee abduction (-0.245±0.23°) while squatting at 60° knee flexion with the non-dominant leg.

DISCUSSION

The purpose of the current study is to compare the lower limb mechanics during SLS between those who have normal DKV and excessive DKV among physically active females. The findings showed that the normal DKV group performed 45° SLS with significantly greater in hip adduction than the excessive DKV group. The DKV is defined as a combination of knee abduction, tibial internal rotation, hip adduction and internal rotation (26). Hip control loss was found to be related to knee valgus, as evidenced by increased hip adduction, external rotation and flexion (7). Thus, the hip abductor muscles play a crucial role in controlling DKV during dynamic tasks.

The participants in the normal DKV group performed SLS with an adducted knee, whereas the participants in the excessive DKV group performed SLS with abducted knee. The presence of knee abduction was found to be positively correlated with the presence of DKV (27), implying that the greater the knee abducted, the greater the presence of DKV. Additionally, normal DKV group performed SLS with abducted hip while the participants in excessive DKV group showed an adducted hip during 60° SLS. At 45° knee flexion of SLS, the normal DKV group showed greater hip adduction than the excessive group. However, during deeper squat (i.e., 60° knee flexion), the normal DKV group was able to switch to hip abduction. When the athlete has poor control of the hip, particularly the gluteus medius muscle, the loaded hip tends to shift into adduction (28) and further cause the femur to rotate internally and the tibia to abduct (i.e., valgus position) (7, 29).

Prior to the test, the screening test enabled us to assess the differentiation in lower limb mechanics among individuals with and without DKV during the SLS test, which differed from previous studies (7, 29, 30). Moreover, previous studies (7, 29, 30) did not compare individuals with and without DKV among physically active females, due to the fact that females had a higher tendency toward knee valgus than males. Therefore, this study compares the lower limb kinematics of individuals with and without DKV among physically active females. The findings showed that there are significant differences in the knee frontal angle for both limbs between normal and excessive DKV groups. The normal DKV group showed an adducted knee while the excessive DKV group performed with an abducted knee for both stance limbs during 60° SLS. Khuu and Lewis., (30) reported that females performed 60° SLS with greater hip adduction and less knee abduction than males. Zeller et al., (7) also stated that the uninjured female athletes showed increased hip adduction during SLS than male athletes. This indicates that women may have difficulties controlling the hip musculature, particularly the gluteus medius muscle, throughout the motion as they depend more on the quadriceps to regulate the knee motions (7). Therefore, strengthening of the gluteus medius to ensure pelvic symmetrical alignment is commonly recommended among female athletes with excessive DKV.

No statistically significant differences were observed in the lower limb joint kinematics of the sagittal plane during the 60° SLS test, which is similar to the findings from previous studies (20, 31). This probably related with the mechanisms of DKV, which involved a blend of the frontal and transverse plane motions instead of sagittal motion only (26). Besides, we had fixed the tested squat depths to 45° and 60° of knee flexion during the SLS test, which may limit the kinematical differences in the plane.

The normal DKV group showed greater hip external rotation angles than the excessive DKV group. On the contrary, the excessive DKV group showed more knee external rotation while performing the 60° SLS test than the normal DKV group for the non-dominant limb only. Willson and Davis (32) found a strong relationship between knee external rotation and knee valgus. Additionally, Zeller et al., (7) observed that women showed greater hip external rotation angles during SLS than men.

The findings of this study showed greater standard deviation values than the mean which indicate more data spread and variability (33). Positive and negative values in kinematics indicated different directions which contribute to increased variability. Knee valgus, for example, had a negative value, whereas knee varus had a positive value. As a result, the data's average values become less than the standard deviation.

The position of the non-stance leg while performing SLS particularly at maximum peak knee flexion squats, may also influence the findings (30). This is because, the non-stance leg positioned at the front showed more significant differences in the frontal hip and pelvis angles than when it was positioned at the side or behind the body (30). However, in the clinical setting, the front position is preferred because poor SLS performance was observed when the other leg was positioned beside or behind the body (34).

There are several limitations in this study that require further investigations. The findings of the study were limited to the lower limb kinematics during SLS at 45° and 60° knee flexion. The exclusion of kinetics data is also a limitation because musculoskeletal models are more susceptible to internal kinetics changes than kinematics (35). Despite this, we manage to discover a different lower limb kinematics across physically active females with and without excessive DKV during two different SLS depths. As SLS performance is also influenced by other factors such as core strength (36), lower limb strength (37), and coordination, investigating these variables may provide a more in-depth understanding of SLS mechanics.

CONCLUSION

Females with excessive DKV showed significantly different lower limb kinematics and motion control strategy compared to females with normal range of DKV. The findings highlighted the importance of DKV screening among physically active females, and the rationale for prescribing individualized exercise intervention to prevent lower limb non-contact injuries. Athletes and coaches may apply our results by designing exercise programs that target specific muscles to reduce excessive DKV.

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