



Original Article

The effects of foot position on lower extremity kinematics during single leg squat among adolescent male athletes



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المخلص

أهداف البحث: حققت هذه الدراسة في تأثير وضع القدم في المستوى العرضي على حركات الأطراف السفلية أثناء القرفصاء بساق واحدة.

طرق البحث: أجريت هذه الدراسة المقطعية بين رياضيين ذكور مدربين تدريباً عالياً. وتمت إضافة فقط المشاركين من ذوي الركبة الطبيعية الروحية عند اختبار الهبوط الإسقاطي الفحصي. قام ١٢ رياضياً مبتدئاً بالوقوف بساق واحدة، مع الحفاظ على زاوية انثناء الركبة عند ٦٠ درجة. طُبقت جلسات القرفصاء بثلاثة أوضاع للقدم: المعتدل (صفر درجة)، وتقريب القدم (١٠- درجة)، وإبعاد القدم (١٠+ درجة). استخدم التحليل الحركة ثلاثي الأبعاد لالتقاط القياسات الحركية للطرف السفلي المفضل لدى المشاركين. تمت مقارنة القياسات الحركية للورك والركبة في المستويات السهمية والجبهية والعرضية أثناء القرفصاء وعلى ثلاثة أوضاع للقدم باستخدام تحليل التباين أحادي الاتجاه "أنوفا".

النتائج: ظهر لدى المشاركين معدلاً طبيعياً من الركبة الروحاء الديناميكية [٥.٣ درجة (± ١.٦)]. لم تُلاحظ أي فروق ذات دلالة إحصائية في انثناء الورك، وتقريب الورك والدوران الداخلي عبر أوضاع مختلفة للقدم. وبالمثل، لم يُلاحظ وجود فروق ذات دلالة إحصائية في ثني الركبة، وتقريب الركبة والدوران الداخلي عبر أوضاع مختلفة للقدم.

الاستنتاجات: لا تؤثر التغييرات الصغيرة في وضع القدم في المستوى العرضي على حركات الطرف السفلي عند القرفصاء بساق واحدة عند الذكور المراهقين المدربين تدريباً عالياً أثناء وضعية الركبة الروحاء الديناميكية ضمن النطاق الطبيعي. وقد توفر نتائجنا إرشادات حول أساليب أكثر أماناً للهبوط، والتمحور والقطع أثناء التدريب والحالات المتعلقة بالألعاب.

الكلمات المفتاحية: السلسلة الحركية من أسفل إلى أعلى؛ أروح الركبة الديناميكية؛ الشباب؛ القرفصاء

Abstract

Objectives: The purpose of this study was to investigate the effect of transverse plane foot position on lower limb kinematics during a single leg squat.

Methods: This was a cross-sectional study conducted among highly-trained male athletes. Only participants who showed normal knee valgus during a drop landing screening test were recruited. Twelve junior athletes performed single leg squats while maintaining a knee flexion angle of 60°. The squats were executed in three foot positions: neutral (0°), adduction (-10°), and abduction (+10°). Three-dimensional motion analysis was used to capture the lower extremity kinematics of the participants' preferred limb. The hip and knee kinematics in the sagittal, frontal, and transverse planes during squatting were compared across the three foot positions using one-way ANOVA.

Results: The participants showed a normal range of dynamic knee valgus (5.3°±1.6). No statistically significant differences were observed in hip flexion (p = 0.322), adduction (p = 0.834), or internal rotation (p = 0.967) across different foot positions. Similarly, no statistically significant differences were observed in knee flexion (p = 0.489), adduction (p = 0.822), or internal rotation (p = 0.971) across different foot positions.

Conclusion: Small changes in transverse plane foot position do not affect lower extremity kinematics during single leg squat in highly trained adolescent males with normal dynamic knee valgus. Our findings may provide guidance on safer techniques for landing, pivoting, and cutting during training and game situations.

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Keywords: Bottom-up kinetic chain; Dynamic knee valgus; Squatting; Youth

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Introduction

Sports that require cutting, pivoting, landing, or sudden deceleration prior to changing direction commonly result in non-contact injuries to the knee joint.¹ This type of injury is associated with weak lower extremity alignment during dynamic tasks and is often referred to as excessive dynamic knee valgus (DKV).² DKV can be defined as a combination of hip adduction, hip internal rotation, knee flexion, knee external rotation, knee abduction, ankle inversion,³ and ankle dorsiflexion.⁴ Moreover, DKV can be distinguished as a body position in which the knee collapses medially from internal-external rotation and/or excessive valgus.²

Excessive DKV can be assessed using different screening tests including single leg squat (SLS), drop vertical jump (DVJ), drop landing, and single leg landing.⁵ During these tests, excessive DKV can be quantified by evaluating two-dimensional (2D) frontal plane projection angle (FPPA) of the knee joint. For example, the typical range 2D knee FPPAs during DVJ are between 7° and 13° in females, and 3° and 8° in males.⁵ Subjects who exceed these angles may be demonstrating kinematics that have an increased risk of non-contact knee injuries, such as patellofemoral pain syndrome (PFPS) and ACL strain.^{2,3,5–8} In addition, these tests simulate common motions in sports. For example, the DVJ test mimics the demands of high-acceleration motions that are common in sports with jump-landing tasks, such as soccer, netball, and rugby.² Meanwhile, the SLS test can simulate functional activities, gait, and motions performed in sports such as running, hockey, and soccer.⁹ SLS is also a reliable clinical evaluation that is commonly used to identify lower limb misalignment, muscle weakness, and core strength deficiencies.^{10,11}

Joint movements of the lower extremities are interdependent during closed chain activities, whereby excessive motion at a joint can overload tissues in the subsequent joints of a kinetic chain.^{12,13} DKV often has proximal lower limb origins consistent with a top-down kinetic chain, such as hip muscle weakness or trunk control deficits.¹⁴ In particular, weakness or aberrant motor control of the hip abductors and external rotators has been implicated in the development of knee injuries.^{14,15} Excessive or aberrant motions at the transverse and frontal planes of the hip joint may cause tibia abduction, foot pronation, and medial motion of the knee joint, all of which indicate DKV.¹⁶ Thus, diminished core and hip muscle strength are related to DKV, and can further affect the kinematics of the entire lower extremity.^{14,16} Indeed, during SLS, hip muscle weakness has been associated with greater medial knee displacement.^{14,17}

By contrast, a bottom-up kinetic chain contradicts the top-down kinetic chain. A bottom-up kinetic chain is concentrated on the ankle joint, and suggests that an increase of strength, especially in small muscles crossing the ankle joint, may affect movements and joint moments in the ankle, knee, and hip joints.¹⁸ Due to the mitered hinge design of the ankle, increased rearfoot pronation results in greater tibial internal rotation and knee valgus.¹⁸ Hence, foot position is also an adjustable factor that could improve excessive DKV, and further reduce the risk for associated lower limb injuries. For instance, Ishida et al.¹⁹ noted that knee rotation during SLS in young females is associated with toe direction, whereas Khamis and Yhizar²⁰ observed that ankle eversion caused tibial internal rotation to occur during foot hyperpronation and natural standing. Foot hyperpronation has also been positively associated with traumatic knee injury.²¹ In addition, the relationship between limited ankle dorsiflexion range of motion (ROM) and PFPS has been described by Piva et al.²² Moreover, a recent meta-analysis showed that reduced dorsiflexion ROM was consistently present among individuals with DKV compared to controls, regardless of whether the method of evaluation used weight bearing or non-weight bearing ROM.²³

Despite the importance of identifying DKV among athletes, its bottom-up kinetic chain has not yet been established, particularly during SLS. Excessive DKV is most likely caused by a combination of hip and ankle muscular strength imbalance. Therefore, comprehensive strategies that focus on the joints that are proximal and distal to the knee should be investigated.²⁴ This is crucial to determining whether or not knee alignment can be modified during functional tasks.²⁴ In addition, previous studies on SLS kinematics mostly involved female subjects who were not screened for excessive DKV, which may have influenced the findings. However, the bottom-up kinetic chain during SLS among physically active males has not yet been investigated. Consequently, this study was conducted to investigate the effects of foot position on hip and knee kinematics during SLS, in state-level male adolescent athletes who exhibited a normal range of DKV.

Materials and Methods

Subjects

This study used a cross-sectional design with purposive sampling. A sample size of 12 participants was determined a priori using GPower software (v.3.1.9.2), based on one-way ANOVA with the p-value set at 0.05. The effect size was calculated based on the association of foot position with knee kinetics and kinematics.¹⁹

All participants were recruited voluntarily through their team's coach. The details of the study methodology were provided and explained to each individual prior to their participation. Participants were encouraged to decide whether or not to participate without the influence of their coach. The study was conducted at a sport science laboratory of a local university. The duration of participation was approximately 30 min for the screening test, and 1.5 h for the 3D SLS test. The test sessions were conducted on separate days, with at least 24 h of rest between sessions.

Twelve state-level male adolescent athletes with a normal range of knee FPPA during DVJ screening test were recruited voluntarily. The participants included seven cyclists, three middle distance runners (400 m and 800 m) and two squash players. All participants were between 13 and 18 years of age and had represented their state in their respective sport at the national level at least once. Each participant had a normal body mass index (BMI) (i.e. between 18.5 and 24.99²⁵) and did not have any lower limb or back injuries at the time of data collection. The protocol of this study was approved by the research ethical committee from a local university and was conducted in compliance with the Declaration of Helsinki. Upon agreement, signed consent was obtained from the participants and their guardians.

Testing procedure

Screening test

Initially, all participants performed a DVJ screening test to confirm their qualification for the study. DVJ is often utilised to assess excessive DKV, which is correlated with increased risk of non-contact knee injuries.²⁶ Participants stood with feet shoulder-width apart on a box 30 cm high. They were instructed to lean forward and drop from the box as vertically as possible, and then immediately perform a maximal vertical jump before landing back on the ground.²⁷ There were no instructions regarding arm movement, other than for the participants to perform the movement naturally.⁶ Markers were attached at both sides of the anterior superior iliac spine (ASIS), greater trochanter, medial and lateral femoral condyle, tibia tubercle, and medial and lateral malleolus. Each participant performed three DVJ trials starting from a standing position, with a 1-min rest interval between trials.²⁸ The rest interval was crucial to avoid fatigue-influenced jumping and landing. The trials were captured from the frontal plane using a digital camera (SONY HDR-CX240, Japan), and were further analysed using Kinovea 0.8.15 (www.kinovea.org). The DVJ screening test and 2D knee FPPA analyses were conducted based on methods developed by Herrington and Munro.⁶ The 2D knee FPPA was used because it is a cost-effective injury-prevention screening tool and is easy to execute.⁵

The knee FPPA was evaluated as the intersection of the line created between ASIS and knee markers and another line created between knee and ankle markers. Normative values for 2D FPPA during DVJ were reported in previous studies whereby 'average' performance for women were within 7°–13°, while those for men were within 3°–8°.^{5,6} Only participants with normal 2D knee FPPA during the DVJ screening test were included in the three-dimensional (3D) SLS test, which was conducted on a separate day with at least 24 h of rest interval after the screening test.

Three dimensional SLS tests

Upon reaching the lab, participants changed into tight clothes, which were necessary for accurate marker placement. Participants' body weight (kg) and height (m) were measured with a digital medical scale (Seca 769, Hamburg,

Germany), and their body fat percentage was evaluated using Omron HBF-360 Electronic Body Fat Percentage Analyser (Kyoto, Japan). Next, participants warmed up for 5 min on a cycle ergometer (Cybex Inc., Ronkonkoma, NY, USA) at 50 RPM with 60 W. Demonstrations by the researcher and familiarisation trials were conducted. Thirty-seven reflective markers were then placed on the participant's sacrum, both sides of ASIS, greater trochanter, heel, second and fifth metatarsals, medial and lateral femoral condyles, and medial and lateral malleolus. Cluster markers were attached on the thigh and leg segments bilaterally. Next, participants were asked to squat using both legs, while the researcher determined the 60° of knee flexion with a clear plastic goniometer. An adjustable plinth was set at the height of the ischial tuberosity during the double limb squat to indicate the desired squat depth (i.e. 60° of knee flexion).²⁹ Participants then stood with both feet on the ground for 10 s to capture their static standing pose.

Participants were instructed to perform an SLS to 60° of knee flexion. They were asked to maintain their hands on their chest and keep the trunk upright while standing on one limb and flexing the knee of opposing limb to 90°. Only the preferred leg was tested, which was identified by asking individuals which leg they used to kick a ball.³⁰ The foot positions (from the heel to the second metatarsal head) of the stance foot were set in three directions, namely 0° (neutral), 10° (toe-out), and -10° (toe-in) relative to the horizontal plane of ankle joint. While tested in different foot directions, participants were asked to maintain their knee directed forward during the start position. During the SLS test, a metronome app, JY Fitness Timer (Alphapod, v.1.0.14, Malaysia), was set at 60 beats per minute to provide desired movement speed. Participants were requested to follow the tempo guided by the metronome which was 5s of lowering and 5s of returning to standing.²⁹ Participants were instructed to touch the plinth with their buttocks to indicate the squat depth of 60° knee flexion and to keep the opposite limb away from the ground without any support from no upper limb.²⁹ The SLS motion was captured at 100 Hz and recorded using Qualisys Track Manager Camera (Qualisys, Sweden). Three SLS trials at 60° of knee flexion were conducted for each foot position. Participants stretched their legs upon the completion of the test session.

The trajectories of the reflective markers that were captured during the test were identified using Qualisys Track Manager Software (Qualisys, Sweden). Then, inverse dynamics calculation was applied to build a musculoskeletal model using V3D software (version 5, Gothenburg, Sweden). The hip and knee kinematics in sagittal, frontal, and transverse planes during SLS were compared across neutral, toe-out, and toe-in foot positions. The flowchart of the study is presented in [Figure 1](#).

Statistical analysis

Data were tested for normal distribution by using Shapiro–Wilk test as it is appropriate for small sample sizes (<50 samples).³¹ A one-way ANOVA was applied to determine the effects of foot positions on hip and knee kinematics. The Bonferroni post hoc test was applied whenever significant differences were detected. All statistical analyses were

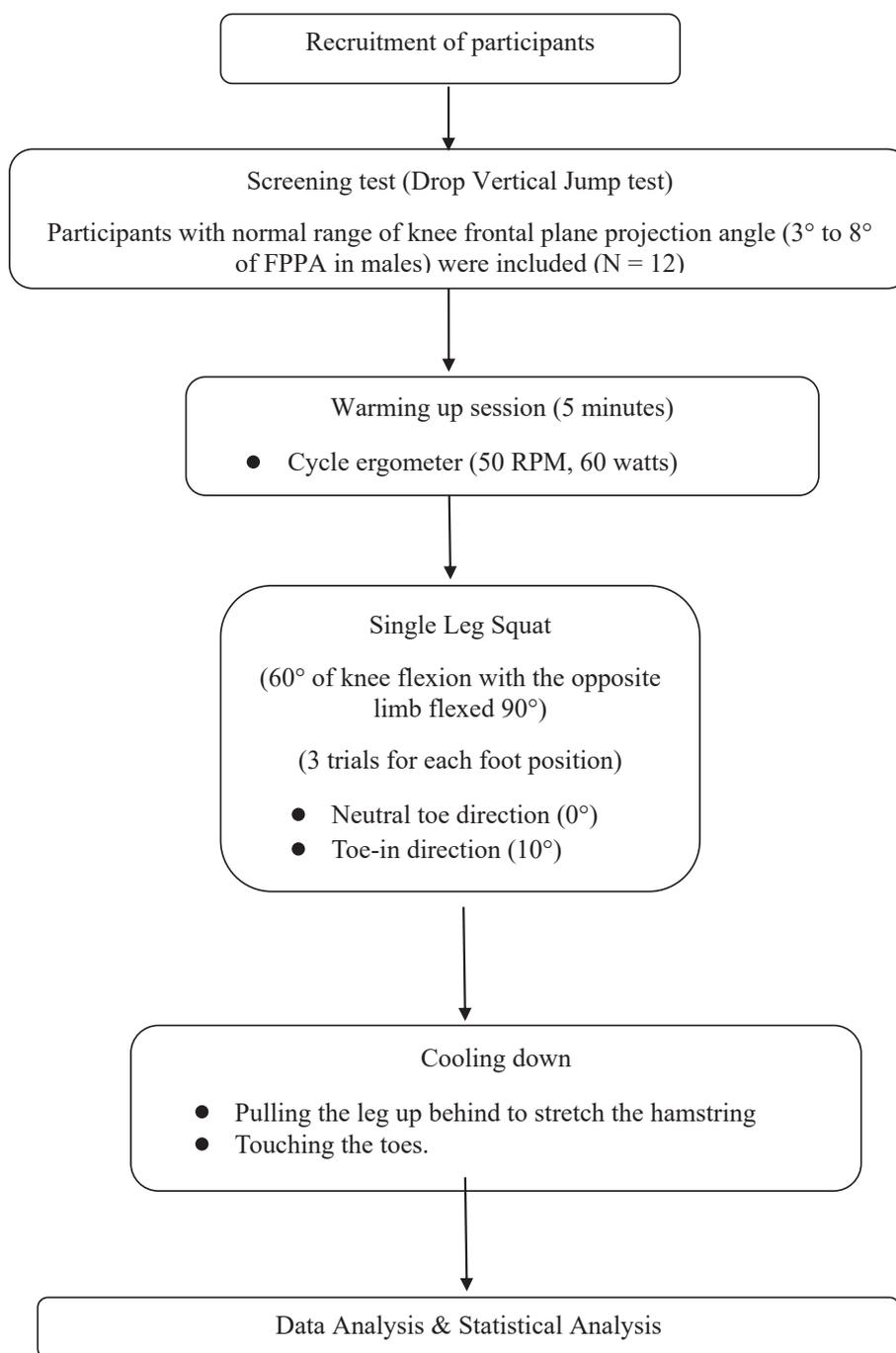


Figure 1: Flowchart of the study.

performed using Statistical Package for the Social Sciences (SPSS) version 22.0 with the level of significance set at $p < 0.05$.

Results

Initially, 20 participants were recruited. However, following the DVJ screening test, only 12 participants showed normal range of DKV ($5.3^\circ \pm 1.6$) and were thus eligible for the 3D SLS test. The physical characteristics of participants are presented in [Table 1](#). All kinematics data showed normal distribution as indicated by Shapiro–Wilk

test. A comparison of hip and knee kinematics during 60° SLS across neutral and toe-in and toe-out foot positions are presented in [Table 2](#).

Table 1: Physical characteristics of participants (N = 12).

Physical characteristics	Mean (SD)
Body mass (kg)	47.78 (6.80)
Height (m)	16.19 (8.00)
Body mass index (BMI) (kg/m ²)	18.13 (1.27)
Body fat percentage (%)	15.23 (2.71)

Table 2: Comparison of hip and knee kinematics of the preferred leg in transverse, frontal and sagittal planes across neutral, and toe-in and toe-out foot positions during single leg squat at 60° knee flexion (N = 12).

Variable	Neutral mean (SD)	Toe-in mean (SD)	Toe-out mean (SD)	p value
Hip Flexion (°)	30.33 (10.60)	28.93 (9.53)	29.64 (9.28)	0.322
Hip Adduction (°)	5.01 (2.49)	3.54 (1.32)	4.48 (1.96)	0.834
Hip Internal Rotation (°)	13.20 (8.26)	13.45 (3.82)	11.32 (4.33)	0.967
Knee Flexion (°)	63.88 (7.60)	62.08 (7.26)	60.69 (9.03)	0.489
Knee Adduction (°)	7.21 (4.17)	7.51 (4.44)	6.97 (3.03)	0.822
Knee Internal Rotation (°)	11.97 (6.72)	10.30 (6.94)	11.90 (4.24)	0.971

Discussion

In this study, we aimed to investigate the bottom-up kinetic chain during SLS among state-level male adolescent athletes who did not have excessive DKV. Overall, there were no statistically significant differences in hip and knee kinematics in all planes across foot positions. In a previous study, it was reported that foot position had a significant main effect on knee flexion angle, but the authors did not observe either a main effect or an interaction between individual foot positions.¹⁹ The discrepancy between our results and those from the previous study by Ishida et al.¹⁹ may be due to differences in sex, age, and physical fitness of the recruited participants. Ishida et al.¹⁹ recruited adult females with undetermined levels of physical fitness. By contrast, we recruited state-level male adolescent athletes who trained regularly. Differences in anthropometrics of males and females including femur length, hip width, and Q-angle may also have influenced the results. Moreover, it has been shown that during SLS, females have significantly greater hip adduction than males, as well as increased hip flexion and external rotation.³²

SLS is a clinical test that resembles the single limb stance position that can be seen in running, walking, and lunging, which are typical motions in sports.⁷ The SLS test has practical relevance in sports that require landing, cutting, and running.²⁹ There was a moderate-to-strong correlation between SLS and lower extremity kinematics of lower extremity jogging.³³ Currently, there are no studies that evaluate the norms for knee FPPA during SLS.

Table 2 showed the hip kinematics during 60° SLS based on different foot positions. Trials were conducted with the right leg (the dominant leg for all participants) as the stance leg. Graci et al.³⁰ investigated SLS at 45° knee flexion among male adults and found that the average hip kinematics were 40.74° for hip flexion, 6.15° for hip adduction, and 1.23° for hip internal rotation. The average knee kinematics were 45.31° for knee flexion, 3.34° for knee adduction, and 6.44° for internal rotation. In contrast to the study by Graci et al.,³⁰ our study investigated SLS at 60° knee flexion among male adolescent athletes. This difference in squat depth may explain the different values of hip and knee kinematics observed in our study. In addition, previous studies^{19,30} did not conduct screening tests to exclude individuals with excessive DKV. Thus, their results may have included individuals with excessive DKV.

Research on the effects of foot positions on DKV is lacking. The majority of the previous studies regarding DKV focused on the top-down kinetic chain, such as trunk and hip strength, rather than the bottom-up kinetic chain. The top-

down kinetic chain results suggest that increased muscular strength around the hip and core may assist in reducing lower extremity joint motions and related external joint moments during running or landing, and thus reduce the frequency of knee injuries.^{34,35} Moreover, Abdullah¹⁷ showed that decreased isometric strength of hip abductors, adductors, and extensors were associated with increased peak knee valgus angle.

On the contrary, bottom-up kinetic chain analyses focus on the influence of motion at the foot and ankle joint on knee joint kinematics. Excessive foot pronation during exercise has been cited as a risk factor for lower limb injuries.^{36,37} In addition, limited ankle dorsiflexion is believed to influence knee valgus.³⁸ Previous research suggests that there is a strong association between foot type and lower extremity injury.³⁹ In a study among volleyball players, reduced dorsiflexion ROM (i.e., less than 45° of dorsiflexion) was associated with a 1.8- to 2.8-fold increased risk of patellar tendinopathy.⁴⁰ This is because reduced dorsiflexion ROM may reduce shock absorption and increase patellar tendon load.⁴⁰

Instead of using subjective raters' evaluation, we quantified lower extremity kinematics using 3D motion capture and analysis, which is the gold standard of motion studies. Moreover, while many previous DKV studies used female subjects, our study focused on highly trained adolescent male athletes. In addition, none of the previous studies screened subjects for excessive DKV prior to motion analysis. By contrast, we included the 2D DVJ screening test to exclude those with excessive DKV from influencing our results. It is crucial for coaches and health practitioners to screen for excessive DKV, particularly in the young athletes, so that preventive measures can be taken early in an athlete's career. The screening test can be conducted using DVJ with 2D knee FPPA analysis. Assessing DKV is one of the major goals in widely-conducted clinical tests. These simple clinical tests provide better predictions of lower extremities injuries that are related to biomechanical risk factors. For example, in a prospective study by Hewett et al.,² the DVJ test was used to predict risk of knee injuries. Injuries are associated with financial, psychological, and missed training-time costs. Using a DKV screening test as a preventive measure could substantially reduce these injury-related costs.

The majority of the previous studies on DKV have focused on the top-down kinetic chain, rather than the bottom-up kinetic chain. In addition, studies on DKV among trained male adolescent athletes are scarce, since previous research has focused on female participants. Furthermore, our participants were screened for excessive

DKV to remove bias in the kinematics data. Hence, our findings were limited to trained male adolescent athletes who exhibited a normal range of DKV. Finally, we did not include kinetic variables (e.g., moments, power), muscle activity, and physiological data (e.g., muscle synergies, efficiency),⁴¹ which could further enhance our understanding regarding the lower limb biomechanics during SLS.

Conclusion

The current study evaluated the effects of foot positions during SLS, which is a crucial motion during sports that require changing direction or landing from a jump. We observed that small changes in transverse plane foot positions (e.g., 10° of toe-in or toe-out rotation) may not affect lower extremity kinematics during SLS with 60° knee flexion among highly trained adolescent males who exhibit DKV within the normal range.

Recommendations

The mechanics of trunk and kinetics data from lower limbs should be included in future studies on SLS to further understand the bottom-up kinetic chain. Moreover, the kinetic chain during SLS can be compared across different type of sports, age groups, gender, and competitive level.

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Conflict of interest

The authors have no conflict of interest to declare.

Ethical approval

The study was approved by the human ethical committee of the Universiti Sains Malaysia (USM/JEPeM/17020122).

Authors' contributions

SS wrote the original protocol, secured funding, and wrote the final manuscript. NMA was responsible for recruitment, data handling, data analysis, and interpretation of results. NFA and MSZM assisted in the data handling and data analysis. All authors have critically reviewed and approved the final draft and are responsible for the content and similarity index of the manuscript.

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