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Original Research

3D Motion Analysis of Single-leg Squat with Association to Hip Strength and Ankle Dorsiflexion

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Abstract

International Journal of Exercise Science 19(1): 1007, 2026. The purpose of this study was to determine if a correlation exists amongst single-leg squat (SLS) depth (defined as peak knee flexion during a SLS) using a 3D motion analysis system, hip strength, and ankle dorsiflexion range of motion (DF ROM) in a healthy population. Seventy-two participants (59.7% female, aged 22.6 $\pm$ 2.79 years) met the inclusion criteria, without current lower extremity injury or previous musculoskeletal surgery. Closed-chain ankle DF ROM, hip abduction and extension strength, and a SLS task were measured. A smartphone inclinometer app (iHandy Level) was used for ankle ROM, an externally fixed handheld dynamometer for hip strength, and a single-camera 3D motion analysis device for the SLS depth. There were statistically significant, but low, positive correlations between right (R) and left (L) ankle DF ROM and the respective SLS depth (R: $r = 0.223$, $p = 0.030$; L: $\rho = 0.373$, $p < 0.001$). Non-significant correlations were found between R and L hip abductor strength to the respective SLS depth and ankle DF ROM. Post-hoc analyses were conducted to determine whether exercise frequency impacted the association between SLS depth and ankle DF ROM. A statistically significant moderate positive correlation existed for individuals exercising $\geq$3x/week (R: $p = 0.003$; L: $p < .001$), but non-significant for those exercising 0-2x/week (R: $p=0.279$; L: $p= 0.174$). Findings are congruent with previous literature regarding the biomechanical influence from ankle mobility to SLS depth; however, hip strength does not appear to affect SLS depth. The methodology of this study offers a feasible, clinically applicable approach for functional movement assessment.

Keywords: Single-leg squat depth, ankle range of motion, hip dynamometry

Introduction

The lower extremity (LE) is defined as a kinetic chain that includes the hip, thigh, leg, and foot in connection.[1] As the body is in motion, a transfer of energy occurs throughout this kinetic chain. Thus, when an impairment occurs at one point along the chain, it will influence the proximal and distal segments in the series, a concept referred to as regional interdependence.[2] A single-leg squat (SLS) is an example of a closed-kinetic chain activity in which the hip, knee, and ankle perform the movement, all while the foot is fixed to the ground. A combination of hip flexion, knee flexion, and ankle dorsiflexion (DF) range of motion (ROM) are required to perform this movement.[1,3] Clinically, the SLS is a widely used functional assessment as joint and muscle

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imbalances within the lower extremity may influence movement quality and performance.[4] Accordingly, understanding the relationships among SLS performance, ankle DF ROM, and hip strength is essential when evaluating lower extremity function.

Previous literature has explored the effects of ankle DF ROM on squat performance in both bilateral and single leg tasks.[4-7] Kim et al and Endo et al examined ankle DF ROM in relation to bilateral squat depth, reporting significant positive correlations between ankle DF and sagittal plane squat depth.[4,6] Thus, greater ankle DF ROM has been associated with greater squat depth. In contrast to sagittal plane assessments, Carroll et al investigated ankle DF ROM in relation to frontal plane knee motion during a visual assessment of SLS, using medial knee displacement as the primary outcome. Participants were categorized into either a fail or pass group of the SLS and found that there were no differences in ankle DF ROM amongst the groups, suggesting no association between ankle DF ROM and medial knee displacement.[7] However, Marcum et al explored the effects of restricting ankle DF ROM during a bilateral squat in healthy, active individuals. The authors concluded that altering the DF ROM did result in increased knee valgus and medial knee displacement, influencing the frontal plane mechanics.[5] While ankle DF ROM has been examined in relation to both sagittal and frontal plane squat mechanics, no studies have investigated its relationship with SLS depth using a 3D motion analysis system.

Three-dimensional motion analysis systems have been used in prior literature to explore hip strength as a contributor to medial knee displacement as it relates to squat performance.[8-9] Carvalho et al investigated the role of frontal plane biomechanics during a SLS using a multi-camera 3D motion analysis system, and reported individuals with patellofemoral osteoarthritis demonstrated greater hip abductor weakness and increased hip adduction during the movement.[8] Additionally, Claiborne et al utilized a multi-camera 3D motion analysis device to evaluate the SLS of healthy individuals and isokinetic testing to determine if hip abductor strength plays a significant role in controlling the frontal plane motion of a SLS.[9] Although both of these prior studies utilized multi-camera 3D motion analysis systems, frontal plane, rather than sagittal plane movement, was assessed in the SLS. To build on these studies, the present study investigated the sagittal plane movement of a SLS and incorporated the VSTPro™, which is a single-camera 3D movement-tracking system that uses infrared technology to conduct 3D kinematic measurements, thereby expanding the feasibility of detailed motion analysis outside of specialized laboratory environments.[10]

In addition to examining hip strength and ankle DF ROM as contributors to squat mechanics, prior research has explored the relationship between these variables themselves. In those studies, various populations and methods were utilized.[11-12] Domínguez-Navarro et al identified a low to moderate correlation between hip abductor strength and ankle DF ROM in young female basketball players, using the Y-balance test and the ForceFrame Strength Testing system.[11] Similarly, Taylor et al evaluated active female athletes using force plate analysis and found that lower ranges of ankle DF ROM correlated to reduced strength and activation of hip flexors, hip extensors, and knee extensors.[12] Collectively, these findings primarily reflect individuals with higher activity levels, suggesting habitual training may influence joint mobility and muscular performance, thereby shaping relationships within the lower extremity kinetic chain. However, it remains unclear whether these associations persist in individuals with lower activity levels as prior investigations have focused on the athletic population.

Throughout the literature, ankle DF ROM and hip abductor and extensor strength have been examined in relation to squat performance in both bilateral and single leg variations. Given the identified gaps in evidence, the primary purpose of this study was investigate the relationships among these variables during a SLS using a single-camera 3D motion analysis device and in a general population of both active and less active individuals. The use of the 3D motion analysis provides reliable and validated measurements for the SLS.[10,13] The following hypotheses were made: (a) positive correlation between hip abductor strength and SLS depth (knee flexion angle); (b) positive correlation between ankle DF ROM and SLS depth (knee flexion angle); and (c) positive correlation between hip abduction and hip extension strength and ankle DF ROM.

Methods

Participants

A priori power analysis was run using G*Power (3.1.9.4) to determine an appropriate sample size for the study. Using a moderate effect size of 0.30 and a desired power of 0.80,[11,14] the estimated sample size was determined to be 67. To account for potential attrition, and for feasibility and time constraints, the desired sample size was set at a maximum of 75. A convenience sample of 72 healthy adults were recruited through email and paper fliers and screened according to inclusion and exclusion criteria. Inclusion criteria included: 18-40 years old, in good health (self-reported), and physically capable of performing a SLS, as determined by a screening process. The screening process, conducted by a licensed Physical Therapist and Orthopaedic Certified Specialist with 12 years of experience, consisted of a single-leg stance for 20 seconds with eyes open and the ability to perform five symmetrical bilateral squats. Exclusion criteria included failure of the aforementioned screening process, current or recent musculoskeletal LE injury within six months of enrollment that resulted in limited physical activity for two or more days, and history of LE musculoskeletal surgery. All subjects signed an informed consent document prior to participating in the study, and all testing procedures were approved by the Institutional Review Board (#24-060). All research within this study is in compliance and accordance with ethical standards outlined by the *International Journal of Exercise Science*.[15]

Protocol

Each participant first completed informed consent documents and provided pertinent demographic information (age, gender, dominant leg, height, weight, and self-reported frequency of exercise per week). Gender options included male, female, non-binary, or prefer not to answer. Dominant leg was defined as the leg with which the participant would kick a ball. After providing this information, each participant was taken through a screening process to ensure safety in the completion of the study. Participants cycled between four stations, receiving standardized instructions at each station. Stations included closed-kinetic chain (CKC) ankle DF ROM, hip extension strength, hip abduction strength, and lastly the SLS task. For ankle DF ROM and hip strength, the participants performed all three trials on one limb with a 30-second rest period between each trial, prior to moving to the contralateral limb. For the SLS task, the participants were allowed three practice trials on each limb, followed by a rest period of one minute prior to the three recorded squat tasks. The average of the three trials was recorded for each objective measure. The participants were blinded to results between trials to minimize testing bias.

Frequency of exercise was used to subgroup allocation criteria, and therefore two subgroups were created: 0-2 times/week (34 participants) and 3+ times/week (38 participants). Subgroups were created based on American College of Sports Medicine guidelines recommending exercise a minimum of three days per week.[16]

More specific information regarding how each variable was measured is as follows:

Ankle Range of Motion.

CKC ankle DF ROM was measured in a standing, weightbearing lunge position, using the iPhone iHandy Level application. This application has been shown to have an excellent intra-rater reliability of 0.97 for measuring CKC ankle DF ROM.[17] Pilot testing for intra-rater reliability of the present study was determined to be 0.99. The top of the iPhone was vertically placed at the tibial tuberosity during the measurement and recorded in degrees (Figure 1).

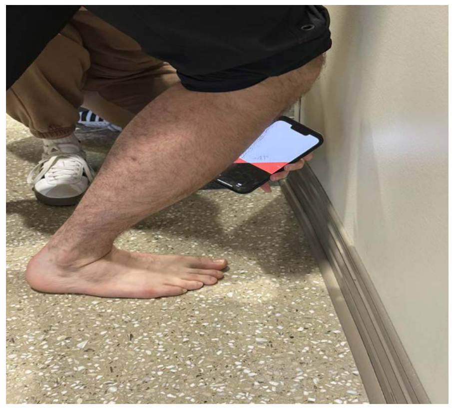

Figure 1. Setup for ankle DF ROM testing.

Hip Strength.

Hip abduction and extension strength were measured in Newtons, using the handheld dynamometer (HHD) (Hoggan microFET2, Scientific L.L.C., Salt Lake City, UT, USA), which was externally fixated (Figures 2 and 3). Test positions were adopted from previously conducted research studies that showed high intra-rater reliability.[18-21] While prone, the HHD was placed ten centimeters superior the popliteal crease for hip extension testing, utilizing a mobilization belt for fixation (Figure 2). For hip abduction strength testing, the HHD was fixated by an investigator's arm stationed against the wall and placed five centimeters superior the lateral malleolus (Figure 3).[20-21] The distance from the greater trochanter to each mark was utilized to calculate torque (Nm). Intra-rater reliability for an externally fixated HHD for hip testing was determined to be good, ranging from 0.82-0.96 for all testing positions.[20] Pilot testing for intra-rater reliability of the present study was determined to be 0.90 for hip extension and 0.80 for hip abduction.

Figure 2. Setup for hip extension strength testing.

Figure 3. Setup for hip abduction strength testing.

Single-Leg Squat Depth.

The VSTPro™ by VirtuSense Technologies (Peoria, IL, USA), a portable single-camera 3D motion analysis device, was utilized to evaluate a participant's SLS form and depth. Depth of the SLS was measured in terms of maximal degrees of closed-chain knee flexion achieved. Inter-rater reliability of the VST Pro™ for knee flexion during a jump landing task had previously been determined to be 0.85.[10] The VST Pro™ was set up on a 16-inch plyometric box platform, located 12 feet away from the participant's mark (Figure 4). Participants stood on one leg with the contralateral limb in neutral hip position and knee flexed to 90 degrees during the SLS.

Figure 4. VSTPro™ set up.

Statistical Analysis

Version 30 of IBM SPSS Statistics (Chicago, IL) was used to perform all statistical analyses for this study. Participant demographics were analyzed using descriptive statistics. Shapiro-Wilk test was used to check for normal distribution ($p>.05$ was considered normal). No outliers were greater than 1.5 quartile range. The outcome data were presented as a mean and standard deviation. For parametric data, Pearson's correlation coefficient (r) was used, which included right (R) and left (L) ankle DF ROM and R SLS depth. For non-parametric data, Spearman's rank was used. This included R and L hip extension strength, R and L hip abduction strength, and L

SLS depth. Based on the non-normal distribution for five of the eight variables, all correlations were determined with Spearman's except for the relationship between R ankle DF ROM and R SLS depth. Both Pearson's and Spearman's correlation coefficients were interpreted as 0.00-0.25 as little, if any, correlation; 0.26-0.49 as low; 0.50-0.69 as moderate; 0.70-0.89 as high; and 0.90-1.00 as very high correlation. The effect size of correlation was interpreted as an absolute value of 0.1-0.3 being a small association, 0.3-0.5 as a medium association, and 0.5-1.0 as a large strength of association.[22] The coefficient of determination (r^2) was determined for significant correlations. Given the directional hypothesis, one-tailed tests were conducted. Confidence intervals at 95% were calculated, and an alpha level of .05 was used for statistical significance. Prior to running post-hoc analyses comparing groups, Levene's test for homogeneity was performed. Pearson's was utilized for normal distribution and Spearman's used for non-parametric.

Results

A total of 72 participants were included in the data analysis (59.7% female) with a mean age of 22.6 $\pm$ 2.79 years. Table 1 demonstrates the averages of age, weight, height, and frequencies of demographics including dominant leg, gender, and frequency of exercise.

Table 1. Demographic Statistics.

Demographic Variable (*n* = 72)	Mean (SD)	Percent (n)
Age (yrs)	22.64 (2.80)	--
Weight (lb.)	165.04 (32.12)	--
Height (in.)	67.74 (4.00)	--
Dominant Leg	--	Right: 91.7 (66) Left: 8.3 (6)
Gender	--	Male: 40.3 (29) Female: 59.7 (43)
Frequency of Exercise	--	0-2 x/week: 47.2 (34) 3+ x/week: 52.8 (38)

Means and standard deviations for all variables are listed in Table 2. Statistically significant, but low, positive correlations were found between R ankle DF and knee flexion during a R SLS, and between L ankle DF and knee flexion during a L SLS (Table 3). The coefficients of determination were 0.05 and 0.14 for the R and L SLS depth, respectively. R and L hip abductor strength showed a non-significant correlation to the respective SLS (Table 3). R and L ankle DF with respective hip abductor and extensor strength were non-significant (Table 3).

Table 2. Mean and Standard Deviation of all Variables.

Variable	**All participants (n = 72)**	**Frequency of Exercise**	
		0-2x/week (n=34)	**3+ x/week (n=38)**
Right DF ROM (degrees)	41.41 (5.55)	41.94 (4.97)	40.94 (6.05)
Left DF ROM (degrees)	39.53 (5.12)	39.63 (4.60)	39.44 (5.61)
Right Hip Extension Strength (Nm)	65.40 (26.02)	63.75 (22.68)	66.88 (28.91)
Left Hip Extension Strength (Nm)	61.13 (24.91)	59.42 (20.88)	62.66 (28.22)
Right Hip Abduction Strength (Nm)	87.00 (31.42)	85.21 (25.05)	88.61 (36.45)
Left Hip Abduction Strength (Nm)	86.88 (34.09)	84.14 (27.94)	89.33 (38.99)
Right SLS depth (degrees)	76.14 (16.17)	74.90 (14.70)	77.25 (17.50)
Left SLS depth (degrees)	71.70 (15.61)	70.38 (12.68)	72.88 (17.93)

Note: DF ROM = dorsiflexion range of motion; SLS = single-leg squat

Table 3. Correlation Results.

Variable 1	Variable 2	Pearson's r	P-value	Confidence Interval
Right DF	Right SLS	0.223	p=0.030*	0.029 - 1.000
Variable 1	**Variable 2**	**Spearman's**	**P-value**	**Confidence Interval**
Left DF	Left SLS	0.373	p<0.001*	0.185 - 1.000
Right Hip Abduction	Right SLS	0.078	p=0.258	(-0.125) - 1.000
Left Hip Abduction	Left SLS	-0.009	p=0.470	(-1.000) - 0.192
Right DF	Right Hip Abduction	-0.133	p=0.134	(-1.000) - 0.070
Left DF	Left Hip Abduction	-0.129	p=0.140	(-1.000) - 0.074
Right DF	Right Hip Extension	-0.177	p=0.068	(-1.000) - 0.025
Left DF	Left Hip Extension	-0.045	p=0.353	(-1.000) - 0.157

Note: DF = dorsiflexion; SLS = single-leg squat; p ≤ 0.05* level (1-tailed) indicates statistical significance

A post-hoc analysis was conducted to determine if exercise frequency impacted the association between ankle DF and SLS depth. Frequency of exercise was recorded as 0-2 times/week and 3+ times/week. R ankle DF ROM and R SLS depth passed Levene's test for homogeneity therefore Pearson's was used. Spearman's was used for L DF ROM to L SLS depth. There was not a significant correlation between ankle DF ROM and SLS depth, irrespective of side, for individuals who reported exercise 0-2 times per week; however, there was a statistically significant low-moderate positive correlation for individuals who reported frequency of exercise ≥3x/week (Table 4). The coefficient of determination was 0.19 for the right side and 0.28 for the left side.

Table 4. Post-Hoc Analyses.

Exercise Frequency	Variable 1	Variable 2	Pearson's r	P-value	Confidence Interval
0-2 x/week	Right DF	Right SLS	-0.104	p=0.279	(-1.000) - 0.189
3+ x/week	Right DF	Right SLS	0.438	p=0.003*	0.189 – 1.000
	Variable 1	**Variable 2**	**Spearman's**	**P-value**	**Confidence Interval**
0-2 x/week	Left DF	Left SLS	0.166	p=.174	(-0.136) - 1.000
3+ x/week	Left DF	Left SLS	0.531	p<.001*	0.297 – 1.000

Note: DF = dorsiflexion; SLS = single-leg squat; p ≤ 0.05* level (1-tailed) indicates statistical significance

Discussion

The purpose of this study was to explore pairwise relationships between hip extensor strength, hip abductor strength, ankle DF ROM, and SLS depth using a single-camera 3D motion analysis device in a generally healthy population. Positive correlations were hypothesized between hip abductor strength and SLS depth; ankle DF ROM and SLS depth; and hip abduction and hip extension strength to ankle DF ROM. Amongst the hypotheses, the present study supports the positive correlation between ankle DF ROM and SLS depth.

Ankle DF ROM was found to be significantly correlated to SLS depth, with the coefficient of determination indicating 5% and 14% of the variability in R and L SLS depth, respectively, can be attributed to ankle DF ROM. Endo et al similarly reported a significantly positive correlation between ankle DF ROM and knee flexion angle during a bilateral deep squat for both the ipsilateral and contralateral limbs. Given the small sample of healthy participants, a symmetrical squat pattern would be expected. While Endo et al used 2D motion analysis during a bilateral squat, the present study employed a single-camera 3D motion analysis during a SLS, enhancing the accuracy and clinical applicability of the measurements.[4,10,13] Kim et al reported comparable associations between ankle DF and squat performance using a digital camera, reinforcing the importance of adequate ankle DF ROM in bilateral squat mechanics.[6] Collectively, these studies highlight the interdependence sagittal plane movements of the ankle and knee, demonstrating how function along the kinetic chain can be impacted by the proximal or distal segments.

In studies which used multi-camera 3D motion analysis, researchers explored the relationship between hip abductor strength and SLS mechanics. Hip abductor weakness was found to contribute to greater medial knee displacement in a SLS; however, these studies did not evaluate SLS in terms of depth as measured by the knee flexion angle.[8,9] In other literature, SLS depth was explored, finding a significant positive correlation between hip abductor strength and SLS depth in individuals with hip-related groin pain. However, similar associations were not observed in a healthy population of adults without the presence of musculoskeletal injury.[23] The discrepancy may reflect the role that musculoskeletal pathology plays in altering body mechanics and movement patterns to avoid increased pain or re-injury.

An important difference in the present study is the use of its methodology. While validity and reliability are essential, clinical applicability is equally important. Carvalho et al assessed hip abductor strength using a HHD in the sidelying position whereas the present study performed testing in supine, a gravity-minimized position.[8] Clinically, strength of the hip abductors is frequently assessed in the sidelying position and with traditional manual muscle testing, rather than a HHD. However, the supine position with an externally fixated HHD provides a standardized and objective way to quantify muscle strength with less examiner-related variability. Claiborne et al utilized a Biodex Isokinetic dynamometer to assess lower extremity strength. Although the Biodex is often described as the gold standard, the HHD is more cost-effective and clinically feasible.[9,24-26] Accordingly, the present study improves clinical relevance compared to the aforementioned studies.

Previous literature has explored the relationship between hip strength and ankle DF ROM across a variety of populations, with studies demonstrating significant positive correlations between ankle DF ROM and both hip extensor and hip abductor strength in athletic groups.[11-12] While the literature supports the interdependence of proximal strength and distal mobility, they were observed in groups with structured and consistent training backgrounds. In contrast, the present study utilized a sample of generally healthy individuals, and the results with the participants as one group, did not reflect this relationship between hip strength and ankle DF ROM. One explanation is that athletic populations tend to participate in more balanced and comprehensive training regimens. Traditionally, athletes will not partake in only a single form of training (i.e. resistance training, cardiovascular conditioning, or flexibility), but rather a combination of all to improve physical fitness and reduce the likelihood of injury. These adaptations may strengthen the linkage between joint mobility and strength-based performance.

This concept aligns with our subgroup analysis, which demonstrated a stronger association between ankle DF ROM and SLS depth among the participants exercising 3+ times/week. In this group, ankle DF ROM accounted for 19% and 28% of the variability of R and L SLS depth, respectively, whereas no meaningful relationship was observed in those exercising 0-2x/week. According to the American College of Sports Medicine guidelines, regular physical activity supports improvements in both strength and flexibility outcomes. Guidelines include resistance and flexibility training two to three days per week.[16,27] Stretching for 30 seconds, three times per day, five days a week for six weeks can be effective to improve ROM that is inhibited by a significant muscular tightness.[28] Together, these factors may enable more active individuals to better utilize available ankle mobility during a SLS, resulting in a clearer and stronger association between ankle DF and SLS depth compared to their less active counterparts.

This study has several limitations that can be addressed in future research. These include the procedural learning curve and muscular fatigue. At times, participants were asked to repeat trials due to technical issues with the VSTPro™ and if the duration count during strength testing was outside of the three to five seconds. Although the HHD was externally fixated, potential limitations remained, such as stabilization through the investigator's arm and required readjustments between trials. Standardized markings were used to minimize these sources of variability.

In a healthy young adult population, this study identified a positive correlation between ankle DF ROM and SLS depth, reinforcing the role of ankle mobility in facilitating closed-chain knee flexion mechanics. In contrast, no relationships were found between hip strength and either SLS depth or ankle DF ROM, which aligns with previous findings in healthy populations despite the methodological differences across studies. The use of a portable, single-camera 3D motion analysis system and externally fixated HHD provides a clinically applicable methodology. Notably, the relationship between ankle DF ROM and SLS depth was more apparent in those engaging in regular physical activity, highlighting how habitual movement patterns may influence functional task performance. Collectively, these findings reinforce the critical role of ankle mobility in lower extremity movement while emphasizing newer technologies and more consistent measures, all that can be translated into clinical practice. Future research should investigate whether these relationships exist amongst individuals with lower extremity pathology or those undergoing rehabilitation following an injury or surgery.

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