Single-Leg Squat Delicacies—The Position of the Nonstance Limb is an Important Consideration

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Published in:
Journal of Sport Rehabilitation

DOI:
10.1123/jsr.2018-0181

Publication date:
2019

Section: Original Research Report

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Running Head: Single leg squat

Journal: *Journal of Sport Rehabilitation*

Acceptance Date: October 14, 2018

DOI: https://doi.org/10.1123/jsr.2018-0181

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Acknowledgements: None

Funding received
We would like to acknowledge the local physiotherapy society and the National Research Foundation for funding this project.

Abstract

Context: The single leg squat task is often used as a rehabilitative exercise or as a screening tool for the functional movement of the lower limb. **Objective:** To establish the effect of three different positions of the non-stance leg on three-dimensional kinematics, muscle activity and centre of mass (CoM) displacement during a single leg squat. **Design:** Within-subjects, repeated-measures design. **Setting:** Movement analysis laboratory. **Participants:** Ten participants, aged 28.2±4.42 years performed three squats to 60° of knee flexion with the non-stance A) hip at 90° flexion and knee at 90° flexion; B) hip at 30° flexion with the knee fully extended; or C) hip in neutral / 0° and the knee flexed to 90°. **Main outcome measures:** Trunk, hip, knee and ankle joint angles, and CoM displacement were recorded with inertial sensors while muscle activity was captured through wireless electromyography. **Results:** Most trunk flexion (21.38°±18.43°) occurred with the non-stance hip in 90° and most flexion of the stance hip (23.10°±6.60°) occurred with the non-stance hip in 0°. *Biceps femoris* activity in the 90° squat was 40% more than in the 0° squat, while *rectus femoris* activity in the 0° squat was 29% more than in the 90° squat. **Conclusion:** The position of the non-stance limb should be standardised when the single leg squat is used for assessment and be adapted to the aim when used in rehabilitation.

Keywords: centre of mass; kinematics; electromyography; assessment; rehabilitation

1. INTRODUCTION

The single leg squat task is used as a rehabilitative exercise[1, 2] or as a screening tool[3, 4] for the functional movement of the lower limb. The presence of pathology influences the way in which the single leg squat is performed. On performing the single leg squat, individuals with pathologies such as patellofemoral pain syndrome (PFPS),[5, 6] anterior cruciate ligament injuries[4, 7] and post hip arthroscopy[8] show a number of unique biomechanical characteristics such increased knee valgus[6, 8] and increased femoral adduction.[5, 8] As such, clinicians use these biomechanical contributions to determine the presence of dysfunction, pathology and risk.

In the clinical arena, the examiner observes the performance of the stance limb, as well as the trunk, during a single leg squat. DiMattia et al.[3] used a clinical rating scale based on the following criteria: hip flexion should not exceed 65°, hip adduction should not exceed 10°, and knee valgus should not exceed 10°. A score of 3 (excellent), 2 (good), 1 (fair) or 0 (poor) would then be given based on the extent to which these criteria were met. Crossley et al.[9] based their clinical rating criteria on an overall impression of trunk, pelvis, hip and knee movement and in this way rated the single leg squat as "good", "fair" or "poor". It should be noted that the body angles upon which these clinical rating criteria are based may be influenced by the position of the non-stance limb, although research on the same is scarce.

The performance of the single leg squat varies across studies which serves to complicate comparisons of the results when studies in the academic sphere are undertaken and compared with those of cohorts of athletes in the clinical sphere. Specifically, the position of the non-stance leg would not be specified[6, 9] or different positions would be adopted.[3, 10-12] Some studies specify that the heel of the non-stance leg should touch the floor while the participant squats off a step,[11, 12] whilst others focus on the flexing of the knee of the non-stance limb to 90°.[3, 10] and the hip of the same limb to 45°[3]

The varying positions of the non-stance leg during a single leg squat proved to be problematical when studies were compared, as the effects of the position of the non-stance leg on the lower limb and trunk kinematics, and muscle activity are largely unknown. Khuu et al.[13] investigated the effect of the non-stance limb in three different positions. However, the three positions tested in their study differ from those used in our study in that the hip flexion angles at which the non-stance hip was positioned was not specified and the 90° hip angle position was not investigated. Also, although Khuu et al.[13] included kinetics (joint moments) as an assessment method, they did not look at muscle activity or centre of mass (CoM) displacement. Furthermore, it is important to establish whether there is in fact a difference between the kinematics of the stance leg and those of the trunk, as a difference serves as motivation to standardise the position of the non-stance leg during the single leg squat so that results can be compared between groups of athletes, as well as within the same group of athletes. The kinematic findings (joint angles) measured three-dimensionally in this study can be directly translated to the clinical arena, while the muscle activity data can be used to explain these findings. Therefore, the aim of this study was to investigate the effect of three different positions of the non-stance leg on the trunk, hip, knee and ankle angles, muscle activity and CoM displacement during a single leg squat task.

2. MATERIALS AND METHOD

2.1 Study design and setting

This study used a within-subjects, repeated-measures design and was conducted in the movement analysis laboratory of the associated tertiary institution.

Data were collected in November 2016. As a flow diagram, Figure 1 shows the enrolment, assessment, data analysis and findings of the study.

2.2 Participants

A post hoc sample size calculation was performed using G*Power (3.1). Five of the outcomes (trunk adduction/abduction, trunk rotation, hip flexion/extension, hip adduction/abduction, knee adduction/abduction) were incorporated into the calculation to get an average power of 0.85. Healthy male and female participants were recruited from the public through invitations sent via email. Participants with auto-immune disease, any disease of the neuromusculoskeletal system, a history of anterior knee pain, anterior-cruciate ligament (ACL) injury or other knee pathologies in the previous six months, and who had undergone any surgical procedure to the lower limb, together with those with a body mass index (BMI) of above 25kg.m^{-2}, were excluded from the study. All participants gave informed, written consent and were allowed to withdraw from the study at any time without suffering any repercussions. Data were treated confidentially and study numbers were allocated to all participants to ensure anonymity. Ethical clearance was obtained from the human research ethics committee of the associated tertiary institution, and the study was conducted according to the internationally-accepted ethical standards and guidelines of the Declaration of Helsinki.

2.3 Instrumentation and Outcome Measures

Joint angles and excursion were captured by the Xsens inertial sensor motion analysis system (MVN Link Biomech system; Xsens Technologies B.V., Enchede, The Netherlands), which consists of 17 motion trackers measuring movement at a rate of 240 Hz. The sensors were attached to the participant at the standardised positions (Figure 2). The MVN system considers segment positions and orientations to calculate an estimate of the CoM.[14] These data were then exported to Matlab (Version 7.2., the Mathworks, Inc., Natick, USA) and the kinematic variables, namely trunk, hip, knee and ankle angles, were calculated continuously throughout a single leg squat.[14] Muscle activity was captured through electromyography (EMG) analysis by using the 8 Sensor Trigno Wireless EMG Set (Analogue and Digital Version) (Delsys Inc., Salford, Greater Manchester, United Kingdom) sampled at 16kHz. The muscle activity of the stance leg was recorded using surface electrodes on the *rectus femoris, biceps femoris, gluteus maximus* and *gluteus medius* muscles. The data were analysed using EMGworks software (Delsys Inc., Salford, Greater Manchester, United Kingdom), and were exported to Matlab (Version 7.2., the Mathworks Inc., Natick, United States of America). Percentage muscle activation were calculated continuously throughout the single leg squat movement. Synchronous data were collected from the EMG analysis and Xsens with the aid of the Delsys Trigger Module (Delsys Inc., Salford, Greater Manchester, United Kingdom).

Spatial calibration of the telemetric electrogoniometer (Zebris; Isny, Germany) was performed before testing. The electrogoniometer was attached to the stance leg and used to ensure that the participant would flex the stance knee to a maximum of 60°. Electrogoniometry were recorded using MyoResearch® (Noraxon, Scottsdale, Arizona) software. A metronome application (Metronome Beats Version 3.4.0) was used for the purpose of maintaining a two-second rhythm for the movement.

2.4 Procedure

Once the status of the candidate had been established as eligible for inclusion and the consent form had been signed, the data collection procedure commenced. The participant was asked to kick a small, air-inflated ball with his/her preferred leg. The leg chosen to kick the ball with, was assigned as the dominant lower limb. In all cases this limb corresponded to the self-reported lower limb dominance. The participant was then asked to remove his/her socks and shoes, and, after dressing in tight fitting lycra shorts, each participant was shown a demonstration of the single leg squat technique. The same instructions, verbal prompts and actions were used each time. The participant was allowed three attempts to become familiar with the technique, and then rested for three minutes to obviate fatigue.

Once the participant was confident with the technique, standard abrade and swab techniques were used prior to the placement of the EMG surface electrodes which were attached with double-sided tape to the following sites: i) *rectus femoris*: halfway along the line between the anterior superior iliac spine and the superior part of the patella; ii) *biceps femoris* (hamstrings): halfway along the line between the ischial tuberosity and the lateral condyle of the tibia; iii) *gluteus maximus*: halfway along the line between the sacral vertebrae and the greater trochanter; iv) *gluteus medius*: halfway along the line from the iliac crest to the greater trochanter (http://www.seniam.org/ accessed: Nov 2016). A maximum isometric voluntary contraction (MIVC) was recorded for each muscle in the positions recommended by the Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles (SENIAM) guidelines (http://www.seniam.org/ accessed: Nov 2016).

The body dimensions of each participant were recorded and entered into the Xsens MVN system. The participant then put on the lycra XSens suit subsequent to which he/she was fitted with the 17 inertial sensors. An "N-pose" was used to calibrate the Xsens system before recording.

The electrogoniometer was attached to the stance leg and connected to the MyoResearch software, thus allowing the knee angle to be measured in real-time.

The position of the stance foot was demarcated on the adjustable step on which the participant performed the single leg squat. The participant performed three squats with the non-stance limb held in each of the following three positions (a total of nine squats on each leg) as shown in Figure 3: (A) The hip at 90° flexion and the knee at 90° flexion (in short referred to as the 90° squat); (B). The hip at 30° flexion with the knee fully extended (in short the 30° squat); and (C). The hip in neutral / 0° and the knee flexed to 90° (in short the 0° squat). A total of 18 squats were therefore performed by each participant. The technique was performed in time with a metronome – two seconds for the single leg squat downward movement and two seconds for the return to the starting position. The participant performed the single leg squat technique three times with his/her arms crossed over the chest, the trunk upright and looking forward, with the stance leg achieving a maximum of 60° of knee flexion or the maximum knee flexion that can be achieved with the heel remaining in contact with the step. The trial was discarded and redone if the participant lost his/her balance, uncrossed his/her arms or allowed the non-stance leg to touch the stance leg.

The starting side (left *vs* right) and the order of the respective positions of the non-stance leg (90°, 30°, 0°) were randomised. The participant performed three squats in each position with a 10 second period of rest between the positions.

2.5 Data reduction and analysis

Nine participants were right dominant and one was left dominant. Data were analysed according to dominance. The results for each non-stance limb position for all three trials were entered into the analysis, resulting in a total sample of 30 squats per position of the non-stance leg (each of the 10 participants did three squats in each of the three positions). The individual squats (n=30) were analysed as independent events. For each squat EMG, whole body CoM, and the joint angles were recorded.

The kinematic data and EMG tracings were imported into MatLab. For further analysis, individual squatting cycles and their corresponding EMG values were grouped. The individual squats were reduced to a percentage as follows: i) 0 % indicated the initiation of the squat (when the knee is fully extended). ii) 100% indicated the completion of the squat (when the knee has returned to full extension). Trunk, hip, knee and ankle angles, CoM positions and EMG were assessed at the instant when the 60° stance knee flexion was reached. The term “trunk” referred to the spinal levels from L5/S1 to C7/T1.

In the peripheral joints: flexion was recorded as positive (+ve), extension as negative (-ve), abduction +ve, adduction –ve, internal rotation +ve and external rotation –ve. In the spine (trunk): flexion was recorded as +ve, extension -ve, lateral flexion towards stance leg +ve, lateral flexion away from stance leg –ve, rotation towards stance leg +ve, rotation away from stance leg –ve.

The raw EMG data were treated with a Butterworth filter (order of four; passband ripple of 3dB; attenuation of 40dB; band pass; first corner frequency of 20 Hz; second corner frequency of 500 Hz). The data were then normalised to MIVC and presented as a root mean square. The EMG data were presented as the % MIVC.

Whole body CoM displacement was recorded on the X-axis (anterior/posterior) and Y-axis (medial/lateral). On the X-axis, anterior movement was +ve and in the Y-axis lateral movement on the stance leg was +ve.

2.6 Statistical analysis

The Shapiro-Wilk test was used for testing the distribution of the data, with the majority of the data not conforming to normal distributions. Kinematic and EMG data for the three squatting positions were compared using Friedman tests, with group differences identified through Dunn's multiple comparison tests. Cohen’s *d* effect sizes were calculated and interpreted as 0.2 (small), 0.5 (medium) and 0.8 (large).[15] All statistical tests were performed in GraphPad 5 (Prism, San Diageo, USA), with the significance level set at $\alpha < 0.05$.

3. RESULTS

Ten participants (seven female and three male) with an average age of 28.2±4.42 years took part in this study. EMG data for one participant was incomplete. The anthropometric measurements were as follows: weight - 60.7±5.21kg; height - 1.67±0.08m; body mass index (BMI) - 21.76±1.64kg/m^2.

The kinematic analysis of the single leg squat when standing on the dominant leg, as well as when standing on the non-dominant leg, is presented in Table 1. During the single leg squat on both the dominant and the non-dominant leg, the most trunk flexion occurred in the 90° squat, less in the 30° squat and even less in the 0° squat. The opposite was found for hip flexion: most hip flexion occurred in the 0° squat, less in the 30° squat and even less in the 90° squat. On both the dominant and non-dominant sides, large effect sizes were found between the 90° and 0°, as well as between the 30° and 0° squat positions.

With squatting on the non-dominant side, the activity of the *biceps femoris* in the 90° squat was 40% more, while it was 43% more in the 30° squat than in the 0° squat. On the other hand, while the activity of the *rectus femoris* in the 0° squat was 29% more, it was 15% more in the 30° squat than in the 90° squat. On the dominant side, *biceps femoris* muscle activity was also higher in both the 90° and 30° squats when compared to the 0° squat, although no difference between the three positions were found for muscle activity in *rectus femoris* (Table 2).

With squatting on the dominant leg, the CoM moved more laterally in the 0° squat and the 90° squat relative to the 30° squat. There was no difference in the CoM displacement in the anterior posterior direction. No difference in the movement of the CoM is present when squatting with the non-stance hip in each of the three positions while standing on the non-dominant leg (Table 3).

4. DISCUSSION

The findings of this study show that there are distinct differences in kinematics, muscle activity and CoM when a single leg squat is performed with the non-stance leg in three different positions. A summary and the implications of the findings are presented in Table 4.

Participants displayed more trunk flexion in the 90° squat, less in the 30° squat and even less in the 0° squat. It was found that with the flexing of the non-stance hip to 90°, the CoM moves. In order to avoid losing balance, the participant compensates and prevents the movement of the CoM, by flexing his/her trunk in order to bring the CoM more to the centre within his/her base of support. This argument is supported by the lack of actual displacement in the anterior/posterior direction of the CoM in this study.

Another reason why no difference in anterior/posterior CoM displacement was observed between the three squats may be due to the flexion of the stance hip. The stance hip presented with the most flexion during the 0° squat, with less in the 30° squat and even less in the 90° squat. Therefore, both trunk flexion and hip flexion may be strategies used to avoid the displacement of the CoM. *Biceps femoris* activity was higher in the 90° squat as opposed to the 0° squat, possibly in an attempt to stabilise the CoM. The difference in stance hip flexion between the 90° squat and the 0° squat was around 12°, which makes the 90° squat more appropriate in cases where hip pathology is aggravated by hip flexion.

During the slight forward trunk lean, which takes place in the 90°-squat, participants also recruited *biceps femoris* to a greater extent and the *rectus femoris* to a lesser extent, conditions which reduce the forces on the anterior-cruciate ligament.[2] The 90° squat might therefore be the position of choice in the initial rehabilitation stages after anterior cruciate ligament reconstruction. However, if a hamstring autograft technique has been used, the strength of the hamstring might be reduced[16] and this position might elicit pain.

On the basis of the clinical rating criteria of Crossley et al.,[9] trunk lateral flexion, forward flexion and rotation are linked to poor performance in the single leg squat test. In our study, differences in trunk movement of less than two degrees were noted for trunk lateral flexion and rotation. These trunk movements would, therefore, not be noticeable upon visual analysis of the single leg squat when it is performed in any of the three positions. However, differences observed in trunk flexion were of the order of four to nine degrees, which might be more evident during visual analysis. Different positionings of the non-stance leg would therefore influence the effective use of this test to compare results within the same group and between different groups of athletes.

Biceps femoris was found to be least active at 0°, while *rectus femoris* was most active at 0°. In the 0° squat, greater recruitment is required of the *rectus femoris* muscle as opposed to that in the 90° squat. In the 90° squat, greater recruitment is required of the *biceps femoris* muscle as opposed to that in the 0° squat. The reason for the increased activity level of *rectus femoris* in the 0° position is most probably as a result of the higher knee extension moment, which occurs in the 0° position as opposed to positions with the non-stance hip in flexion.[13] This would suggest that if a physiotherapist were to be primarily concerned in evaluating the recruitment of the *rectus femoris* muscle during the single leg squat, then the 0° squat would be more appropriate, whereas the 90° squats would be more useful in evaluating the recruitment of the *biceps femoris* muscle during the single leg squat. An example to elucidate this assumption follows: In the case of a patient with a previous hamstring injury, the 90° squat would be a more suitable screening tool than the 0° squat to assess the hamstring function, hip stability and pain response would be. If a patient had a previous *rectus femoris* strain, the 0° squat would be more suitable. Also, should the single leg squat be used as a rehabilitative exercise, an adaptation to the position of the non-stance leg would activate one muscle more than the other, as indicated by the diagnosis of the patient.

Greatest activity in the *gluteus medius* muscle was noted in the 90°-squat position. However, this finding presented only on the non-dominant side, which might indicate that different recruitment strategies are necessary for the two respective sides. Also, greater hip adduction was noted in the 90° squat with large effect sizes, which were not statistically significant. In cases where the single leg squat is primarily used to screen for *gluteus medius* weakness, such as in patients with anterior knee pain,[17, 18] the 90° squat might be more effective than the 0° and 30° squats on account of the high level of activation in the 90° squat.

As described by Crossley et al.,[9] the activity of the g*luteus medius* muscles plays a crucial role during the clinical rating of the single leg squat test. Stickler et al.[19] showed that a stronger *gluteus medius* muscle, as measured with a dynamometer, relates to good performance on the single leg squat test, while Crossley et al.[9] proved that earlier onset of *gluteus medius* muscle activity, measured using EMG, relates to good performance on the single leg squat.

The CoM displacement laterally relative to the stance leg was found to be similar for the 90° and 0° squats, while it was much less for the 30° position. This may hint at the slightly more demanding nature of the 90° and 0° squats owing to the position of the non-stance limb. A larger lateral displacement of the CoM might indicate that the 90° and 0° squats require more central or core stability to perform correctly.[11]

Although Crossley et al.[9] prefers no knee adduction to be present, the amount of knee adduction measured in our study was lower than the 10° cut-off stated in the grading criteria of DiMattia et al.[3] Knee valgus during the single leg squat is more prevalent in patients with patellofemoral pain.[6] There was a two-degree difference in knee adduction between each of the squats, which would most probably not be evident from visual observation in the clinical setting.

There was no evidence of any difference in the rotation at the knee for the three respective squats. From a clinical perspective, the position of the non-stance leg would make no difference when the single leg squat is used as a clinical test in patients with known rotational instability in the knee (e.g.in the case of a previous cruciate ligament disruption). It is important to note that this study did not calculate joint power or moments and that the assumptions are limited to kinematic findings.

Qualified physiotherapists base their judgements of performance in the single leg squat test, as assessed in the clinical setting, mainly on the kinematics at the hip and knee,[10] although the position of the trunk and pelvis also feature.[9] In most cases, differences in joint angles at the lowest position of the squat, as presented in Table 1, are small, and although statistically significant, would most probably not be visible upon visual analysis of movement patterns in the clinical setting. Furthermore, although the differences in joint angles may not be visible, it is important to remember that differences in muscle activity and recruitment should be taken into account during the clinical decision-making process. However small these differences, they are in most cases larger than the Xsens system's standard error of the estimate (SEM) of. 0.11° and 0.33°.[20]

Although the small sample size may increase the risk for a Type II error, the addition of effect sizes gave valuable insights into the differences between the respective squatting positions. In this study, although none of the participants were professional or elite athletes, the levels and frequencies of physical activity were not considered and may influence the results. The results of the study can be generalised to healthy individuals in the normal population and caution should be observed when applying these results to professional or elite athletes. The preliminary findings from the study can be extrapolated into future clinical-related research endeavours where larger samples would be included. In further attempts to validate the single leg squat, future research needs to investigate the influence of the position of the arms, the speed of the squat and the use of a step on kinematics, kinetics and muscle activity. Furthermore, the investigation of the muscle activity in additional muscles such as the *vastus medialis, vastus lateralis, gastrocnemius and tibialis anterior* will be a valuable addition to the research.

5. CONCLUSIONS

Differences mainly in trunk and stance hip kinematics, activity of the *rectus femoris* and *biceps femoris* muscles and the displacement of the CoM occur when the single leg squat is performed with the non-stance hip in 90°, 30° or 0° flexion. The position of the non-stance hip should be kept constant when the single leg squat is used to assess lower limb function during follow-up visits. When the single leg squat is used as a rehabilitative exercise, the 90° squat position can be used to emphasise the activity of *biceps femoris*, and the 0° squat position to emphasise the activity of *rectus femoris*.

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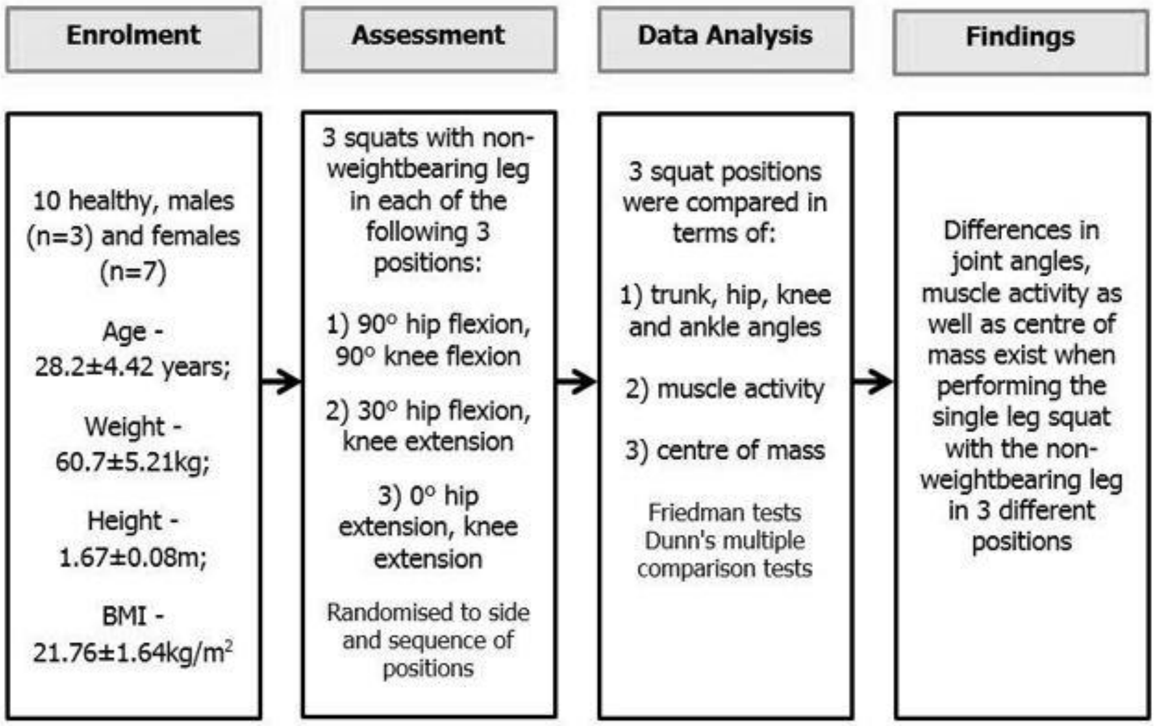

Figure 1 – A flow diagram showing the enrolment, assessment, data analysis and findings of the study

Figure 2 – Standardised placements of inertial sensors as prescribed by XSens Technologies B.V. (with kind permission from Xsens Technologies B.V.)

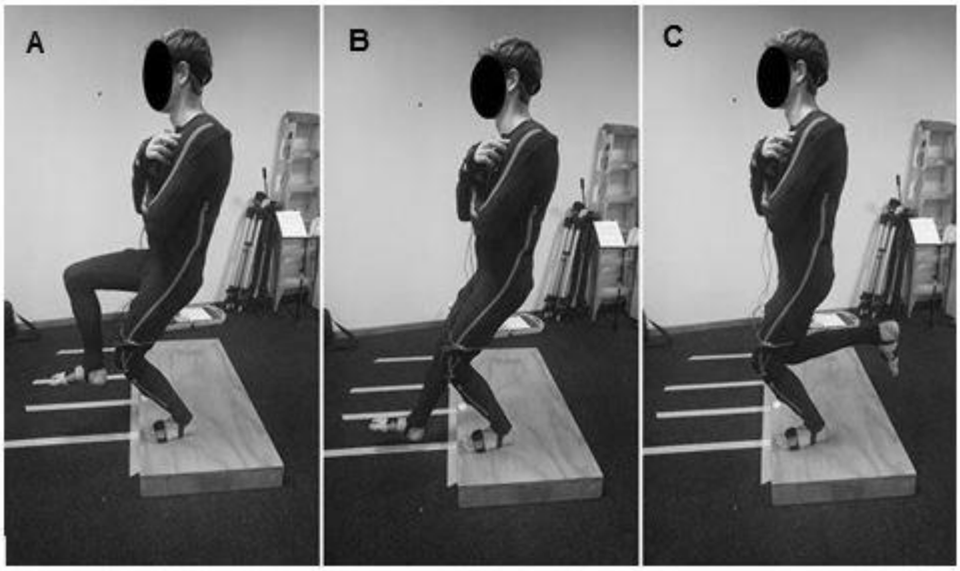

Figure 3 – The single leg squat while standing on the left leg with the right non-stance leg in the three different positions. (A) The hip at 90° flexion and the knee at 90° flexion (in short, – a 90° squat). (B) The hip at 30° flexion with the knee fully extended (in short, – a 30° squat). (C) The hip in neutral / 0° and the knee flexed at 90° (a 0° squat).

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Table 1 Kinematic joint angles at 60° knee flexion for three different single leg squats based on non-supporting leg positions

Standing on dominant leg						
	0°	30°	90°	Effect size 90° versus 30°	Effect size 90° versus 0°	Effect size 30° versus 0°
Sagittal plane: flexion/extension						
Trunk	12.50±13.77	16±14.76*	21.38±18.43*†	0.32	0.55	0.25
Hip	23.10±6.60	11.62±4.53*	8.57±7.21*	0.51	2.10	2.03
Knee	58.40±3.19	59.80±2.60	58.96±2.67	0.32	0.19	0.48
Ankle	30.99±6.43	31.90±5.50	30.11±6.43†	0.30	0.14	0.15
Frontal plane: Adduction/ Abduction						
Trunk	-2.97±3.29	-2.35±4.39	-0.49±3.81*†	0.45	0.70	0.16
Hip	4.20±6.50	3.76±4.40	4.79±4.30	0.24	0.11	0.080
Knee	-7.11±9.29	-8.62±10.77	-6.76±8.80	1.19	0.04	0.20
Ankle	6.03±9.98	7.10±11.75	6.26±12.57	0.07	0.02	0.02
Transverse plane						
Trunk	-0.89±3.95	-1.78±4.71	0.49±3.69†	0.54	0.36	0.20
Hip	-1.26±5.08	-2.88±3.54*	-1.88±4.89	0.23	0.12	0.37
Knee	6.66±10.54	5.61±9.45	6.58±11.22	0.09	0.01	0.10
Ankle	3.56±4.83	3.96±4.91	3.58±5.85	0.07	<0.01	0.08
Standing on non-dominant leg						
	0°	30°	90°	Effect size 90° versus 30°	Effect size 90° versus 0°	Effect size 30° versus 0°
Sagittal plane: flexion/extension						
Trunk	13.06±13.40	17.57±15.66*	21.42±17.78*	0.23	0.53	0.31

Hip	21.36±6.70	12.81±3.99*	8.79±7.07*†	0.70	1.83	1.55
Knee	60.17±1.88	60.12±2.79	60.20±2.97	0.03	0.01	0.02
Ankle	33.24±2.56	32.89±2.08	32.43±3.13	0.17	0.28	0.15
Frontal plane: Adduction/ Abduction						
Trunk	-0.69±3.58	-0.62±2.92	-0.68±3.06	0.02	<0.01	0.02
Hip	5.21±4.25	4.93±3.99	-3.53±2.92	2.42	2.4	0.07
Knee	4.57±2.59	3.8±2.67	5.70±2.85†	0.69	0.41	0.29
Ankle	2.75±8.23	3.31±7.76	2.52±8.03	0.10	0.03	0.09
Transverse plane						
Trunk	1.73±8.28	-0.323±5.13*	-0.41±4.36*	0.02	0.32	0.30
Hip	-5.12±7.23	-5.26±8.15	-5.63±7.44	0.05	0.07	0.01
Knee	1.65±6.01	1.94±5.63	2.98±6.96	0.16	0.20	0.05
Ankle	-1.93±3.93	-2.44±4.36	-1.74±4.29	0.16	0.05	0.12

*significantly different from 0°
† significantly different from 30°

Table 2 Muscle activity at 60° knee flexion for three different single leg squats based on non-stance leg positions

	Standing on dominant leg			Standing on non-dominant leg		
	0°	30°	90°	0°	30°	90°
Rectus femoris	23.17±20.89	20.58±14.55	20.09±14.03	16.97±12.63	11.47±7.76 *	13.2±12.47*
Biceps femoris	7.50±5.90	9.14±6.18*	12.18±9.53*	8.98±5.68	12.86±9.61*	12.56±6.08*
Gluteus maximus	5.47±5.16	5.46±3.79	7.22±6.96	8.14±5.77	8.06±5.32	9.11±5.15
Gluteus medius	27.05±29.36	36.67±45.37	31.18±33.63	10.56±7.51	13.24±10.81	15.33±10.55 *†

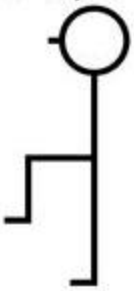
Values represent percentage maximal voluntary contraction; all values relevant to muscles on stance leg
*significantly different from 0°
†significantly different from 30°

Table 3 Centre of mass displacement at 60° knee flexion for three different single leg squats based on non-stance leg positions

	Standing on dominant leg			Standing on non-dominant leg		
	0°	30°	90°	0°	30°	90°
X-axis (Anterior/Posterior)	9.89±31.70	8.02±33.03	10.28±32.44	1.94±35.78	1.67±32.2	6.55±30.33
Y-axis (Medial/Lateral)	17.00±29.62	4.50±29.62*	13.29±29.58†	1.02±20.72	1.12±16.34	7.72±34.99

CoM – centre of mass
*significantly different from 0°
† significantly different from 30°

Table 4 Summary and implications of main findings

Non-stance leg position	**Finding or implication**
0° squat 	– Least amount of trunk flexion – Stance hip in most flexion – More lateral displacement of the CoM than in the 30° squat: more demanding test position – More *rectis femoris* than *biceps femoris* muscle activity: might be most comfortable post ACL reconstruction (when a hamstring autograft technique was used) in the later phases of rehabilitation – Most appropriate position when evaluating *rectus femoris* function
30° squat 	– More trunk flexion than in the 0° squat but less than in the 90° squat – Stance hip in more flexion than in the 90° squat but less than in the 0° squat – Least CoM displacement: least demanding test position – good position to start rehabilitation with, before progressing to more demanding positions
90° squat 	– Most trunk flexion: reduces the forces on the anterior-cruciate ligament[2] – Stance hip in least flexion: most appropriate where hip pathology is aggravated by hip flexion – Greatest *gluteus medius* activity (specifically on the non-dominant side): appropriate when focus is on hip and pelvic stability, especially when screening patients with anterior knee pain[17, 18] – More lateral displacement of the CoM than in the 30° squat: more demanding test position – More *biceps femoris* than *rectus femoris* muscle activity: might elicit pain if hamstring autograft technique has been used for ACL reconstruction – Most appropriate position when evaluating *biceps femoris* function

CoM – centre of mass; ACL – anterior cruciate ligament
Squat positions can be varied in order to vary muscle activity when the single leg squat is used as a rehabilitative exercise
To note: kinetics (forces and loads) have not been measured and may influence assumptions and implications