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<http://dx.doi.org/10.1016/j.ptsp.2019.01.007>

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Type	Article
URL	This version is available at: http://usir.salford.ac.uk/id/eprint/49929/
Published Date	2019

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A Systematic Review of the Discriminating Biomechanical Parameters during the Single Leg Squat

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1 **Abstract**

2 **Objective:** To determine whether there are common biomechanical parameters when analysing the
3 single leg squat movement to compare pathological and non-pathological groups and whether these
4 parameters are able to effectively distinguish between groups.

5 **Methods:** Five electronic databases were searched using MESH terms, keywords and phrases across
6 four constructs: squat, biomechanical measures, region of interest, study design. Studies were
7 selected based on inclusion of a quantitative biomechanical measure, compared between a
8 pathological and a non-pathological group, and participants performed a single leg squat movement.

9 **Results:** Fifteen studies were included and reviewed, where the majority of studies investigated
10 patellofemoral pain. There was considerable variation in the biomechanical outcome measure used
11 to compare between groups. The frontal plane projection angle was the most commonly reported
12 measure. There was considerable variation in the manner in which the single leg squat was
13 performed.

14 **Conclusion:** Due to variation in how the single leg squat was performed, it was not possible to
15 determine specific biomechanical parameters that distinguish between pathological and non-
16 pathological groups. Frontal plane projection angle appeared to be a parameter that could be
17 effectively utilised. Standardisation of the single leg squat movement is needed to allow comparison
18 between studies of pathological and non-pathological groups.

19

- 1 **Keywords**
- 2 Single leg squat, biomechanics, injury
- 3

INTRODUCTION

The single leg squat (SLS) is a movement task regularly used in clinical practice as it simulates common everyday tasks, such as stair ascent and descent, as well as sporting activities¹ and is often pain provoking. This task is part of the growing field of observational movement screening tests, which have become an increasingly used tool to identify individuals who might be at risk of musculoskeletal injury enabling targeted interventions to reduce the potential risk. A variety of methods are currently used to assess movement during a single leg squat, ranging from visual qualitative assessments,² to assessment involving 3D motion capture using inertial sensors.³ Visual observational movement screening tests offer a cost-effective, time-efficient method of assessing movement ability in both a clinical or field setting for a large number of participants and provide instant results. Qualitative type assessment of the SLS grade an individual's ability to perform the task against benchmarked criteria.⁴ The qualitative based criteria within the tests are often based on the ability to perform gross movements and could be subject to rater bias through a subjective interpretation of whether the movement meets the required criteria. Additionally, the ability of movement screening tests to predict musculoskeletal injuries is low.⁵⁻⁷

The use of objective biomechanical measures provides the researcher or clinician with the ability to quantitatively assess movement during a given task and provide greater fidelity in understanding the movement and potentially removes subjective interpretation. Biomechanical measures, such as kinematic and kinetics parameters, have also been used to validate movement screen tasks.⁸⁻¹⁰ In addition to providing objective measures, a further use of biomechanical measures is the ability to understand the mechanisms and, therefore, the potential causes of injury to the musculoskeletal system. The range of biomechanical methods and outcome measures, however, is vast and can encompass the use of marker based motion capture systems or inertial measurement units through to dynamic medical imaging such as video fluoroscopy to obtain a kinematic analysis of movement. Force platforms, pressure plates, in-shoe pressure systems and inverse dynamic analyses are commonly employed for kinetic analysis of movement. Identifying the biomechanical parameters and methods that have been used previously to analyse these tasks would help researchers and clinicians to develop standardised methods. This would enable the quantification of parameters associated with injury, potentially facilitating the development of training interventions. However, it is not currently known which potential parameters characterise and discriminate between pathological groups. The aim of this systematic review, therefore, was to determine whether there are common biomechanical parameters utilised when analysing the single leg squat movement comparing pathological and non-pathological groups and whether these

1 parameters are able to effectively distinguish between pathological and non-pathological groups
 2 providing some insight in to the mechanisms and causes of joint injury.

3
 4

METHOD

Search strategy

6 A systematic search of PUBMED, CINAHL, SCOPUS, EMBASE and DELPHIS databases was performed;
 7 the latest search was completed in February 2018. A combination of Medical Subject Headings
 8 (MeSH) terms, keywords and phrases were derived in consultation with the author group to search
 9 for relevant articles (Table 1). Search terms were truncated and wildcard operators used where
 10 appropriate to reduce the number of required key words. Near operators were used in order to
 11 identify different combinations of phrases. The search terms were divided into four constructs:
 12 squat related, biomechanical measures, region of interest, and study design. The Boolean operator
 13 ‘AND’ was used between constructs, with the exception of study design where the ‘NOT’ operator
 14 was used. Inclusion criteria consisted of: study performed a comparison between two groups,
 15 participants performed squat-based manoeuvre, and biomechanical related measures were used to
 16 quantify differences between groups.

17

Table 1: MeSH terms, key words and phrases used in the systematic search of databases. A Boolean operator used between each character presented in parenthesis after each category heading. Inverted commas represent phrase, asterix represents truncated term with wildcard operator, ‘n’ represents near operator with the number of words within which the term should appear.

Category	MeSH terms	Key words and phrases
Squat related (AND)		Squat “Step down” “Small knee bend”
Biomechanical measures (AND)	Biomechanics Kinematics Kinetics Torque Motion Pressure Accelerometry	Kinematic* Kinetic* Kinesio* Force* “Centre of pressure” n3 Angle* Moment* Torque* Jerk Velocit* “Angular velocity” Acceleration* Impulse* “Angular impulse” “Vector coding” “Coupling angles”

		Stereophotogrammetr* "Computed tomography" MRI "Magnetic resonance imag*" Motion "Motion analysis" Mechanics Fluroscop* IMU "Inertial measurement unit" Distance* Displacement* "2D video" Load Sway
Region of interest (AND)	Lower extremity Hip Joint Knee joint Foot joint	"Lower Extremity" "Lower Extremities" "Lower Limb" Hip Knee Ankle Foot Feet Leg Shank Thigh Femur Tibia Pelvis
Study design (NOT)	Surgical procedures Case reports Consensus Meta-analysis Clinical conference Scientific integrity review	

1

2 Following the search in each database the results were imported into an Endnote (version X7) library
 3 (Clavariate Analytics, Philadelphia, USA). Duplicates were identified and removed from the list using
 4 the built-in function within Endnote. Remaining references were then exported as a text file. A
 5 custom written MATLAB (MathWorks, Massachusetts, USA) Graphical User Interface (GUI) function
 6 was created to assist with the screening of the study titles and abstracts. The GUI imported the text
 7 file from Endnote, parsed the author name, year of publication, article title and abstract, and
 8 displayed this information for each article in turn. The tool automatically excluded articles that were

1 not full text articles based on the Endnote text export format that places inverted commas around
2 the title of the article for journal articles (i.e. articles that did not have inverted commas around their
3 title were excluded). A pool of eight reviewers screened the titles and abstracts of the articles. The
4 articles were equally divided into four groups of articles which were then assigned to pairs of
5 authors for title and abstract screening, where each reviewer of the pair screened all assigned
6 articles. Articles were screened and excluded based on the following criteria: no single leg squat
7 task, no quantitative biomechanical measures, not lower limb, no human participants, strength
8 measures only, electromyography only, simulation study, cadaver study, surgical intervention, not
9 original article, no comparison between pathological and non-pathological groups, reliability study
10 only and validity study only. The results between the reviewers of each pair were compared and
11 where disagreement over the inclusion or exclusion of an article occurred, the lead author reviewed
12 the article and made the final decision for inclusion or exclusion. As the purpose of the review was to
13 investigate squat movements that are conducted without outside influence that could affect the
14 performance of the movement the full text records of the selected articles were then reviewed and
15 excluded based on the following criteria: increased load during the squat movement, concerned
16 with resistance training, included vibration, included a fatiguing protocol, squat movements that
17 involved isometric contractions and studies that included movements with eyes closed. In addition,
18 studies including participants with neurological impairments were excluded in order to focus on
19 musculoskeletal conditions.

20

21 Articles that were included in the final review were then assessed for methodological quality using a
22 modified version of the STROBE checklist.¹¹ The STROBE checklist is a reporting standard, however,
23 due to the lack of an appropriate tool to assess the methodological quality of observational studies,
24 the STROBE checklist was deemed a reasonable tool to adopt as it is generally expected that
25 observational studies should include all items within the checklist. The articles were assessed against
26 each item of the STROBE checklist and given a score of 1 where the article met the criteria and 0
27 where it did not. An additional two items were added to the STROBE checklist: “Did the article report
28 or provide reference to appropriate evidence of the validity of the outcome measure?” and “Did the
29 article report or provide reference to appropriate evidence of the reliability of the outcome
30 measure” in order to score the article based on the robustness of the outcome measures. As some
31 items of the STROBE checklist were not applicable to all articles, the final score was normalised with
32 respect to the number of applicable answers and expressed as a percentage. A pool of eight
33 reviewers scored the included articles that were equally divided across four groups of reviewers,
34 where each reviewer scored each article that was allocated to their group. The scores from the pairs

- 1 of reviewers were assessed for agreement; disagreements were then assessed and settled by the
- 2 lead author.

RESULTS

Identification of Studies

The initial search resulted in a total of 6162 articles: 2628 duplicates were removed and a further 272 articles were removed as they were not journal articles, resulting in 3262 articles that were screened (Figure 1). Following the screening of the titles and abstracts according to the initial exclusion criteria, 392 articles remained. After reviewing the full text articles, 15 articles were included in the review.

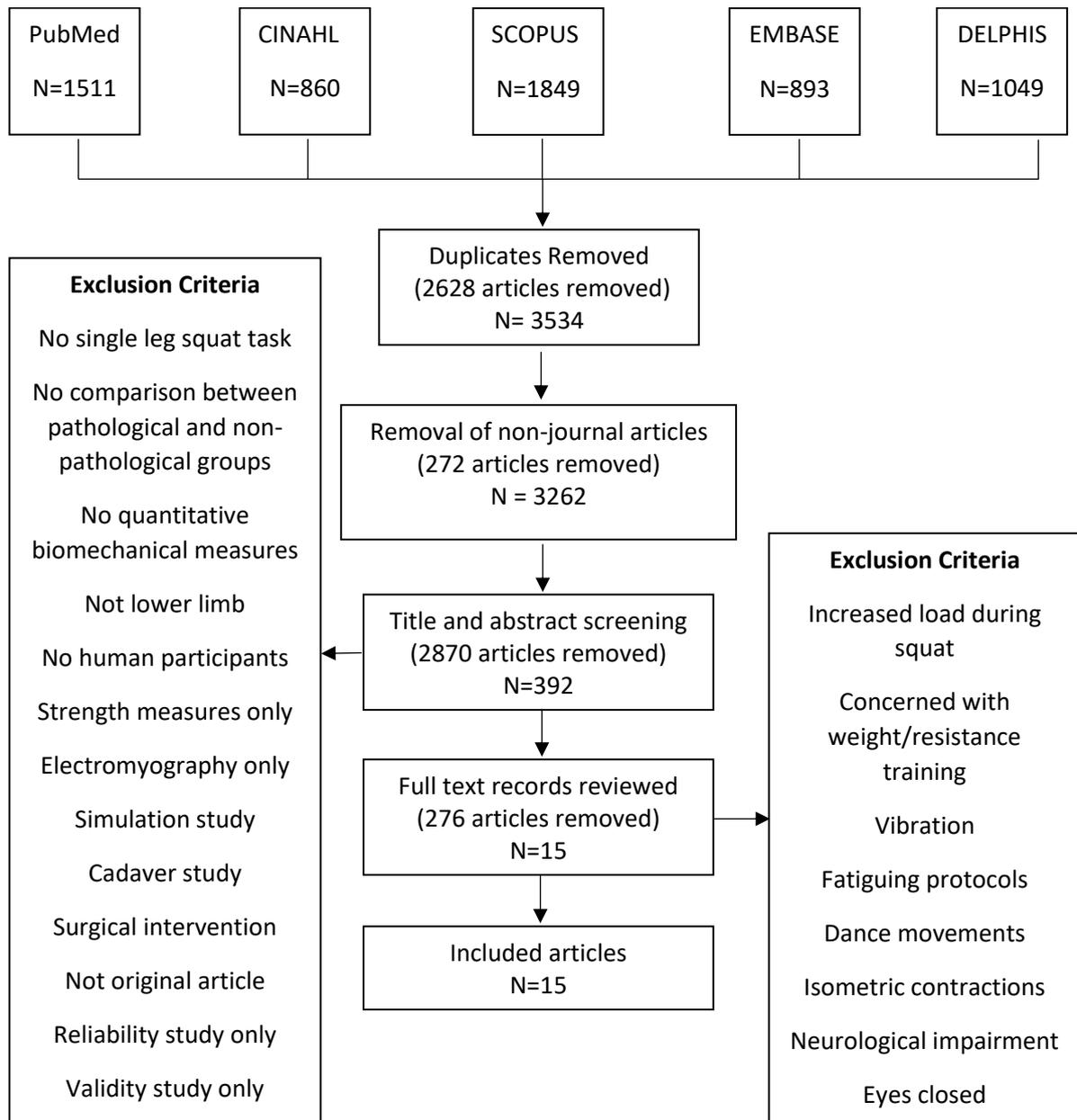


Figure 1: Flow diagram of study selection process

1 **Study Characteristics**

2 The included studies all investigated a group comparison between an injured and a non-injured
3 cohort (Table 2). The most common condition that was investigated was patellofemoral pain (n=11)
4 ¹²⁻²², followed by anterior cruciate ligament injury (n = 3)²³⁻²⁵ and one study on hip chondropathy.²⁶
5 Of the studies that investigated patellofemoral pain eight included female participants only,^{12 13 17-22}
6 while three studies investigated both females and males.¹⁴⁻¹⁶ Of the studies that investigated
7 anterior cruciate ligament injury two had both male and female participants^{23 25} and one had male
8 participants only.²⁴ The study on hip chondropathy included both male and female participants.²⁶
9 The average ages of participants were generally between 20 and 30 years old (Table 2); one study
10 examined adolescent females²² and one study had average ages of 37 and 35 years for their
11 pathological and control groups respectively.²⁶

12

13 **Squat Characteristics**

14 There were large variations in the manner in which the SLS was performed and wide spread
15 omissions in the description of the methods (Table 3). When asking participants to perform the
16 squat movement all studies except for one required a natural movement, i.e. participants were not
17 instructed to maintain prescribed orientations for the supporting leg, pelvis or trunk. The study of
18 Scholtes and co-workers²¹ asked participants to perform a single leg squat under natural and cued
19 conditions. The cued condition required participants to maintain their knee over the middle of the
20 foot. The depth of squat required of participants varied across the included studies and ranged from
21 45° of knee flexion to maximal depth achievable (Table 3). The studies also varied in the method
22 used to standardise the depth of the squat ranging from using a goniometer,^{17 18} an
23 electrogoniometer,¹³ or an external target (i.e. buttocks touching a plinth).²⁶ The majority of studies
24 (n = 11), however, did not standardise the depth of squat during the data collection, although some
25 studies did provide feedback during practice trials prior to data collection and some provided
26 feedback as to the speed of the squat using a metronome (Table 3). Only three studies explicitly
27 stated the position of the unsupported leg during the squat movement where the leg was placed
28 behind the participant^{16 25} or kept the toes in contact with the ground with the heel raised.¹³ The
29 most common position for the arms during the movement was across the chest (n=5), with one
30 study placing them on the pelvis,¹² two studies placing them by their sides^{13 21} and one behind their
31 backs.²⁴ The remaining studies (n = 6) did not specify where the arm were placed or were self-
32 selected by the participants (Table 3). None of the studies included a qualitative measure of the
33 movement.

34

1 **Biomechanical Measures**

2 The biomechanical outcome parameters reported by the studies primarily consisted of 3D kinematic
3 parameters; some studies reported 2D projection angles and two studies reported pressure-related
4 outcome variables (Table 4). With regards to the 3D kinematics the outcome measures included
5 trunk lean, contralateral pelvis drop, peak hip adduction, hip internal rotation, peak knee abduction,
6 knee flexion, patellar flexion/extension, patellar mediolateral rotation, patellar displacement and
7 ankle flexion (Table 4). Studies utilising 2D projection angles reported knee valgus angle or femoral
8 angle in the frontal plane.^{12 13 20 21} All cases which used the frontal plane projection angle compared
9 participants with patellofemoral pain to control participants. One study utilised open MRI to
10 determine patella displacement in 2D.¹⁸ The majority of studies reported single indices extracted
11 from the measured data (e.g. maximum angle) with exception of one study which additionally
12 utilised Principal Component Analysis on the 3D kinematic waveforms.²⁴ Five studies provided
13 evidence for the validity and reliability of the outcome measures,^{16 20 21 23 25} one study reported
14 evidence of validity only,¹⁷ six studies reported evidence of reliability only^{12-15 18 26} and four studies
15 reported no evidence for either validity or reliability.^{19 20 22 24}

16

17 **Comparisons between Pathological and Non-Pathological Groups - Summary of Results**

18 A range of biomechanical parameters were used to compare various pathological groups. The most
19 commonly used parameter was the frontal plane projection angle, which was used to compare
20 patellofemoral pain with control participants. The frontal plane projection angle, however, was not
21 used to compare other conditions, such as anterior cruciate ligament injury.

22

23 Patellofemoral pain participants had a greater knee frontal plane projection angle compared to
24 controls, ranging from 4° to 8°.^{12 13 20 21} Patellofemoral pain participants also demonstrated a 2.6°
25 greater ipsilateral trunk lean,^{14 15} a 2.9° greater pelvis drop,¹⁵ greater hip adduction (24°±6.5 vs.
26 19.2°±6) and knee abduction (10.5°±6.4 vs. 6.8°±5.3),¹⁴ and greater frontal plane hip adduction
27 (19.7°± 7.7 vs. 14.2°±6.5)²¹ compared to control participants (Table 4). A 'Dynamic Valgus Index',
28 defined as the sum of the hip and knee angles and intended to provide a more comprehensive
29 representation of movement than a single angle, demonstrated that patellofemoral pain participants
30 had greater movement both in 2D (31.1°±13.4 vs. 18.3°±18.0) and 3D (12.4°±9.8 vs. 1.81°±13.4)
31 than control participants.²¹ Patellofemoral pain participants also demonstrated greater lateral
32 displacement and tilt of the patella compared to control participants during the squat movement
33 when the supporting knee was flexed to 15° and 30°. However, the largest difference was observed
34 at 0° of knee flexion (75%±8 vs. 58%±7; lateral patella displacement, 13.1°± 5.8 vs. 8.1°±4.1; lateral

1 patella tilt).¹⁸ In terms of kinetics related parameters, patellofemoral pain participants had a 32%
2 relative group difference in force compared to controls.¹⁶ Control participants demonstrated a
3 higher centre of pressure range (7.72cm mean difference), a higher peak power absorption
4 (0.92W/Kg mean difference) and a higher peak power generation (0.87W/Kg) compared to
5 patellofemoral pain participants.²² One study found no significant group differences between
6 patellofemoral pain and control participants.¹⁷

7
8 Participants with anterior cruciate ligament injury demonstrated greater knee translation
9 (9.1mm±2.5 vs. 6.7mm±2.4),²³ knee external rotation (18.9°±34.3 vs. 38.8°±12.2; males only),²⁵ hip
10 rotation (9.1°±8 vs. 1.7°±6.1; females only),²⁵ knee flexion (73.9°±13.3 vs. 66.2°±9.9; females only)²⁵
11 and hip flexion (29.9°±18.4 vs. 48°±11.3; females only)²⁵ compared to control participants (Table 4).
12 One study found no group differences between anterior cruciate ligament injury and control
13 participants.²⁴

14
15 The study on hip chondropathy participants showed a greater range of medial/lateral and
16 anterior/posterior centre of pressure compared to control participants (Table 4).

17 18 **Quality of studies**

19 The normalised scores for the STROBE assessment of the articles ranged from 50% to 93.1% (Table
20 5). None of the studies reported the dates of recruitment, exposure, data collection or follow-up.
21 Other items that had few studies (< 6) scoring points were “Describing efforts to address potential
22 sources of bias”, “Explaining how the study size was arrived at”, “Reporting of evidence for the
23 validity of the outcome measure” and “Discussed the generalizability (external validity) of the study
24 results”.

Table 2: Study characteristics

Author	Year	Title	Participant Groups	Number in each group	Age (mean \pm standard deviation or range)	Activity level	How sex was treated in analysis
Carry et al	2017	Postural Stability and kinetic change in subjects with patellofemoral pain after a nine-week hip and core strengthening intervention	Females with patellofemoral pain	7	14.20 \pm 0.75		Single-sex study
			Control	7	14.12 \pm 0.86		
Hatton et al	2004	Impairment of Dynamic Single-Leg Balance Performance in Individuals With Hip Chondropathy	Hip chondropathy	63 (41 females)	37.36 \pm 11.6		Considered as a covariate for correlations
			Healthy controls matched for age, sex and physical activity level	60 (36 females)	35.7 \pm 9.7		
Herrington	2014	Knee valgus angle during single leg squat and landing in patellofemoral pain patients and controls	Females with unilateral patellofemoral pain	12	24 \pm 3.2	Participants completed at least 3 hours of sport training per week	Single-sex study
			Asymptomatic controls	30	20.4 \pm 1.4		
Kvist	2005	Sagittal tibial translation during	Unilateral non-operated anterior	12 (4 females)	28	All participants took part in	Not considered

		exercises in the anterior cruciate ligament-deficient knee	cruciate ligament injury	Non-injured controls	17 (nine females)	29	competitive sports	
Levinger et al	2007	Femoral medial deviation angle during a one-leg squat test in individuals with patellofemoral pain syndrome	Females with patellofemoral pain syndrome	12 females	37.4±9.41		Physically active; 3 hours per week for pain group, 4.1 hours per week for control group	Single-sex study
			Female controls	13 females	23.9±7.84			
Nakagawa et al	2012	Frontal plane biomechanics in males and females with and without patellofemoral pain	Females with patellofemoral pain syndrome	20 females	22.3±3.1			Main effect and interaction included
			Female controls	20 females	21.8±2.6			
			Males with patellofemoral pain syndrome	20 males	24.2±4.4			
			Male controls	20 males	23.5±3.8			
Nakagawa et al	2015	Trunk biomechanics and its association with hip and knee kinematics in patients with and	Patellofemoral pain	30 (10 females)	22.7±3.4			Not considered
			Control	30 (10 females)	22.3±3.0			

Rathleff et al	2014	without patellofemoral pain	Patellofemoral pain	23 (10 females)	25.8±7.4		Not considered
		Increased medial foot loading during drop jump in subjects with patellofemoral pain	Control	20 (10 females)	26.6±3.1		
Scholtes and Salsich	2017	A dynamic valgus index that combines hip and knee angles: assessment of utility in females with patellofemoral pain	Females with patellofemoral pain	20 females	22.4±4.3		Single-sex study
			Controls	16 females	21.6±3.0		
Song et al	2015	Effects of femoral rotational taping on pain, lower extremity kinematics and muscle activation in female patients with patellofemoral pain	Patellofemoral pain	16 females	25.7±6.1		Single-sex study
			Controls	8 females	28.6±5.7		
Souza et al	2010	Femur rotation and patellofemoral kinematics: a	Patellofemoral pain	15 females	30.8±8.9	198±188 minutes per week	Single-sex study

		weight-bearing magnetic resonance imaging analysis	Pain free	15 females	29.1±4.2	175±141 minutes per week	
St-Ogne et al	2004	Interjoint coordination in lower limbs in patients with a rupture of the anterior cruciate ligament of the knee joint	Injured (ruptured anterior cruciate ligament)	6 males	27.7±7.5		Single-sex study
			Control	9 males	25.3±7.4		
Willson and Davis	2008a	Lower extremity mechanics of females with and without patellofemoral pain across activities with progressively greater task demands	Injured (patellofemoral pain)	20 females	23.3±3.1	Tegner activity rating = 6.3±1.4	Single-sex study
			Control	20 females	23.7±3.6	Tegner activity rating = 6.9±1.3	
Willson and Davis	2008b	Utility of the frontal plane projection angle in females with patellofemoral pain	Injured (patellofemoral pain)	20 females	23.3±3.1	Tegner activity rating = 6.3±1.4	Single-sex study
			Control	20 females	23.7±3.6	Tegner activity rating = 6.9±1.3	
Yamazaki et al	2010	Differences in kinematics of single leg squatting between	Injured (anterior cruciate ligament)	63 (31 females)	male: 26.4; 16-51 female: 25.5; 14-47		Tested difference between sexes in ACL group

anterior cruciate ligament-injured patients and healthy controls.	Control	26 (12 females)	male: 26.2; 22-35 female: 23.2; 19-33
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Table 3: Description of Squat Movement

Author	Year	Unsupported leg position	Squat method			Natural or cued
			Arm position	Depth of squat	Depth of squat standardised?	
Carry et al	2017	Not stated	Self-selected by participant	Self-selected to the end of range	No	Natural, although stipulated trunk had to remain upright
Hatton et al	2004	Not stated	Folded across chest	60° of knee flexion	Yes, buttocks needed to have touched a plinth positioned behind participant	Natural
Herrington	2014	Not stated	Hands on pelvis	Knee flexion of at least 45° but no greater than 60°	Not during recorded trials. Depth of squat checked during practice trials.	Natural
Kvist	2005	Not stated	Not stated	Maximum depth possible with unassisted rise	No	Natural

Levinger et al	2007	Toe tips in contact with ground with heel raised	At sides	45° of knee flexion	Audio cue from electrogoniometer when target knee flexion angle reached	Natural
Nakagawa et al	2012	Not stated	Not stated	60° of knee flexion Participants required to perform squat at a speed of 2 seconds down, 2 seconds up.	Depth of squat not checked. Digital metronome used to control speed of squat.	Natural
Nakagawa et al	2015	Not stated	Not stated	Knee flexion greater than 60°. Required to perform at a speed of 15 squats per minute	Digital metronome used to control speed of squat.	Natural
Rathleff et al	2014	Behind weight bearing leg	Across chest	90° of knee flexion	Visual observation by investigator	Natural
Song et al	2015	Not stated	Across chest	45° of knee flexion Perform at a speed of 30° per second	Goniometer used initially to check depth. Then visual observation	Natural

Scholtes et al	2017	Not stated	Arms by side	At least 60° of knee flexion	Visual observation by investigator	against a marker placed on a wall.	Natural and cued Cued condition required participants to maintain their knee over the foot.
Souza et al	2010	Not stated	Not stated (required not to touch sides of scanner)	Approximately 50° of knee flexion Participants required to squat to approximately 50° then slowly rise pausing at 45°, 30°, 15° and 0° for image collection	Plastic goniometer attached to side of leg		Natural
St-Ogne	2004	Not stated	Arms behind back	Not specified	No		Natural
Willson and Davis	2008a	Not stated	Not stated	Beyond 60° of knee flexion. Verbal cadence, 15	No		Natural

Willson and Davis	2008b	Not explicitly stated. From figure it can be speculated that the knee of unsupported leg flexed to approximately 90°	Arms across the chest	squats per minute. Beyond 60° of knee flexion. Verbal cadence, 15 squats per minute.	Participants given feedback during practice trials. Not monitored during trials.	Natural
Yamazaki et al	2010	Unsupported leg behind participant	Arms across the chest	Perform half squat over 10 seconds on injured, than non-injured leg.	No	Natural

Table 4: Biomechanical outcome parameters

Author	Year	Outcome measures Outcome parameters	Hardware and software	Evidence of validity	Evidence of reliability	Results
Carry et al	2017	3D kinematics and kinetics	Vicon – plug-in gait	No	No	Peak power absorption: 0.92W/KG higher in control group (p=0.0029)
		Peak knee flexion	Bertec force platforms			Peak power generation: 0.87 W/Kg higher in control group (P = 0.0081)

Peak power
absorption

CoP range:
7.73cm higher in control group (P = 0.0403)

Peak power
generation

CoP mean distance

Average distance from
mean CoP

RMS distance

RMS distance from
mean CoP range

Maximum distance
between any two CoP
location

95% CI circle area

Hatton et al

2004

CoP path length

Wii Balance
Board

No

Yes

Range of CoP in
anterior/posterior and
medial/lateral
directions

Greater Medial/Lateral CoP range in hip
chondropathy (p = 0.023)
Control = 3.14cm±0.45
Hip Chon = 3.5cm±0.77

Standard deviation of
CoP in A/P and M/L
directions

Greater Anterior/Posterior SD of CoP in hip
chondropathy (p = 0.043)
Control = 1.19cm±0.31
Hip Chon = 1.37cm±0.47

Herrington	2014	2D frontal plane projection angle of knee valgus at lowest point of knee flexion	Digital video camera at 50Hz. Video digitised using Quintic software	No	Yes	<p>Significant difference between injured limb of PFP group and control (non-dominant side) and injured limb to non-injured limb with PFP group.</p> <p>Control: $8.4^{\circ} \pm 5.1$ PFP injured: $16.8^{\circ} \pm 5.4$ PFP non-injured: ~ 10.</p>
Kvist	2005	Maximum knee flexion angle Maximum tibial translation	Computerised goniometer linkage at 2000Hz	Yes	Yes	<p>Significantly more knee translation in ACL injured leg compared to control group, and ACL injured leg to non-injured leg within ACL group.</p> <p>ACL injured: $9.1\text{mm} \pm 2.5$ ACL non-injured: $8.1\text{mm} \pm 3.7$ Control: $6.7\text{mm} \pm 2.4$</p>
Levinger et al	2007	2D frontal plane kinematics Femoral frontal angle: anterior superior iliac spine to midline of the femoral condyles Foot longitudinal alignment from second toe to midline of the malleoli Femoral deviation: horizontal deviation of the lower marker on	Single video cameras placed perpendicular to the frontal plane at 50Hz. Marker data digitised using Peak Motus (version 7)	No	Yes	<p>Significant difference in femoral frontal angle between right knee of PFP group (injured knee) and right knee of control group (no indication of limb dominance).</p> <p>PFP: $11.75^{\circ} \pm 3.61$ Control: $7.79^{\circ} \pm 4.22$</p> <p>No significant difference in femoral deviation between right knee of PFP group (injured knee) and right knee of control group (no indication of limb dominance).</p> <p>PFP: $2.54^{\circ} \pm 1.29$ Control: $2.02^{\circ} \pm 1.11$</p>

		the thigh relative to a marker on the second toe.				Note: a significant difference was found between ages of groups
		Each parameter calculated as the difference between initial posture and posture at 45° knee flexion				PFP: 37.4 years ± 9.41 Control: 23.9 years ± 7.84
Nakagawa et al	2012	3D kinematics	Flock of Birds electromagnetic sensors with MotionMonitor software	No	Yes	No significant difference between groups for knee excursion
		Maximum excursion of ipsilateral trunk lean				Female PFP: 64.7° ± 3.8° Male PFP: 66.1° ± 3.5°
		Contralateral pelvic drop				Female controls: 65.2° ± 2.9° Male controls: 67.4° ± 3.2°
		Hip adduction				Females (with or without PFP) had greater ipsilateral trunk lean than males (with or without PFP)
		Hip Internal rotation				Female PFP: 11.1° ± 4.6° Male PFP: 7.5° ± 3.9°
		Knee Abduction				Female controls: 7.5° ± 3.5° Male controls: 6.4° ± 2.3°
						PFP groups (males and females) had greater ipsilateral trunk lean than controls Mean difference = 2.6°
						PFP had greater pelvic drop than controls (mean difference = 2.9°)

Female PFP: $11.3^\circ \pm 4.3^\circ$
Male PFP: $9.2^\circ \pm 4.6^\circ$
Female controls: $6.6^\circ \pm 2.9^\circ$
Male controls: $7.1^\circ \pm 4.5^\circ$

Females (with or without PFP) had greater hip adduction than males (with or without PFP) (mean difference = 6.9°). PFP had greater hip adduction than controls (mean difference, 4.0°):

Female PFP: $20.4^\circ \pm 6.0^\circ$
Male PFP: $13.9^\circ \pm 7.3^\circ$
Female controls: $14.3^\circ \pm 4.6^\circ$
Male controls: $7.2^\circ \pm 3.8^\circ$;

Females with PFP had greater hip internal rotation than males with PFP (mean difference, 5.8°), control females (mean difference, 5.9°) and control males (mean difference = 6.1°)

Female PFP: $15.6^\circ \pm 5.8^\circ$
Male PFP: $9.8^\circ \pm 4.8^\circ$
Female controls: $9.7^\circ \pm 5.4^\circ$
Male controls: $9.5^\circ \pm 4.3^\circ$;

Females (with or without PFP) had greater knee abduction than males (with or without PFP) (mean difference = 3.9°)

PFP had greater knee abduction than controls (mean difference, 3.4°)

Female PFP: $11.2^\circ \pm 4.6^\circ$:
Male PFP: $7.1^\circ \pm 3.5^\circ$
Female controls: $7.2^\circ \pm 3.3^\circ$
Male controls: $4.2^\circ \pm 2.3^\circ$;

Nakagawa et al	2015	3D kinematics	Flock of Birds electromagnetic sensors with MotionMonitor software	No	Yes	PFP have greater peak ipsilateral trunk lean compared to controls. PFP: $9.8^\circ \pm 5.2$ Control: $6.9^\circ \pm 4.4$	
		Peak ipsilateral trunk lean					
		Peak hip adduction				PFP have greater peak hip adduction compared to controls PFP: $24.0^\circ \pm 6.5$ Control: $19.2^\circ \pm 6.0$	
		Peak knee abduction				PFP have greater peak knee abduction compared to controls PFP: $10.5^\circ \pm 6.4$ Control: $6.8^\circ \pm 5.3$	
Rathleff et al	2014	In-shoe pressure distribution	Pedar, Novel	Yes	Yes	PFP 9% higher peak absolute force compared to controls (P = 0.01), relative group difference of 32%.	
Scholtes and Salsich	2017	2D frontal plane projection angle	Dartfish	Yes	Yes	PFP greater knee FPPA (p=0.014) PFP: $11.48^\circ \pm 7.45$ Control: $4.14^\circ \pm 9.62$	
		2D dynamic valgus index (DVI)				PFP greater hip FPPA (P = 0.03) PFP: $19.66^\circ \pm 7.70$ Control: $14.15^\circ \pm 6.53$	
		3D kinematics				Vicon – Visual3D	
		Hip adduction Hip medial rotation Knee abduction Knee lateral rotation				PFP greater 2D DVI (P = 0.01) PFP: $31.14^\circ \pm 13.36$ Control: $18.3^\circ \pm 17.97$	
						PFP greater 3D DVI (P = 0.01)	

		3D dynamic valgus index				PFP: 12.41° ± 9.77 Control: 1.81° ± 13.44
Song et al	2015	3D kinematics Peak excursion in stance leg for: Hip flexion/extension, abduction/adduction, internal/external rotation Patellar flexion/extension, mediolateral rotation, mediolateral tilt Patellar displacement in mediolateral, anteroposterior and proximodistal planes	Fastrak, Polhemus	Yes	No	No group significant group differences for 3D kinematics
Souza et al	2010	2D kinematics Patella displacement, expressed as percentage of total patella width Medial/lateral patella tilt angle	Vertically open Magnetic Resonance Imaging (0.5T). General Electric Medical Systems	No	Yes	PFP greater lateral patella displacement at 0° knee flexion (p=0.011) PFP: 75% ± 8% Control: 58% ± 7% PFP greater lateral patella tilt at 0° knee flexion (p=0.03). PFP: 13.1° ± 5.8° Control: 8.1° ± 4.1°

		Medial/lateral femoral rotation				PFP greater medial femoral rotation at 0° knee flexion (p<0.037). PFP: 12.2° ± 5.0° Control: 6.2° ± 5.2°
		Patella rotation				
St-Ogne	2004	3D kinematics	Optotrack	No	No	No differences between groups found during single leg squat movement.
		Thigh flexion/extension				
		Thigh abduction/adduction				
		Knee flexion/extension				
		Ankle flexion/extension				
		Principle Component Analysis conducted on waveforms				
Willson and Davis	2008a	3D kinematics at 45° of knee flexion	Vicon – Visual3D	No	No	PFP had greater knee external rotation (P = 0.06), less internal rotation excursion (P = 0.05), greater hip adduction (P = 0.012), and greater contralateral pelvic drop (no P value). PFP group had decreased hip internal rotation (P = 0.01) and more femoral external rotation (no P value). PFP had less internal rotation excursion (P = 0.005).

						Not possible to determine values as only reported figures and the average difference between groups for all activities.
Willson and Davis	2008b	3D kinematics of the hip and knee at count of 2 during squat (authors state that knee flexion at the count of 2 is associated to peak knee extension moment during running and jumping) 2D Frontal Plane Projection Angle at count of 2 during squat Peak knee extensor moment	Vicon – Visual3D Bertec Fore Platforms FPPA: Digital image (equipment used not stated) and CorelDraw to determine angle.	Yes	Yes	No group difference in knee flexion angle. PFP group greater medial position of the knee during squats (difference between groups = 4.1°; P=0.012).
Yamazaki et al	2010	3D kinematics of hip and knee at maximum knee flexion	Fastrak, Polhemus	Yes	Yes	Uninjured male ACL leg less external knee rotation than dominant leg of male control (P=0.0090) Uninjured leg of male ACL group: 18.9° ± 34.3 Dominant leg of male control group: 38.8° ± 12.6 Uninjured leg of female ACL group significantly more external hip rotation (P=0.001), knee flexion (P=0.0070) and hip flexion (P<0.0001) than dominant leg of female control.

Hip rotation

Uninjured leg of female ACL group: $9.1^\circ \pm 8.0$

Dominant leg of female control: $1.7^\circ \pm 6.1$

Knee flexion

Uninjured leg of ACL group: $73.9^\circ \pm 13.3$

Control: $66.2^\circ \pm 9.9$

Hip flexion

Uninjured leg of ACL group: $29.9^\circ \pm 18.4$

Control: $48.0^\circ \pm 11.3$

ACL = anterior cruciate ligament; CoP = Centre of Pressure; SD = standard deviation; FPPA = frontal plane projection angle; PFP = patellofemoral pain.

Table 5: Normalised score for STROBE checklist

Paper	STROBE score
Carry et al., 2017	75.9%
Hatton et al., 2014	75.9%
Herrington, 2014	72.4%
Kvist, 2005	58.6%
Lavinger et al., 2007	74.1%
Nakagawa et al., 2012	83.3%
Nakagawa et al., 2015	74.1%
Rathleff et al., 2014	93.1%
Scholtes et al., 2017	85.7%
Song et al., 2015	85.7%
Souza et al., 2010	86.2%
St-Ogne et al., 2004	50%
Willson and Davis, 2008a	72.4%
Willson and Davis, 2008b	83.3%
Yamazaki et al., 2010	58.6%

DISCUSSION

1
2 The aim of this systematic review was to identify the biomechanical parameters used when
3 performing a biomechanical analysis of the single-leg squat (SLS) and determine which parameters
4 detected differences between pathological and non-pathological groups. The frontal plane knee
5 projection angle was the most commonly used parameter, but was limited to studies of individuals
6 with patellofemoral pain. Therefore, the ability of biomechanical parameters to distinguish between
7 pathological and non-pathological groups is likely condition-specific.

8
9 Summarising the data extracted from the studies some general observations can be made.

10 Generally, there was greater frontal plane motion in the injured groups than in the healthy control
11 groups. This was true whether the measure was from a 2D angle,^{12 13 17 20 21} 3D motion capture,^{14 15 21}
12 or medial / lateral range of centre of pressure motion.²⁶ This was also true throughout the kinematic
13 chain with differences being noted in the knee, hip, pelvis and trunk. Peak knee flexion,²⁵ peak hip
14 internal rotation and knee internal rotation excursion¹⁹ were variables noted to be less in the injured
15 group than in the healthy control group. Overall, though, this review observed substantial variability
16 in methodology when using a biomechanical analysis of the SLS to investigate group differences. The
17 majority of studies (11 out of 15) investigated patellofemoral pain meaning there was some
18 consistency in the patient group of interest; however, due to the inconsistencies and omissions in
19 the description of methodology, drawing overall substantiated conclusions was not possible.

20
21 The ankle is a crucial part of the lower extremity kinematic chain providing a stabilising role during
22 the closed chain task of the SLS. Despite the ankle's role during the SLS it was only included in one
23 paper.²⁴ As these data were likely collected in all the studies, the omission of such data likely speaks
24 to the challenges of fitting complex, multi-variable analyses within publication constraints. To
25 present a more complete picture, it may be prudent to move toward including full body data where
26 possible or alternatively in an appendix if available.

27
28 Force or kinetic data during the SLS were not extensively reported in the studies. Only four papers
29 included these data in any form, and there was no overlap between the variables being analysed. As
30 kinetic data can better represent joint loading and ultimately the causes of joint injuries are often
31 attributed to the loading placed on the musculoskeletal system,²⁷ it would be important to include
32 these in future studies. It must be noted that this review article excluded articles that performed
33 musculoskeletal modelling (i.e. joint reaction force, muscle force analysis, etc) due to the complex
34 nature of the analysis precluding them from being employed in a typical clinical environment.

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While the majority of the studies included only a single sex, three of the studies included both males and females and did not report how sex was considered in the analysis.^{14 16 23} Sex-specific movement patterns during the single leg squat have been previously noted where females perform the single leg squat with less trunk flexion,^{28 29} and with more pelvic rotation,^{28 29} hip adduction,^{1 15 28 29} and knee abduction^{15 28} than males. Females have also been reported to have less ipsilateral trunk flexion¹ than males, although Nakagawa¹⁵ found the opposite while others^{28 29} reported no difference. The observed differences in the dependent measures between males and females could obscure potential group differences if including them within the same group or not accounting for sex differences in the statistical analysis.

As age affects SLS performance, it is important to consider the age of the individual when assessing the SLS. Between childhood and adolescence, SLS performance improves with increasing age.³⁰ In adults, elderly participants have been shown to exhibit alterations in muscle activation during an increased resisted SLS movement, which may be a contributing factor to injury in the elderly³¹. Additionally, the effects of ageing on muscle mass, strength and neuromuscular control are well known³²⁻³⁴. The studies in this review included participants who were young to middle-aged adults with mean ages ranging from 14.1 to 37.3 years old. As a result, this review is unable to suggest if the ability of biomechanical measures to discriminate between pathological groups is affected by age.

Of the studies that reported activity level, participants were generally of recreational level in five studies,^{12 13 18-20} with one study investigating competitive athletes.²³ Physically active participants have been shown to demonstrate greater knee and hip flexion during the SLS, indicating a greater depth of squat, and are likely to be rated as having better performance compared to less physically active participants.³⁵ Level of physical activity of participants should be considered when comparing between groups and between results of different studies. Comparing of studies that used a common biomechanical outcome parameter (frontal plane knee projection angle), two studies investigated physically active participants at a recreational level,^{12 13} with one study investigating inactive participants,²¹ although an indication of activity level was not mentioned. Frontal plane knee projection angle did not appear to differ between these studies, suggesting that activity level did not affect this biomechanical outcome parameter. However, it is important to consider methodological differences and the omission of activity level in one study makes it difficult to draw a robust

1 conclusion. Future research should examine the effect of activity level on biomechanical parameters
2 during the SLS.

3
4 All studies evaluated the SLS without requiring the participants to maintain a specific posture or
5 adopt a specific movement pattern or orientation of body segments during the movement. This
6 approach is often adopted in clinical evaluations to assess the cognitive control of movement.³⁶ The
7 analysed movements, therefore, indicate how participants self-select to perform the task. One study
8 also included a cued task to evaluate the participant's ability to correct the movement pattern.²¹ The
9 differences noted between the un-cued and cued movement indicated that the self-selected
10 movement pattern does not necessarily evaluate an individual's ability to perform the movement
11 correctly. The goals and methods of cognitive movement control assessment are different compared
12 to a preferred movement pattern assessment,³⁷ therefore, the movement evaluation model within
13 studies should be carefully considered when interpreting results from studies.

14
15 There was considerable variability or omission in the details of how the single leg squat was
16 performed. Twelve of the 15 studies did not report the position of the unsupported leg during the
17 SLS while two reported that it was behind the supporting leg. The position of the unsupported leg
18 affects both kinematic and kinetic outputs measured in the stance leg,³⁸ making comparisons
19 between studies that have adopted different positions for the unsupported leg difficult. One study
20 allowed the toes of the unsupported leg to be in contact with the ground.¹³ This additional point of
21 contact might also affect the measured variables by providing kinaesthetic and proprioceptive
22 feedback as well as an additional base of support. The positions of the arms during the squat also
23 varied across studies, ranging from arms across the chest, to arms by the side, to arm out stretched
24 in front. Although the effect of arm position on SLS kinematics and kinetics has not been
25 investigated, the position of the arms has been shown to influence knee valgus moments during
26 dynamic sports,³⁹ suggesting arm position will influence performance of a given task. The position of
27 the arms will influence the position of the overall centre of mass and lead to kinematic changes,
28 especially in the trunk, again making comparison between studies difficult if the position of the arms
29 is not standardised or consistent.

30
31 The majority of studies did standardize the squat depth with one study not specifying the depth,²⁴
32 and two studies going to a maximum depth or self-selected end of range.^{22 23} The range of depth was
33 extensive, varying from 45 degrees of knee flexion^{13 17} to 90 degrees of knee flexion.¹⁶ Despite this
34 variation between studies, based on an analysis of stepdown from different heights,⁴⁰ it may be

1 more important to standardize the point at which the variables are measured. In a repeated
2 measures analysis, when the dependent variables were analysed at peak knee flexion, the stepdown
3 from a 16 cm step appears to use a different movement pattern than the stepdown from a 24 cm
4 step. However, when analysed at 60 degrees of knee flexion, only trunk flexion was different
5 between the tasks. Thus, if peak knee flexion may be different between groups, it may also be
6 important to include a standardised angle at which data are analysed. However, depending on the
7 research question, peak angles throughout the movement may also be of interest.^{15 17 23} Another
8 consideration is whether a peak angle is used or the change in the angle over a time frame (i.e.
9 excursion). The use of excursion may obscure differences when there is an offset in the initial
10 position that contributes to the difference in peak angles. This situation is noted in Willson et al¹⁹
11 where differences in peak angles were noted, but not in excursions. In addition, the definition of
12 'zero' and its relation to a neutral joint position is important to consider. Differences in the definition
13 of the neutral joint angle will influence the absolute angles reported, requiring a clear and consistent
14 definition of the neutral angle to ensure comparisons between groups are valid.

15

16 The SLS is often used as a tool to assess movement due to its perceived relationship to functional
17 movement, yet the relationship between the SLS and more dynamic sporting tasks must be
18 considered. The SLS is typically performed in a controlled manner in a bid to simulate activities of
19 daily living, such as walking down stairs. However, it is the more dynamic movements seen in sports,
20 for example, that may be the likely causative factor for joint injury. The velocity of the SLS influences
21 the latency of hip muscle activation,⁴¹ and may have subsequent effects on lower limb kinematics
22 and kinetics. Therefore, the slow velocity in which the SLS is performed will not produce the same
23 demands on the musculoskeletal system of the lower limb as a faster dynamic task. Of the studies
24 reported in this review only two standardised the velocity of performing the SLS.^{14 15} Although the
25 SLS has been shown to be related to pathology and injury,⁴² which suggests a relationship between
26 SLS performance and functional movement, evidence on a direct comparison is limited. Movement
27 patterns during the SLS are related to observed patterns during single leg landing⁴³ and bilateral
28 drop jump tasks,^{43 44} but further research is needed to establish the relationship between SLS and
29 dynamic performance. With the development of inertial measurement units the possibility of
30 establishing kinematic relationships and specific clinical measures such as the SLS can be established.

31

32 The current systematic review had a number of limitations. The review was not constrained to a
33 single type of pathology; therefore, it was not possible to combine the results and perform a meta-
34 analysis to determine possible effect sizes for the discriminatory power of the biomechanical

1 outcome parameters. The choice of not constraining the type of pathology was made, as it was not
2 known prior to undertaking the study which pathologies are assessed using a single leg squat
3 movement. The current review was also limited to only including cross-sectional studies that
4 compared a pathological to non-pathological group. To determine the biomechanical measures that
5 are indicative of alterations in movement a review of studies that have examined changes in
6 biomechanical parameters during the single leg squat following an intervention would be needed.

7
8 A number of research and clinical recommendations can be stated as a result of this review. Firstly, it
9 is important to standardise and report the position of the unsupported leg and arms during the SLS
10 as differing positions can alter the kinematic profile when performing the movement.

11 Recommendations on the position to adopt include placing the unsupported leg behind with the
12 knee flexed to 90°, and arms across the chest. To account for the differences in depth of squat
13 employed in studies, it would be beneficial to report parameters at different levels of knee flexion
14 during the SLS. This would allow a comparison of studies irrespective of the depth of squat. Many
15 studies only reported kinematics of a single joint, however, the relationship between kinematics and
16 pathology are likely to be multifactorial and therefore it is important to consider the entire kinetic
17 chain. These data should be presented in the paper, or as an appendix or supplementary material as
18 appropriate. In addition, many biomechanics laboratories are equipped with force platforms but
19 very few studies report kinetic findings on the SLS. It is suggested that kinetic data should be
20 considered in future reporting. Due to the known differences in kinematic parameters when
21 performing the SLS the inclusion of sex as a covariate must be considered in future studies. Clinical
22 recommendations ~~again~~ must be circumspect, however, the clinician should consider the following
23 points when using the SLS as a tool to assess a patient. Frontal plane motion appears to be the most
24 important factor related to patellofemoral pain in females and should be the focus of the
25 assessment; consistency in the position of the unsupported leg and arms should be employed; and it
26 should be considered that males and females may perform the movement differently irrespective of
27 pathology.

28 29 **CONCLUSION**

30 The SLS provides a controlled means to assess dynamic movement during a simulated movement
31 that occurs in activities of daily living and sporting activities. Through the use of biomechanical
32 measures it is possible to obtain quantitative, and potentially less biased than visual observational
33 measures, measures of movement that will assist in elucidating the mechanisms of joint injuries.

34 This review found large variability in the parameters used to distinguish between pathological and

1 non-pathological groups. Of the biomechanical parameters reported by studies, frontal plane
2 kinematics showed the most differences between pathological and non-pathological groups. This
3 review also found large variability in the way in which the SLS was performed and the dependent
4 variables used to determine groups differences. Based on this review a series of recommendations
5 are suggested for future studies: 1) standardising the position of the unsupported leg during the SLS;
6 2) standardising arm position during the SLS; 3) reporting kinematic for all joints, included as an
7 appendix if necessary; 4) giving more consideration to kinetic outcome parameters; and 5)
8 considering sex as a covariate.

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