Lower Limb Biomechanics Before and After Anterior Cruciate Ligament Reconstruction: a Systematic Review

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Abstract

This review aimed to synthesise the findings of literature that have assessed the changes in lower limb biomechanics following anterior cruciate ligament (ACL) reconstructive surgery. Systematic searches of CINHAL, MEDLINE, SCOPUS, and SPORTDiscus databases were run. All included studies had presented biomechanical variables pre- and post-surgery for the same participants. Articles were categorised by the analysed movement, and effect sizes were calculated. Fifty-four studies met the inclusion criteria, providing data on gait (n=31), balance (n=12), joint position sense (n=5), stair ambulation (n=4), pivoting (n=6), and landing (n=5). Measures of balance performance and joint position sense showed improvements from pre- to post-surgery. Changes in joint kinematics were inconsistent between studies, however increased knee flexion excursion, and reduced tibial anterior translation and internal rotation post reconstruction were identified. Joint kinetics reduced in magnitude in the early stages after surgery (≤5 weeks), then increased later in recovery (≥24 weeks). Risk of bias assessment identified most articles had a moderate or high risk (low=5; moderate=21; high=11) resulting from participant retention and surgical intervention differences. The results of the review identified that although lower limb biomechanics did alter following reconstruction, few variables provided consistent results across studies and tasks. The low methodological quality of some articles may have contributed to these inconsistent findings. Alternatively, differences across studies may have resulted from individual coping strategies of participants that have previously been suggested to be present before reconstructive surgery, and future research should look to explore individual coping strategies to ACL reconstruction.

1. Introduction

Anterior cruciate ligament (ACL) rupture is an injury that results in knee instability (Moses et al., 2012), and early onset of osteoarthritis (Barber et al., 1990; von Porat et al., 2004). ACL deficient knees have increased laxity, and altered biomechanics during movement tasks (Georgoulis et al., 2003; Keays et al., 2003). To alleviate ACL deficiency related symptoms and restore healthy biomechanics, the ligament is often reconstructed (Grindem et al., 2014). Surgical reconstruction aims to improve the stability of the knee by the mechanical role of the damaged ligament being restored by a graft.

The success of reconstructions, measured as return to previous activity level and avoidance of further musculoskeletal complications is often good but other times poor (Ardern et al., 2011; Kessler et al., 2008). An increased risk of re-injury and early onset osteoarthritis compared to uninjured participants has been identified after ACL reconstruction (Paterno et al., 2012; von Porat et al., 2004). These outcomes may be due to treatment failing to restore healthy lower limb biomechanics, resulting in unhealthy joint movement patterns.

Systematic reviews have previously identified altered biomechanics in the ACL deficient and reconstructed knee (Hart et al., 2016; Petersen et al., 2014). These reviews have shown decreases in muscle strength, and altered biomechanics in ACL injured knees. Currently no systematic evaluation of the literature surrounding the changes in biomechanics that occur because of reconstructive surgery is available. This information may inform future research and physical therapy treatments by providing insight into the biomechanical changes that occur following ACL reconstruction. Therefore, the aim of this study was to systematically synthesise literature that has explored changes to pre-operative lower limb biomechanics following ACL reconstructive surgery and rehabilitation.

2. Methods

2.1 Search strategy

A search strategy (Supplemenary Method 1) including terms relating to ACL reconstruction, and biomechanics (O'Connor et al., 2011) was ran in CINHAL, MEDLINE, SCOPUS, and SPORTDiscus from inception to 8th November 2019. No restrictions were placed on article type, meaning peer reviewed articles, conference abstracts and doctoral theses were included in the review. This decision was made to ensure all relevant data were captured and the quality of the evidence assessed solely on its methodological quality. Reference lists of accepted articles were searched for additional papers that met the inclusion and exclusion criteria.

2.2 Inclusion and exclusion criteria

After the removal of duplicates, the titles and abstracts of the identified articles were independently assessed for inclusion and exclusion criteria by reviewers JM and KC. Where data were duplicated in different articles (e.g. doctoral thesis and peer-reviewed article) both sources were included at this stage and only excluded after data analyses revealed no new information. Inclusion criteria were: human participants with a ruptured ACL who underwent reconstructive surgery; data collected within 12 weeks before and 52 weeks after surgery; and biomechanical outcome measures. Exclusion criteria were: concurrent knee ligament injuries; knee osteotomy; and isokinetic torque assessments. Isokinetic strength data were excluded due to the existing body of evidence showing a clear link between strength deficiencies and ACL reconstruction (Ardern & Webster, 2009; Petersen et al., 2014). Where other biomechanical variables were present within an article assessing isokinetic strength, these data were included. Where the inclusion and exclusion criteria were met by at least one reviewer, full texts were independently screened against the criteria. No conflicts between reviewers were encountered when including articles based on full texts.

2.3 Data extraction

Data extraction consisted of kinematic and kinetic biomechanical variables of the involved limb before and after ACL reconstructive surgery, participant information, study design, surgical characteristics, and data collection methods. Where data were not available, the author was contacted. If data were still unable to be sourced, WebPlotDigitizer (https://automeris.io/WebPlotDigitizer/), software with high reliability (Pearson's $r = 0.999$) and validity ($r = 0.989$) (Drevon et al., 2017) designed to extract data from digital plot images, was used.

2.4 Data analysis

Means and SDs were used to calculate Cohen's *d* effect sizes (ES; negligible <0.2, small $0.2 \leq d < 0.5$, medium $0.5 \leq d < 0.8$ and large ≥ 0.8; Cohen, 1988) and 95% confidence intervals (CI; Hedges & Olkin, 1985). Other summary statistics were converted to mean and SD (Wan et al., 2014) and data on multiple groups combined to provide overall statistics (Goon et al., 1968) prior to calculating ES (Supplementary Method 2).

ES data were presented as ES±95% CI where a positive ES was an increase in the variable due to surgery, except measures of balance where an improved balance performance, shown as a reduction in centre of pressure (CoP) length, was presented as a positive ES. As the research question of this review often differed from the identified articles, information on the statistical significance was unavailable. Therefore, where the CIs of ES did not cross zero, these effects were viewed as significant (Hedges & Olkin, 1985), and presented in bold.

2.5 Methodological assessment

Methodological quality was assessed using a custom assessment tool, adapted from Cochrane Collaboration's tool for assessing risk of bias (Higgins et al., 2011), and The Effective Public Practice Health Project: Quality Assessment Tool for Quantitative Studies (Armijo-Olivo et al., 2012; Thomas et al., 2004), to detect risk of bias present in a one group pretest-posttest experimental research (Supplementary Method 3).

3. Results

3.1 Study selection

Excluding duplicates, the literature search identified 1365 articles. Of these, 54 were found to meet the inclusion criteria and no further articles were identified through searches of reference lists (Figure 1). Data on the performance of gait (n=31), balance (n=12), joint position sense (n=5), stair ambulation (n=4), pivoting (n=6), and landing (n=5) were identified. As the biomechanical demands of the knee differ depending on the task that is performed, articles were categorised by the analysed movement. Where data on more than one movement were presented, the article was considered separately for each task.

*****************************INSERT-FIGURE-1*****************************

3.2 Gait

Thirty-one articles assessed gait biomechanics however, eight articles were not included due to duplicate (DeVita et al., 1996; Ferber, 2001; Hartigan, 2009; Knoll et al., 2004a; Tagesson & Kvist, 2016; Tagesson et al., 2015) or unavailable data (Azus et al., 2017; Laforest et al., 2017), resulting in 23 articles undergoing analysis (Table 1). Kinematic outcome measures such as joint excursions and tibial translation were the most commonly reported data (Table 1). Spectral differential entropy, a method of quantifying movement variability, were presented in one study (Tsivgoulis et al., 2011). Kinetics and muscle activation formed the other outcome measures.

*****************************INSERT-TABLE-1*****************************

Knee range of motion (RoM) during gait appeared to increase following reconstruction, supported by large ESs for increased knee flexion excursion at 24 (**0.97±0.46**) and 48 weeks post operation (**3.40±3.06**; Favre et al., 2006; Majewska et al., 2017). Additionally, significant medium to large effects for increased minimum and maximum knee flexion angle at 16, 32, and 48 weeks post operation (Knoll et al., 2004b) were identified. Greater sagittal joint RoMs may show a greater use of the involved limb during gait.

Kinematic changes during the stance and swing phases of gait were less consistent. There were no significant differences in knee excursion during stance (24 weeks: −0.10±0.44, 0.29±0.64; 48 weeks: 0.34±0.49; Asaeda et al., 2017; Di Stasi et al., 2015; Roewer et al., 2011). Medium and large increases in peak knee flexion angle were observed during weight acceptance of stance (24 weeks: 0.15±0.54, **0.66±0.50**; 48 weeks: **0.80±0.31**; Roewer et al., 2011; Teng et al., 2017). Average knee angle data demonstrated mostly non-significant differences with a significantly more flexed position three weeks post-surgery being the exception (Devita et al., 1997; Ferber et al., 2004; Shabani et al., 2015). These ESs suggest that although in some patients a greater RoM is achieved after reconstructive surgery the kinematic changes may not be present in all populations.

One objective of reconstructive surgery is to restore the anterior stability of the knee; however, a significant decrease during stance, significant increase at heel strike and no change over a full stride in tibial translation were identified compared to pre-operative values with small to large effects (Beard et al., 2001; Tagesson et al., 2010). Average tibial anteroposterior position was also found to be the same during stance (0.33±0.37), and swing (0.37±0.37) phases at 40 weeks post-surgery (Shabani et al., 2015), questioning the success of surgery to restore anterior tibial stability during walking. Further evidence for the failure of ACL reconstruction to change mechanical stability during gait is shown by no differences in tibial rotation (24 weeks: 0.19±0.69; 48 weeks: 0.00±0.49 & 0.60±2.00; Asaeda et al., 2017; Claes et al., 2011; Favre et al., 2006) or abduction excursion (0.69±2.00; Favre et al., 2006) after surgery. These findings should only be considered in the context of walking gait where the relatively low external forces may insufficient to fully capture the instability of the ACL deficient knee.

Acute reductions in knee extensor impulse were present five (**−1.39±1.03**) weeks post-surgery (Devita et al., 1997), and despite only one significant difference, knee extension moment was greater compared to pre-operative values (Figure 2) in all investigations. Increased quadriceps force may result in greater shear forces and therefore strain on the ACL, however identified electromyography (EMG) data suggests that this may be mitigated by increased hamstring activation (**0.85±0.66**) providing eccentric control (Tagesson et al., 2010). Hip kinetics did not show clear changes related to funcitonal capacity with no significant difference in hip flexion moment (0.06-0.33; Wellsandt et al., 2017), or hip extension moment during stance (−0.35-−0.53; Wellsandt et al., 2017).

*****************************INSERT-FIGURE-2*****************************

Data on the frontal plane kinetics of the knee were also available however all ESs were non-significant, and no clear trend was present. Medial compartment tibial forces also did not alter due to ACL reconstruction with non-significant negligible to small ESs ($-0.06 \le d \le 0.34$) identified at 24 and 48 weeks post-surgery for peak tibial medial compartment contact forces (Gardinier et al., 2012; Manal & Buchanan, 2013; Wellsandt et al., 2016).

Data from force and pressure platforms were available in three articles (Mittlmeier et al., 1999; Moya-Angeler et al., 2017; Teng et al., 2017). Maximum vertical force was shown to be significantly reduced at heel strike (12 weeks: **−1.04±0.35**; 24 weeks: **−1.65±0.38**; 48 weeks: **−1.29±0.36**) and during stance (12 weeks: **−1.45±0.37**; 24 weeks: **−2.52±0.44**; 48 weeks: **−1.06±0.35**). However, another article found no changes in vertical force when extracted between initial contact and peak knee flexion (24 weeks: 0.20±0.48; 48 weeks: 0.28±0.48). A small ES was also found for reductions in anterior force during stance (48 weeks: **−0.42±0.33**). Posterior force also showed changes with medium to large effects with a medium increase at 24 weeks (**0.75±0.34**) and a large decrease at 48 weeks (**−1.46±0.37**) post-surgery. Data on vertical impulse as both a percentage of the uninjured limb and an absolute value were available. Relative impulse appeared to remain unchanged (6 weeks: −0.16±0.88; 12 weeks: 0.60±0.90; 24 weeks: 0.65±0.90) after reconstructive surgery. In contrast, absolute impulse showed medium to large effects for decreased values at 12 (**−0.57±0.34**), 24 (**−1.82±0.39**), and 48 (**−1.03±0.35**) weeks post-surgery. No clear functional outcomes appeared to be supported through analysis of the force data.

One article investigated the regularity of the mediolateral and anteroposterior movement of the pelvis through spectral differential entropy (Tsivgoulis et al., 2011). A lower value represents a more regular signal. In both axes of movement, regularity was increased from pre- to post-surgery (23-36 weeks) with large and medium ESs, respectively (mediolateral: **1.07±0.34**; anteroposterior: **0.71±0.33**).

3.3. Balance tasks

Twelve articles analysed balance tasks however, four articles were excluded for duplicate or unavailable data (Di Stasi, 2011; Kim & Park, 2009; Tagesson & Kvist, 2016; Tagesson et al., 2015), resulting in eight articles being included in the analysis (Table 2). Analysis of the CoP was used to assess balance performance in six articles. Knee kinematics and muscle activations made up the remaining outcomes (Table 2). Task constraints included unilateral or bilateral stance, eyes opened or closed, and static and dynamic balance.

*****************************INSERT-TABLE-2*****************************

Data supported an improvement in single leg static balance performance at 24 and 48 weeks post-surgery with significant medium to large ESs (Figure 3) (Heijne & Werner, 2007; Ma et al., 2014; Ogrodzka-Ciechanowicz et al., 2018). A medium effect (**0.53±0.37**) was also found for improvements in dynamic balance 12 weeks after surgery (Tuğcu et al., 2013). These data support that after ACL reconstruction and rehabilitation proprioceptive systems recover to above pre-operative levels. Data on the performance of bilateral balance (Bartel et al., 2019; Gokalp et al., 2016) revealed a drop in performance at 4 (**−1.24±0.55**) weeks post-surgery, before improving to above pre-surgery values (**0.46±0.38**; **0.75±0.52**) at 12 weeks. This highlights the importance of adequate post-operative rehabilitation in the successful restoration of proprioceptive function.

*****************************INSERT-FIGURE-3*****************************

Muscle activations also supported improvements in neuromuscular function after reconstructive surgery with greater activity identified in the hamstring (**1.04±0.64**) and gastrocnemius (**0.69±0.62**), and no changes in the soleus (0.41±0.61), vastus medialis (0.42±0.61) or vastus lateralis (0.45±0.61) five weeks after surgery (Tagesson et al., 2010). No significant changes in the position of the tibia and angle of the knee during stance (Di Stasi et al., 2012), suggested no changes in structural stability during balance tasks resulted from surgery. This result is possibly due to the external stresses associated with the task being mitigated by muscular mechanisms, reducing signs of structural laxity (Papadonikolakis et al., 2003).

3.4 Joint Position Sense

Five articles were identified that explored joint position sense, however a measure of variance was not present in two articles (Reider et al., 2003; Shidahara et al., 2011), resulting in three articles being analysed (Table 2). Outcome variables were threshold for detection of passive movement, and passive and active recall. All data collections were conducted using an isokinetic dynamometer. Differences in movement directions and angular velocities used were present between the articles (Table 2).

Large positive ESs were found for joint position sense at 16, 20, and 24 weeks post-surgery compared to pre-surgery values (Jurevičienė et al., 2012; Ordahan et al., 2015; Figure 4), supporting that proprioceptive function of the knee was improved after reconstructive surgery. Increasing positive effects of threshold to detect passive motion data also supported improved proprioceptive function after surgery, and the role of rehabilitation after treatment (Ma et al., 2014; 24 weeks: extension 0.33±0.34; flexion **0.68±0.35**; 48 weeks: extension **0.47±0.34**; flexion **1.09±0.36**).

*****************************INSERT-FIGURE-4*****************************

3.5 Stair ambulation

Six articles analysed stair walking biomechanics, however no usable data could be accessed for two of these (Isaac et al., 2005; McGrath et al., 2017) resulting in four included studies (Table 3). Kinematic and kinetic data on both stair ascent and descent were available. Two articles used a single surgical method, with the other articles using a combination of either graft locations or number of bundles (Table 3).

*****************************INSERT-TABLE-3*****************************

No significant changes in Knee RoM during stair ascent or descent following surgery (Table 4) were identified. Data did not support a restoration of structural stability during stair ambulation with no changes in knee frontal plane excursion or tibial rotation (Claes et al., 2011). These findings may have resulted from the external forces associated with the task not revealing the instabilities in the ACL deficient knee.

*****************************INSERT-TABLE-4*****************************

Joint kinetics did not appear to support any clear functional improvements in stair ambulation. Peak hip moment during stair descent reduced after surgery (hip: **−0.73±0.64**; Lepley et al., 2016) with no changes during ascent in the hip extensor moment (24 weeks: 0.48±1.06; 28 weeks: −0.50±0.63). Additionally, a large significant decrease in the knee extensor moment (Kowalk et al., 1997; Lepley et al., 2016) was identified. Frontal plane kinetics had non-significant small and negligible ESs for peak knee abduction moment during descent and ascent, respectively.

3.6 Pivot tasks

Changes in lower limb biomechanics during a dynamic cutting task were assessed in six articles (Table 3) however, two pairs of articles were considered together due to duplicate methodology (Lam et al., 2010, 2011; Smale et al., 2019a, 2019b). Tibial rotation, collected using motion capture, during a pivot tasks was the outcome for all but one article, which analysed dynamic joint stiffness (Table 3).

Data supported that ACL reconstruction is able to increase rotation stability of the tibia during a pivot task. Rotational excursion of the tibia relative to the femur was found to be the same 24 weeks post-surgery (−0.33±0.70; Claes et al., 2011) and significantly decrease 41 weeks post-surgery (**−0.97±0.93**; Lam et al., 2011). This finding further supports the conclusion that changes in mechanical stability may only be identified in tasks associated with large external forces. Joint stiffness did not significantly alter due to reconstructive surgery (0.63±0.69; Smale et al., 2019a)

3.7 Hop landing

Five articles were identified that assessed lower limb biomechanics during a hop landing. One article was excluded from analysis as no data were presented (Letchford et al., 2016), and two articles were considered together due to reporting the same study, meaning three articles were included (Table 3). Landing was analysed in all articles however, two were during a horizontal hop and the other during a vertical drop (Table 3). No outcome variables were present in both articles.

Data showed an initial reduction in task performance with a decrease in knee extension moment at 24 weeks post-surgery (**−1.76±0.77**), before increasing at 48 weeks (**1.12±0.70**). This pattern was not seen in knee stiffness (0.00±0.65; Smale et al., 2019a) or knee abduction moment with no changes at either 24 (−0.33±0.66) or 48 (−0.38±0.66) weeks post-surgery. Structural stability of the knee appeared to be restored during landing with reduced tibial rotation (24 weeks: **−1.91±0.79**; 48 weeks: **−1.48±0.74**), and a decrease in anterior tibial translation (24 weeks: **−1.99±0.80**; 48 weeks: **−1.60±0.75**). Muscle response time was shown to significantly decrease in the quadriceps and hamstring muscles (semitendinosus 24 weeks: **−0.92±0.61**; 48 weeks: **−0.98±0.61**; rectus femoris 24 weeks: **−0.67±0.59**; 48 weeks: **−0.80±0.60**), suggesting ACL reconstruction and rehabilitation had positive effects on the neuromuscular control during landing.

3.8 Risk of bias

Quality assessment identified that few articles had a low risk of bias (low=5; moderate=22; high=12), with the most common causes of a weak rating being failure to report participant retention details and inconsistent surgical procedure and timing. Where articles presented results on separate groups undergoing surgery, data were combined, and therefore the methods of this review were the cause for certain risks of bias. Full results of the quality assessment are provided in Table 5.

*****************************INSERT-TABLE-5*****************************

4.0 Discussion

The aim of this review was to systematically synthesise literature that has explored the changes to pre-operative lower limb biomechanics following ACL reconstructive surgery and rehabilitation. Changes in the biomechanics of balance, joint position sense, gait, stair ambulation, pivoting, and hop landings were identified after ACL reconstruction. Restoration of the mechanical role of the ACL through reconstruction was only evidenced in certain tasks by reductions in tibial movement. Proprioceptive function increased with improvements in balance performance, joint position sense, and muscle response time. Findings for other biomechanical variables such as joint moments and angles were inconsistent, potentially as a result of errors associated with low methodological quality of some of the articles or individual biomechanics responses to ACL reconstruction.

Quality ratings identified that a moderate risk of bias was present in most articles. Failure to report information on participant retention, differences in surgical approach, and inconsistent intervention timings were the most common reasons for weak ratings. Where participant retention is poor or not reported, there is a risk of data only showing participants that were capable of completing the movement, and therefore a risk of bias towards more favourable outcomes. Articles often presented data on separate groups undergoing ACL reconstruction through different techniques. The methods of this review combined these data to provide an overall effect of surgery however; this resulted in inconsistent interventions and therefore a risk of bias. Therefore, the risks of bias should only be considered in relation to the question posed by this review, and may be one cause of the differing results identified in a number of biomechanical variables.

Measures of proprioceptive function assessed through balance and joint position sense provided the most consistent results. These data support that, despite not restoring the lost mechanoreceptors (Dhillon et al., 2012), proprioceptive function appears to improve after ACL reconstruction to greater levels than prior to surgery.

Increasing ESs with time since surgery (Figure 2) also suggest that proprioceptive recovery continues up to at least 48 weeks post-surgery.

Kinematic and kinetic variables did not present any clear changes after ACL reconstruction except for an increase in sagittal plane knee RoM, and an acute reduction and subsequent increase in knee extensor moment. These findings may be due to individual coping strategies that have been previously identified in ACL injured participants (Alkjær et al., 2002), however as there were no data on individual responses this hypothesis is purely theoretical. Data did not fully support that ACL reconstruction restored the mechanical stability of the knee. Reduced tibial translation and rotation were identified in some movements due to reconstruction however; this was not universal across all tasks. In tasks involving lower external forces (e.g. gait) it may be that the errors associated with the calculation of such variables were greater than the resulting movement of the tibia (Cappozzo et al, 1996). In contrast, tasks such as pivoting and landing, where reduced tibial movement was identified, are associated with greater external forces and therefore may have allowed identification of instability in the ACL deficient limb.

The findings of this review show that lower limb biomechanics of certain movement tasks change after ACL reconstruction. Proprioception was consistently found to improve, whereas kinematic and kinetic variables appeared to demonstrate different coping strategies between participants. A limitation of the presented review and identified research exploring changes due to surgery is the failure to include a true control comparison. As no data were included on ACL deficient patients not undergoing surgery, the presented findings cannot be fully attributed to ACL reconstruction. Where the time between injury and reconstruction is high this limitation is mitigated as adaptations that occur without treatment would have already manifested and therefore the changes can be more confidently explained by the surgical intervention. Future experimental research should look to ensure methodological quality is high and include intra-participant analyses to explore whether individual responses are present. Additionally, clinical practitioners should be aware of the potential variability in responses to reconstruction when making treatment decisions. Risk of bias assessments highlighted that reporting of participant retention was low resulting in a risk of data representing participants who had more favourable treatment outcomes, and therefore should be included in future articles.

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Table 1. Experimental procedures of research assessing the effect of ACL reconstruction on walking gait

	Participant Information	Time Since Injury (Mean±SD weeks)	Graft Details	Post-Test Timings (weeks)	Outcome Measures
Asaeda et al. (2017)	n = 32 height: 1.66±0.09 m mass: 65±12 kg	64.4±171.1	SB, SBA or DB HA	48	Excursion of tibia rotation and knee flexion during stance; and peak internal knee extension and external adduction moment
Beard et al. (2001)	n = 11	188.0±120.0	SB HA (n=6) and SB BPB (n=5)	25	Patella tendon angle (a measure of tibial translation); during stance; at heel strike; and the average during gait cycle
Claes et al. (2011)	n = 16	144.0±92.0	SB (n=8) or DB (n=8) HA	24	Excursion of tibia rotation during the gait cycle
Devita et al. (1997)	n = 9 mass: 76 kg	2	SB BPB	3 & 5	Average knee and hip angle during stance; average knee and hip extensor impulse during stance; negative work at the knee; and positive work at the knee and hip
Di Stasi et al. (2015)	n = 39	11.1±10.1	SB HA or SB allograft	24	Average knee and hip angle during stance; and average knee and hip extensor impulse during stance
Favre et al. (2006)	n = 2 height: 1.90±0.00 m mass: 82±5 kg	30.0±22.0	SB BPB	48	Knee flexion, rotation, and abduction excursion during one gait cycle
Ferber et al. (2004)	n = 10 height: 1.66±0.20 m mass: 79±13 kg	273.6±244.8	SB BPB	12	Average knee and hip angle during stance; knee and hip extensor impulse during stance; and knee and hip work during stance
Gardinier (2013)	n = 13 height: 1.74±0.10 m mass: 79±14 kg	8.9±4.4	SB HA or SB allograft	24	Estimated peak tibiofemoral contact force during stance; and estimated peak medial compartment contact force during stance
Hartigan et al. (2009)	n = 19	11.3±11.3	SB HA or SB allograft	24	Knee flexion excursion during mid-stance
Hartigan et al. (2012)	n = 38	8.9±8.5	SB HA or SB allograft	24	Knee flexion moment at peak flexion
Knoll et al. (2004b)	n = 25 height: 1.77±0.80 m mass: 84±9 kg	81.7	SB BTB	6, 16,32, & 48	Peak knee extension and flexion angle
Kumar et al. (2018)	n = 37	7.0±3.0	SB HA (n=27), or allograft (n=10)	24 & 48	Knee adduction moment impulse; and peak knee adduction moment and angle
Majewska et al. (2017)	n = 40	NR	SB HA	24	Hip, knee, and ankle excursion in the sagittal plane during a gait cycle
Mittlmeier et al. (1999)	n = 10 height: 1.70 m mass: 76 kg	NR	SB BPB	6, 12, & 24	Total impulse as a percentage of the uninvolved limb, relative heel loading as a percentage of total impulse
Moya-Angeler et al. (2017)	n = 71 mass: 86±2 kg	NR	SB HA	12, 24, & 48	Maximum vertical force at heel contact and during single leg stance; vertical impulse; and maximum anterior and posterior force

Robbins et al. (2011)	n = 1 height: 1.58 m mass: 76 kg	16	SB HA	6, 12, 24, & 36	Knee flexion, extension, and excursion angle during mid-stance; peak knee flexion and extension moment during mid-stance; and peak knee adduction moment and impulse
Roewer et al. (2011)	n = 26	NR	SB HA or SB allograft	24	Peak knee flexion angle, and joint excursion during weight acceptance; and internal hip and knee extensor moments at peak knee flexion
Shabani et al. (2015)	n = 15 height: 1.72±0.09 m mass: 71±14 kg	18.8±17.2	SB BPB	40	Average knee angle in the sagittal, axial and frontal planes during the stance and swings phases; and average anteroposterior translation of the tibia during the stance and swing phases
Tagesson et al. (2010)	n = 19	60	QB HA	5	Maximum anterior tibial translation; and peak EMG activation of the vastus medialis, vastus lateralis, hamstring, gastrocnemius, and soleus during stance
Teng et al. (2017)	n = 33	8.1±6.0	SB HA (n=23) or SB allograft (n=10)	24 &48	Peak knee flexion angle and moment between first contact to the first knee flexion angle peak; and peak vertical ground reaction force between first contact to the first knee flexion angle peak
Tsivgoulis et al. (2011)	n = 20 height: 1.77±0.07 m mass: 82±11 kg	≤8	DB HA	Range 24 - 36	Spectral differential entropy (a measure of variability) of pelvis movement in the anteroposterior and mediolateral axes
Wellsandt et al. (2016)	n = 22	≤28	QB HA or SB allograft	24 & 48	Peak external knee flexion and adduction moment; knee adduction impulse during stance; and estimated peak medial compartment contact force during stance
Wellsandt et al. (2017)	n = 19 mass: 85±16 kg	14.3±10.3	QB HA or SB allograft	24	Peak hip extension, and flexion angle and moment during stance; peak hip adduction angle and moment during the first half of stance; and hip excursion during stance

Single bundle (SB), single bundle augmentation (SBA), double bundle (DB), quadruple bundle (QB), hamstring autograft (HA), bone patella bone autograft (BPB), not reported (NR), electromyography (EMG)

Table 2. Experimental procedures of research assessing the effect of ACL reconstruction on balance and joint position sense tasks

	Participant Information	Time Since Injury (Mean±SD weeks)	Graft Details	Post-Test Timings (weeks)	Task Analysed	Outcome Measures
Balance						
Bartels et al. (2019)	n = 54 height: 1.77±0.10 m mass: 80±17 kg	15.9±16.9	QB HA	6 & 12	Double leg static balance with eyes open and closed, on hard and soft ground	Stability index calculated from fluctuations in the CoP
Di Stasi et al. (2012)	n = 40	11.2±10.2	QB HA (n=16) or SB allograft (n=24)	24	Single leg static balance with eyes open	Knee flexion angle and anterior tibia position
Gokalp et al. (2016)	n = 30	26.8±18.4	SB BPB	4, 8, & 12	Double leg static balance with eyes open and closed, on hard and soft ground	Stability index combining scores from all conditions
Heijne and Werner (2007)	n = 68 height: 1.74±0.08 m mass: 74±11 kg	34 (SD NR)	SB BPB (n=34) or HA (n=34)	12 & 20	Single leg static balance with eyes open	Summation of distance between origin and CoP
Ma et al. (2014)	n = 67 height: 1.67±0.02 m mass: 65±3 kg	18.6±8.3	SB (n=20), SBA (n=21), or DB (n=26) HA	24	Single leg static balance with eyes closed	CoP path length
Ogrodzka-Ciechanowicz et al. (2018)	n = 31 height: 1.75±0.08 m	NR	SB HA	24	Single leg static balance with eyes open	CoP path length
Tagesson et al. (2010)	n = 19	60 (SD NR)	QB HA	5	Single leg static balance with eyes open	Maximum anterior tibial translation and peak EMG activation of the lower limb muscles
Tuğcu et al. (2013)	n = 58	Median=15.8	BPB	13	Single leg static and dynamic balance with eyes open	Stability index calculated from fluctuations in balance board
Joint Position Sense						
Jurevičienė et al. (2012)	n = 15 height: 1.78±0.03 m mass: 79±4 kg	NR	SB HA	16 & 24	Knee angle recall during passive flexion and extension at 2 and 10 deg·s^{-1}	Error between target angle and recall value
Ma et al. (2014)	n = 30 height: 1.67±0.02 m mass: 65±3 kg	18.6±8.3	SB (n=20), SBA (n=21), or DB (n=26) HA	24	Knee passively extended or flexed at 0.2 deg·s^{-1} from an angle of 45 deg	Time from initialisation of movement to time of detection
Ordahan et al. (2015)	n = 20	59.6 (SD NR)	HA	24	Knee angle recall during active flexion and extension	Error between target angle and recall value

Single bundle (SB), single bundle augmentation (SBA), double bundle (DB), quadruple bundle (QB), hamstring autograft (HA), bone patella bone autograft (BPB), centre of pressure (CoP), not reported (NR), electromyography (EMG)

Table 3. Experimental procedures of research assessing the effect of ACL reconstruction on pivot, stair ambulation, and hop landing tasks

	Participant Information	Time Since Injury (Mean±SD weeks)	Graft Details	Post-Test Timings (Mean±SD weeks)	Task Analysed	Outcome Measures
Pivot						
Claes et al. (2011)	n = 16	144.0±92.0	SB (n=8) or DB (n=8) HA	24	Step down and 90 deg pivot on affected limb	Rotational excursion of the tibia
Hemmerich et al. (2011)	n = 17 height:1.74±0.08 m mass: 82±14 kg	27.6±41.6	SB (n=9) or DB (n=8) HA	18.4±6.4	90 deg cut whilst jogging	Maximum internal and external tibial rotation of the inside and outside limb
Lam et al. (2011)	n = 10 height: 1.76±0.10 m mass: 69±9 kg	41.2±15.6	DB HA	41.2±15.6	Two footed drop landing followed by immediate 90° pivot on affected limb	Rotational excursion of the tibia
Smale et al. (2019)	n = 17	50.0±74.8	DB HA (n=15), BTB (n=2), Achilles allograft (n=1), or iliotibial band autograft (n=1)	42±7	45 deg cut whilst jogging	Dynamic knee stiffness
Stair Ambulation						
Claes et al. (2011)	n = 16	144.0±92.0	SB (n=8) or DB (n=8) HA	24	Stair descent (rise: 25 cm)	Rotational excursion of the tibia
Kowalk et al. (1997)	n = 7 mass: 90 kg	NR	SB BPB	24.0 (range: 12.8-45.2)	Stair ascent (rise: 23 cm; run 25 cm)	Sagittal hip, knee, and ankle excursion; peak internal hip and knee extensor, and ankle plantar flexor moment; peak hip, knee, and ankle power; and hip, knee, and ankle work
Lepley et al. (2016)	n = 20 height: 1.72±0.08 m mass: 76±12 kg	5.3±2.2	SB HA (n=9) or BPB (n=11)	28.3±2.9	Stair ascent and descent (rise: 17 cm; run 25 cm)	Knee and hip flexion and abduction angle at initial contact, peak during stance, and excursion during one gait cycle; and peak internal knee and hip extension and adduction moment
Mittlmeier et al. (1999)	n = 10 height: 1.70 m mass: 76 kg	NR	SB BPB	6, 12, & 24	Stair descent (rise: 17 cm; run 33 cm)	Total impulse as a percentage of the uninvolved limb
Hopping						

Oberländer et al. (2014)	n = 18 height: 1.80±0.08 m mass: 85±12 kg	Range: 12-24	QB HA	24 & 48	Single leg hop for a given distance (0.75 × height)	Peak internal knee extension and abduction, ankle plantar flexion moments; average tibial rotation; and maximum anterior tibial translation
Oliver et al. (2019)	n = 23 height: 1.78±0.08 m mass: 71±11 kg	Range: 8-12	SB BPB	16 & 24	Hop landing from a height of 25 cm	Response time from landing to peak activation of lower limb muscles
Smale et al. (2019)	n = 17	50.0±74.8	DB HA (n=15), BTB (n=2), Achilles allograft (n=1), or iliotibial band autograft (n=1)	42±7	Hop landing during a self-selected distance jump	Dynamic knee stiffness

Single bundle (SB), double bundle (DB), quadruple bundle (QB), hamstring autograft (HA), bone patella bone autograft (BPB), not reported (NR)

Table 4. Cohen's *d* effect sizes (ES) and 95% confidence intervals (95%CI) of kinematic changes during stair ascent and descent due to anterior cruciate ligament reconstruction

	Ascent (ES±95%CI)	**Descent (ES±95%CI)**
Sagittal hip excursion	0.95±1.11[b]	0.18±0.62[c]
	−0.36±0.62[c]	
Hip extension angle at IC	−0.30±0.62[c]	−0.11±0.62[c]
Peak hip extension angle	0.26±0.62[c]	0.20±0.62[c]
Frontal hip excursion	0.03±0.62[c]	0.21±0.62[c]
Hip abduction angle at IC	−0.24±0.62[c]	0.23±0.62[c]
Peak hip adduction angle	0.27±0.62[c]	−0.36±0.62[c]
Sagittal knee excursion	0.61±1.07[b]	−0.13±0.62[c]
	0.01±0.62[c]	
Knee flexion angle at IC	0.04±0.62[c]	−0.03±0.62[c]
Peak knee flexion angle	−0.31±0.62	−0.13±0.62
Frontal knee excursion	0.31±0.62	0.32±0.62
Knee abduction angle at IC	0.01±0.62	0.29±0.62
Peak knee abduction angle	0.15±0.62	0.06±0.62
Tibial rotation excursion		−0.23±0.70[a]
Sagittal ankle excursion	−0.62±1.07[b]	

[a]Claes et al. (2011); [b]Kowalk et al. (1997); [c]Lepley et al. (2016). Initial contact (IC)

Table 5. Assessment of quality of analysed studies (excluding articles with repeated data) exploring changes in lower limb biomechanics due to ACL reconstruction

	Participants	Withdrawals	Study design	Intervention integrity	Data collection	Overall rating
Asaeda et al. (2017)	1	3	1	1	1	2
Bartels et al. (2019)	1	2	3	1	1	2
Beard et al. (2001)	1	3	1	3	1	3
Claes et al. (2011)	1	1	1	3	1	2
Devita et al. (1997)	1	3	1	1	1	2
Di Stasi et al. (2012)	1	2	1	3	1	2
Di Stasi et al. (2015)	1	3	1	3	1	3
Favre et al. (2006)	2	3	1	1	1	2
Ferber et al. (2004)	1	3	1	1	1	2
Gardinier (2013)	1	2	1	3	1	2
Gokalp et al. (2016)	1	3	1	1	1	2
Hartigan et al. (2009)	1	3	1	3	1	3
Hartigan et al. (2012)	1	3	1	3	1	3
Heijne and Werner (2007)	1	1	1	1	1	1
Hemmerich et al. (2011)	1	1	2	3	1	2
Jurevičienė et al. (2012)	1	3	3	1	1	3
Knoll et al. (2004b)	1	3	3	1	1	3
Kowalk et al. (1997)	1	3	3	1	1	3
Kumar et al. (2018)	1	2	1	3	1	2
Lam et al. (2011)	1	1	2	1	1	1
Lepley et al. (2016)	1	1	2	3	1	2
Ma et al. (2014)	1	1	1	1	1	1
Majewska et al. (2017)	1	3	1	1	1	2
Mittlmeier et al. (1999)	1	3	3	1	1	3
Moya-Angeler et al. (2017)	1	1	1	1	1	1
Oberländer et al. (2014)	1	3	1	1	1	3
Ogrodzka-Ciechanowicz et al. (2018)	1	1	1	1	1	1
Oliver et al. (2019)	1	1	1	1	1	1
Ordahan et al. (2015)	1	3	1	1	1	2
Robbins et al. (2011)	3	1	1	1	1	2
Roewer et al. (2011)	1	3	3	3	1	3
Shabani et al. (2015)	1	3	1	1	1	2
Smale et al. (2019a)	1	3	3	3	1	3
Tagesson et al. (2010)	1	3	1	1	1	2
Teng et al. (2017)	1	2	1	3	1	2
Tsivgoulis et al. (2011)	1	3	3	1	1	3
Tuğcu et al. (2013)	2	3	1	1	1	2
Wellsandt et al. (2016)	1	2	1	3	1	2
Wellsandt et al. (2017)	1	1	1	3	1	2

1 = strong; 2 = moderate; 3 = weak

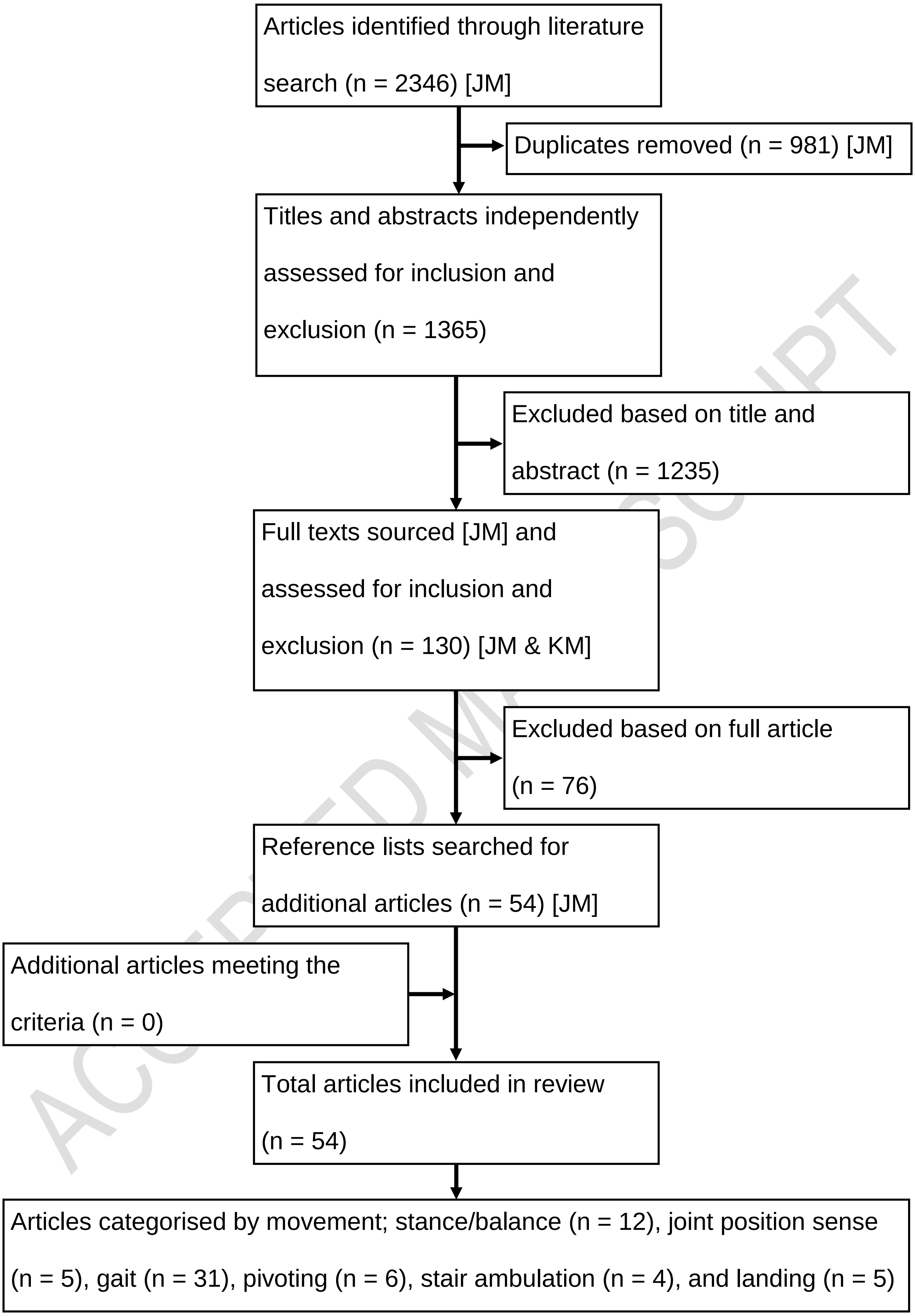
Articles identified through literature search (n = 2346) [JM]
Duplicates removed (n = 981) [JM]
Titles and abstracts independently assessed for inclusion and exclusion (n = 1365)
Excluded based on title and abstract (n = 1235)
Full texts sourced [JM] and assessed for inclusion and exclusion (n = 130) [JM & KM]
Excluded based on full article (n = 76)
Reference lists searched for additional articles (n = 54) [JM]
Additional articles meeting the criteria (n = 0)
Total articles included in review (n = 54)
Articles categorised by movement; stance/balance (n = 12), joint position sense (n = 5), gait (n = 31), pivoting (n = 6), stair ambulation (n = 4), and landing (n = 5)

Figure 1

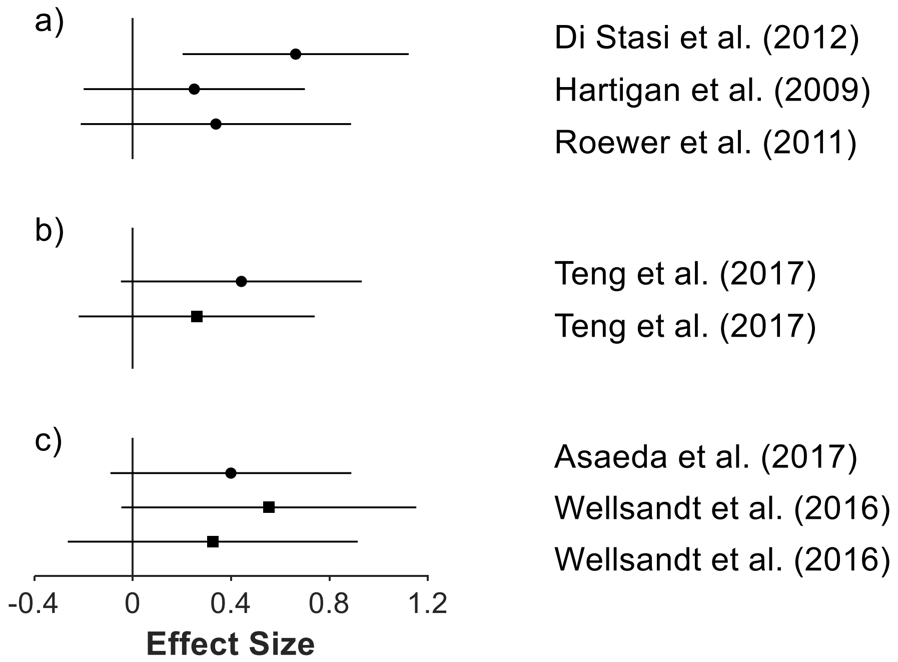
a)
Di Stasi et al. (2012)
Hartigan et al. (2009)
Roewer et al. (2011)
b)
Teng et al. (2017)
Teng et al. (2017)
c)
Asaeda et al. (2017)
Wellsandt et al. (2016)
Wellsandt et al. (2016)
-0.4
0
0.4
0.8
1.2
Effect Size

Figure 2

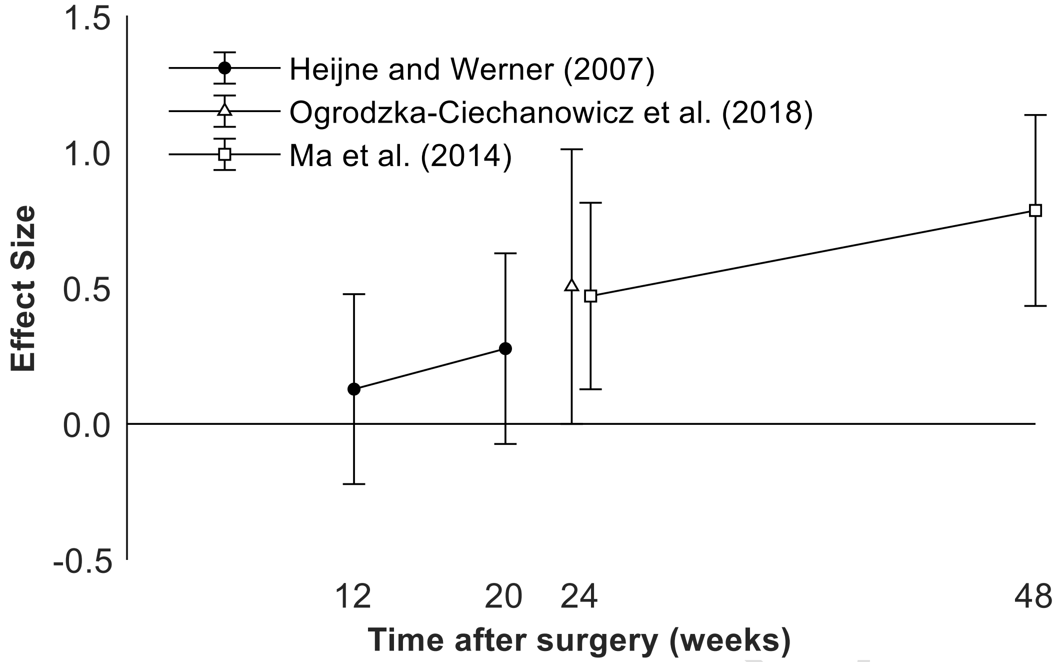
Heijne and Werner (2007)
Ogrodzka-Ciechanowicz et al. (2018)
Ma et al. (2014)
1.5
1.0
0.5
0.0
-0.5
Effect Size
12
20
24
48
Time after surgery (weeks)

Figure 3

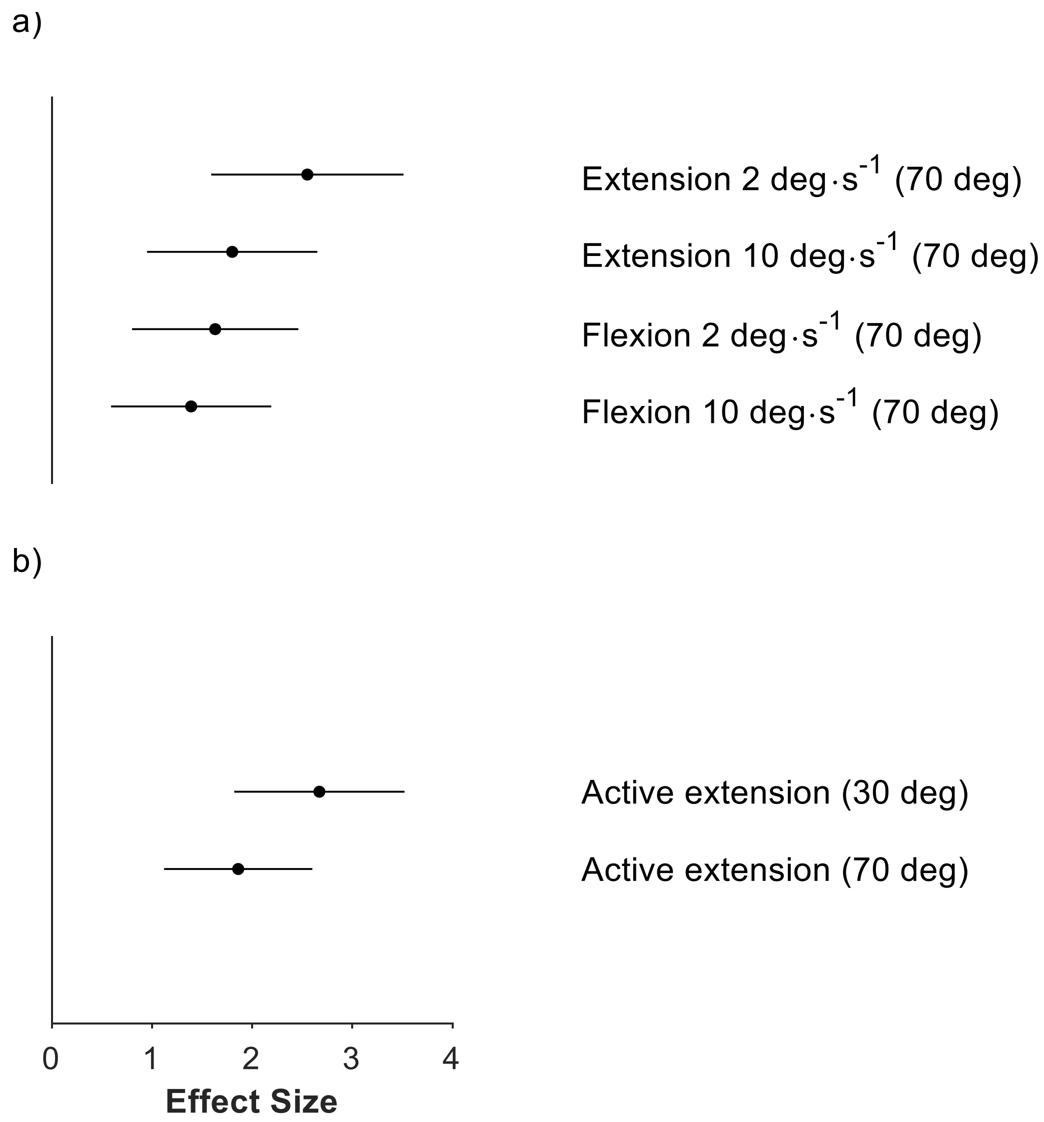
a)
Extension 2 deg·s-1 (70 deg)
Extension 10 deg·s-1 (70 deg)
Flexion 2 deg·s-1 (70 deg)
Flexion 10 deg·s-1 (70 deg)
b)
Active extension (30 deg)
Active extension (70 deg)
0
1
2
3
4
Effect Size

Figure 4

Figure 1. Flow diagram depicting the literature search. Where articles assessed more than one movement task (n = 7) they were included in both categories. Reviewers completing each task are shown in square brackets. There were no conflicts between reviewers in inclusion and exclusion decisions when reviewing full texts.

Figure 2. Forest plot of effect sizes and 95% confidence intervals for internal knee extension moment during gait at a) peak knee flexion angle during stance, b) maximum during initial stance, and c) maximum during stance at 24 (●) and 48 (■) weeks post ACL reconstruction.

Figure 3. Effect sizes and 95% confidence intervals for 3 studies measuring static balance performance comparing pre-surgery to post-surgery data, where positive effects were improvements.

Figure 4. Forest plot of effect sizes and 95% confidence intervals for data on a) passive (Jurevičienė et al., 2012) and b) active (Ordahan et al., 2015) knee joint position sense at 20 and 24 weeks post−surgery compared to pre−surgery values.