

1 Lower Limb Biomechanics Before and After Anterior Cruciate Ligament

2 Reconstruction: a Systematic Review

3

4 Joseph M. Moore, Kimberly Cessford, Alexander P. Willmott, Dipak Raj, Timothy A.

5 Exell, Jenny Burbage, David R. Mullineaux

6 PII: S0021-9290(20)30251-7

7 DOI: <https://doi.org/10.1016/j.jbiomech.2020.109828>

8 Reference: BM 109828

9 To appear in: Journal of Biomechanics

10 Accepted Date: 2 May 2020

11 Please cite this article as: J.M. Moore, K. Cessford, A.P. Willmott, D. Raj, T.A. Exell,

12 J. Burbage, D.R. Mullineaux, Lower Limb Biomechanics Before and After Anterior

13 Cruciate Ligament Reconstruction: a Systematic Review, Journal of Biomechanics

14 (2020), doi: <https://doi.org/10.1016/j.jbiomech.2020.109828>

15

1 **Submission Type:** Original Article

2 **Title:** Lower Limb Biomechanics Before and After Anterior Cruciate Ligament

3 Reconstruction: a Systematic Review

4 **Authors**

5 Joseph M. Moore¹, Kimberly Cessford^{1,2}, Alexander P. Willmott³, Dipak Raj⁴, Timothy

6 A. Exell¹, Jenny Burbage¹, and David R. Mullineaux³

7 School of Sport, Health and Exercise Science, University of Portsmouth, UK²

8 Department of Sport and Exercise Sciences, University of Chichester, UK²

9 School of Sport and Exercise Science, University of Lincoln, UK³

10 Department of Orthopaedics, Pilgrim Hospital, United Lincolnshire Hospitals NHS

11 Trust, UK⁴

12 **Corresponding Author**

13 Joseph M. Moore

14 School of Sport, Health and Exercise Science; University of Portsmouth

15 Spinnaker Building, Cambridge Road, Portsmouth, PO1 2ER

16 Email: joseph.moore@port.ac.uk Tel: +44 2392 846392 Fax: NA

17 **Word Count:** 3489 (abstract: 247)

18 **Key Words:** gait; balance; kinematics; kinetics

19 **Abstract**

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

43 1. Introduction

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

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

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

67 literature that has explored changes to pre-operative lower limb biomechanics
68 following ACL reconstructive surgery and rehabilitation.

69 **2. Methods**

70 *2.1 Search strategy*

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

79 *2.2 Inclusion and exclusion criteria*

80 After the removal of duplicates, the titles and abstracts of the identified articles were
81 independently assessed for inclusion and exclusion criteria by reviewers JM and KC.
82 Where data were duplicated in different articles (e.g. doctoral thesis and peer-
83 reviewed article) both sources were included at this stage and only excluded after
84 data analyses revealed no new information. Inclusion criteria were: human
85 participants with a ruptured ACL who underwent reconstructive surgery; data
86 collected within 12 weeks before and 52 weeks after surgery; and biomechanical
87 outcome measures. Exclusion criteria were: concurrent knee ligament injuries; knee
88 osteotomy; and isokinetic torque assessments. Isokinetic strength data were
89 excluded due to the existing body of evidence showing a clear link between strength
90 deficiencies and ACL reconstruction (Ardern & Webster, 2009; Petersen et al.,

91 2014). Where other biomechanical variables were present within an article assessing
92 isokinetic strength, these data were included. Where the inclusion and exclusion
93 criteria were met by at least one reviewer, full texts were independently screened
94 against the criteria. No conflicts between reviewers were encountered when
95 including articles based on full texts.

96 *2.3 Data extraction*

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

104 *2.4 Data analysis*

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

111 ES data were presented as $ES \pm 95\%$ CI where a positive ES was an increase in the
112 variable due to surgery, except measures of balance where an improved balance
113 performance, shown as a reduction in centre of pressure (CoP) length, was
114 presented as a positive ES. As the research question of this review often differed

115 from the identified articles, information on the statistical significance was unavailable.
116 Therefore, where the CIs of ES did not cross zero, these effects were viewed as
117 significant (Hedges & Olkin, 1985), and presented in bold.

118 *2.5 Methodological assessment*

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

125 **3. Results**

126 *3.1 Study selection*

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

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

136 *3.2 Gait*

137 Thirty-one articles assessed gait biomechanics however, eight articles were not
138 included due to duplicate (DeVita et al., 1996; Ferber, 2001; Hartigan, 2009; Knoll et
139 al., 2004a; Tagesson & Kvist, 2016; Tagesson et al., 2015) or unavailable data (Azus
140 et al., 2017; Laforest et al., 2017), resulting in 23 articles undergoing analysis (Table
141 1). Kinematic outcome measures such as joint excursions and tibial translation were
142 the most commonly reported data (Table 1). Spectral differential entropy, a method
143 of quantifying movement variability, were presented in one study (Tsigoulis et al.,
144 2011). Kinetics and muscle activation formed the other outcome measures.

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

146 Knee range of motion (RoM) during gait appeared to increase following
147 reconstruction, supported by large ESs for increased knee flexion excursion at 24
148 (**0.97±0.46**) and 48 weeks post operation (**3.40±3.06**; Favre et al., 2006; Majewska
149 et al., 2017). Additionally, significant medium to large effects for increased minimum
150 and maximum knee flexion angle at 16, 32, and 48 weeks post operation (Knoll et
151 al., 2004b) were identified. Greater sagittal joint RoMs may show a greater use of the
152 involved limb during gait.

153 Kinematic changes during the stance and swing phases of gait were less consistent.
154 There were no significant differences in knee excursion during stance (24 weeks:
155 -0.10 ± 0.44 , 0.29 ± 0.64 ; 48 weeks: 0.34 ± 0.49 ; Asaeda et al., 2017; Di Stasi et al.,
156 2015; Roewer et al., 2011). Medium and large increases in peak knee flexion angle
157 were observed during weight acceptance of stance (24 weeks: 0.15 ± 0.54 ,
158 **0.66±0.50**; 48 weeks: **0.80±0.31**; Roewer et al., 2011; Teng et al., 2017). Average
159 knee angle data demonstrated mostly non-significant differences with a significantly
160 more flexed position three weeks post-surgery being the exception (Devita et al.,

161 1997; Ferber et al., 2004; Shabani et al., 2015). These ESs suggest that although in
162 some patients a greater RoM is achieved after reconstructive surgery the kinematic
163 changes may not be present in all populations.

164 One objective of reconstructive surgery is to restore the anterior stability of the knee;
165 however, a significant decrease during stance, significant increase at heel strike and
166 no change over a full stride in tibial translation were identified compared to
167 pre-operative values with small to large effects (Beard et al., 2001; Tagesson et al.,
168 2010). Average tibial anteroposterior position was also found to be the same during
169 stance (0.33 ± 0.37), and swing (0.37 ± 0.37) phases at 40 weeks post-surgery
170 (Shabani et al., 2015), questioning the success of surgery to restore anterior tibial
171 stability during walking. Further evidence for the failure of ACL reconstruction to
172 change mechanical stability during gait is shown by no differences in tibial rotation
173 (24 weeks: 0.19 ± 0.69 ; 48 weeks: 0.00 ± 0.49 & 0.60 ± 2.00 ; Asaeda et al., 2017; Claes
174 et al., 2011; Favre et al., 2006) or abduction excursion (0.69 ± 2.00 ; Favre et al.,
175 2006) after surgery. These findings should only be considered in the context of
176 walking gait where the relatively low external forces may insufficient to fully capture
177 the instability of the ACL deficient knee.

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

186 moment (0.06-0.33; Wellsandt et al., 2017), or hip extension moment during stance
 187 (-0.35--0.53; Wellsandt et al., 2017).

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

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

195 Data from force and pressure platforms were available in three articles (Mittlmeier et
 196 al., 1999; Moya-Angeler et al., 2017; Teng et al., 2017). Maximum vertical force was
 197 shown to be significantly reduced at heel strike (12 weeks: -1.04 ± 0.35 ; 24 weeks:
 198 -1.65 ± 0.38 ; 48 weeks: -1.29 ± 0.36) and during stance (12 weeks: -1.45 ± 0.37 ; 24
 199 weeks: -2.52 ± 0.44 ; 48 weeks: -1.06 ± 0.35). However, another article found no
 200 changes in vertical force when extracted between initial contact and peak knee
 201 flexion (24 weeks: 0.20 ± 0.48 ; 48 weeks: 0.28 ± 0.48). A small ES was also found for
 202 reductions in anterior force during stance (48 weeks: -0.42 ± 0.33). Posterior force
 203 also showed changes with medium to large effects with a medium increase at 24
 204 weeks (0.75 ± 0.34) and a large decrease at 48 weeks (-1.46 ± 0.37) post-surgery.
 205 Data on vertical impulse as both a percentage of the uninjured limb and an absolute
 206 value were available. Relative impulse appeared to remain unchanged (6 weeks:
 207 -0.16 ± 0.88 ; 12 weeks: 0.60 ± 0.90 ; 24 weeks: 0.65 ± 0.90) after reconstructive surgery.
 208 In contrast, absolute impulse showed medium to large effects for decreased values
 209 at 12 (-0.57 ± 0.34), 24 (-1.82 ± 0.39), and 48 (-1.03 ± 0.35) weeks post-surgery. No

210 clear functional outcomes appeared to be supported through analysis of the force
211 data.

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

217 3.3. Balance tasks

218 Twelve articles analysed balance tasks however, four articles were excluded for
219 duplicate or unavailable data (Di Stasi, 2011; Kim & Park, 2009; Tagesson & Kvist,
220 2016; Tagesson et al., 2015), resulting in eight articles being included in the analysis
221 (Table 2). Analysis of the CoP was used to assess balance performance in six
222 articles. Knee kinematics and muscle activations made up the remaining outcomes
223 (Table 2). Task constraints included unilateral or bilateral stance, eyes opened or
224 closed, and static and dynamic balance.

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

226 Data supported an improvement in single leg static balance performance at 24 and
227 48 weeks post-surgery with significant medium to large ESs (Figure 3) (Heijne &
228 Werner, 2007; Ma et al., 2014; Ogrodzka-Ciechanowicz et al., 2018). A medium
229 effect (**0.53±0.37**) was also found for improvements in dynamic balance 12 weeks
230 after surgery (Tuğcu et al., 2013). These data support that after ACL reconstruction
231 and rehabilitation proprioceptive systems recover to above pre-operative levels. Data
232 on the performance of bilateral balance (Bartel et al., 2019; Gokalp et al., 2016)
233 revealed a drop in performance at 4 (**-1.24±0.55**) weeks post-surgery, before

234 improving to above pre-surgery values (**0.46±0.38; 0.75±0.52**) at 12 weeks. This
235 highlights the importance of adequate post-operative rehabilitation in the successful
236 restoration of proprioceptive function.

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

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

247 *3.4 Joint Position Sense*

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

255 Large positive ESs were found for joint position sense at 16, 20, and 24 weeks post-
256 surgery compared to pre-surgery values (Jurevičienė et al., 2012; Ordahan et al.,
257 2015; Figure 4), supporting that proprioceptive function of the knee was improved

258 after reconstructive surgery. Increasing positive effects of threshold to detect passive
259 motion data also supported improved proprioceptive function after surgery, and the
260 role of rehabilitation after treatment (Ma et al., 2014; 24 weeks: extension 0.33 ± 0.34 ;
261 flexion 0.68 ± 0.35 ; 48 weeks: extension 0.47 ± 0.34 ; flexion 1.09 ± 0.36).

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

263 3.5 Stair ambulation

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

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

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

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

277 Joint kinetics did not appear to support any clear functional improvements in stair
278 ambulation. Peak hip moment during stair descent reduced after surgery (hip:
279 -0.73 ± 0.64 ; Lepley et al., 2016) with no changes during ascent in the hip extensor
280 moment (24 weeks: 0.48 ± 1.06 ; 28 weeks: -0.50 ± 0.63). Additionally, a large

281 significant decrease in the knee extensor moment (Kowalk et al., 1997; Lepley et al.,
282 2016) was identified. Frontal plane kinetics had non-significant small and negligible
283 ESs for peak knee abduction moment during descent and ascent, respectively.

284 3.6 *Pivot tasks*

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

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

297 3.7 *Hop landing*

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

304 Data showed an initial reduction in task performance with a decrease in knee
305 extension moment at 24 weeks post-surgery (-1.76 ± 0.77), before increasing at 48
306 weeks (1.12 ± 0.70). This pattern was not seen in knee stiffness (0.00 ± 0.65 ; Smale et
307 al., 2019a) or knee abduction moment with no changes at either 24 (-0.33 ± 0.66) or
308 48 (-0.38 ± 0.66) weeks post-surgery. Structural stability of the knee appeared to be
309 restored during landing with reduced tibial rotation (24 weeks: -1.91 ± 0.79 ; 48 weeks:
310 -1.48 ± 0.74), and a decrease in anterior tibial translation (24 weeks: -1.99 ± 0.80 ; 48
311 weeks: -1.60 ± 0.75). Muscle response time was shown to significantly decrease in
312 the quadriceps and hamstring muscles (semitendinosus 24 weeks: -0.92 ± 0.61 ; 48
313 weeks: -0.98 ± 0.61 ; rectus femoris 24 weeks: -0.67 ± 0.59 ; 48 weeks: -0.80 ± 0.60),
314 suggesting ACL reconstruction and rehabilitation had positive effects on the
315 neuromuscular control during landing.

316 3.8 Risk of bias

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

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

324 4.0 Discussion

325 The aim of this review was to systematically synthesise literature that has explored
326 the changes to pre-operative lower limb biomechanics following ACL reconstructive
327 surgery and rehabilitation. Changes in the biomechanics of balance, joint position

328 sense, gait, stair ambulation, pivoting, and hop landings were identified after ACL
329 reconstruction. Restoration of the mechanical role of the ACL through reconstruction
330 was only evidenced in certain tasks by reductions in tibial movement. Proprioceptive
331 function increased with improvements in balance performance, joint position sense,
332 and muscle response time. Findings for other biomechanical variables such as joint
333 moments and angles were inconsistent, potentially as a result of errors associated
334 with low methodological quality of some of the articles or individual biomechanics
335 responses to ACL reconstruction.

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

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

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

354 Kinematic and kinetic variables did not present any clear changes after ACL
355 reconstruction except for an increase in sagittal plane knee RoM, and an acute
356 reduction and subsequent increase in knee extensor moment. These findings may
357 be due to individual coping strategies that have been previously identified in ACL
358 injured participants (Alkjær et al., 2002), however as there were no data on individual
359 responses this hypothesis is purely theoretical. Data did not fully support that ACL
360 reconstruction restored the mechanical stability of the knee. Reduced tibial
361 translation and rotation were identified in some movements due to reconstruction
362 however; this was not universal across all tasks. In tasks involving lower external
363 forces (e.g. gait) it may be that the errors associated with the calculation of such
364 variables were greater than the resulting movement of the tibia (Cappozzo et al,
365 1996). In contrast, tasks such as pivoting and landing, where reduced tibial
366 movement was identified, are associated with greater external forces and therefore
367 may have allowed identification of instability in the ACL deficient limb.

368 The findings of this review show that lower limb biomechanics of certain movement
369 tasks change after ACL reconstruction. Proprioception was consistently found to
370 improve, whereas kinematic and kinetic variables appeared to demonstrate different
371 coping strategies between participants. A limitation of the presented review and
372 identified research exploring changes due to surgery is the failure to include a true
373 control comparison. As no data were included on ACL deficient patients not
374 undergoing surgery, the presented findings cannot be fully attributed to ACL
375 reconstruction. Where the time between injury and reconstruction is high this
376 limitation is mitigated as adaptations that occur without treatment would have already

377 manifested and therefore the changes can be more confidently explained by the
378 surgical intervention. Future experimental research should look to ensure
379 methodological quality is high and include intra-participant analyses to explore
380 whether individual responses are present. Additionally, clinical practitioners should
381 be aware of the potential variability in responses to reconstruction when making
382 treatment decisions. Risk of bias assessments highlighted that reporting of
383 participant retention was low resulting in a risk of data representing participants who
384 had more favourable treatment outcomes, and therefore should be included in future
385 articles.

386 **References**

- 387 Alkjær, T., Simonsen, E.B., Magnusson, S.P., Aagaard, H., Dyhre-Poulsen, P., 2002.
388 Differences in the movement pattern of a forward lunge in two types of anterior
389 cruciate ligament deficient patients: copers and non-copers. *Clinical Biomechanics*
390 17, 586-593.
- 391 Ardern, C.L., Webster, K.E., 2009. Knee flexor strength recovery following hamstring
392 tendon harvest for anterior cruciate ligament reconstruction: a systematic review.
393 *Orthopedic Reviews* 1, 1-12.
- 394 Ardern, C.L., Webster, K.E., Taylor, N.F., Feller, J.A., 2011. Return to sport following
395 anterior cruciate ligament reconstruction surgery: a systematic review and meta-
396 analysis of the state of play. *British Journal of Sports Medicine* 45, 596-606.
- 397 Armijo-Olivo, S., Stiles, C.R., Hagen, N.A., Biondo, P.D., Cummings, G.G., 2012.
398 Assessment of study quality for systematic reviews: a comparison of the Cochrane
399 Collaboration Risk of Bias Tool and the Effective Public Health Practice Project
400 Quality Assessment Tool: Methodological research. *Journal of Evaluation in Clinical*
401 *Practice* 18, 12-18.
- 402 Asaeda, M., Deie, M., Fujita, N., Kono, Y., Terai, C., Kuwahara, W., Watanabe, H.,
403 Kimura, H., Adachi, N., Sunagawa, T., Ochi, M., 2017. Gender differences in the
404 restoration of knee joint biomechanics during gait after anterior cruciate ligament
405 reconstruction. *The Knee* 24, 280-288.
- 406 Azus, A., Teng, H.-L., Tufts, L., Wu, D., Ma, C.B., Souza, R.B., Li, X., 2017.
407 Biomechanical factors associated with pain and symptoms following anterior cruciate
408 ligament injury and reconstruction. *PM&R* 10, 56-63.

- 409 Barber, S.D., Noyes, F.R., Mangine, R.E., McCloskey, J.W., Hartman, W., 1990.
410 Quantitative assessment of functional limitations in normal and anterior cruciate
411 ligament-deficient knees. *Clinical Orthopaedics and Related Research* 255, 204-214.
- 412 Bartels, T., Brehme, K., Pyschik, M., Pollak, R., Schaffrath, N., Schulze, S., Delank,
413 K.-S., Laudner, K., Schwesig, R., 2019. Postural stability and regulation before and
414 after anterior cruciate ligament reconstruction - A two years longitudinal study.
415 *Physical Therapy in Sport* 38, 49-58.
- 416 Beard, D.J., Murray, D.W., Gill, H.S., Price, A.J., Rees, J.L., Alfaro-Adrián, J., Dodd,
417 C.A., 2001. Reconstruction does not reduce tibial translation in the cruciate-deficient
418 knee an in vivo study. *The Journal of Bone and Joint Surgery* 83, 1098-1103.
- 419 Cappozzo, A., Catani, F., Leardini, A., Benedetti, M. G., Della Croce, U., 1996.
420 Position and orientation in space of bones during movement: experimental artefacts.
421 *Clinical Biomechanics* 11, 90-100.
- 422 Claes, S., Neven, E., Callewaert, B., Desloovere, K., Bellemans, J., 2011. Tibial
423 rotation in single- and double-bundle ACL reconstruction: a kinematic 3-D in vivo
424 analysis. *Knee Surgery, Sports Traumatology, Arthroscopy* 19, 115-121.
- 425 Cohen, J., 1988. *Statistical Power Analysis for the Behavioral Sciences*. Lawrence
426 Erlbaum Associates, NJ.
- 427 Devita, P., Hortobagyi, T., Barrier, J., Torry, M., Glover, K.L., Speroni, D.L., Money,
428 J., Mahar, M.T., 1997. Gait adaptations before and after anterior cruciate ligament
429 reconstruction surgery. *Medicine and Science in Sports and Exercise* 29, 853-859.
- 430 DeVita, P., Hortobagyi, T., Money, J., Torry, M., Glover, K., Speroni, D., Barrier, J.,
431 Mahar, M., Lochmann, J., 1996. Gait adaptations before and after ACL

- 432 reconstruction surgery. In American Society of Biomechanics: Conference
433 Proceedings of the 20th Annual Meeting. Georgia Institute of Technology, Atlanta.
- 434 Dhillon, M.S., Bali, K., Prabhakar, S., 2012. Differences among mechanoreceptors in
435 healthy and injured anterior cruciate ligaments and their clinical importance.
436 *Muscles, Ligaments and Tendons Journal* 2, 38-43.
- 437 Di Stasi, S.L., 2011. The fickle ACL deficient athlete: investigation of the non-coper
438 response to injury, surgery, and neuromuscular training. PhD. thesis, University of
439 Delaware, Newark.
- 440 Di Stasi, S.L., Hartigan, E.H., Snyder-Mackler, L., 2012. Unilateral stance strategies
441 of athletes with ACL deficiency. *Journal of Applied Biomechanics* 28, 374-386.
- 442 Di Stasi, S.L., Hartigan, E.H., Snyder-Mackler, L., 2015. Sex-specific gait
443 adaptations prior to and up to 6 months after anterior cruciate ligament
444 reconstruction. *Journal of Orthopaedic and Sports Physical Therapy* 45, 207-214.
- 445 Drevon, D., Fursa, S.R., Malcolm, A.L., 2017. Intercoder reliability and validity of
446 WebPlotDigitizer in extracting graphed data. *Behaviour Modification* 41. 323-339.
- 447 Favre, J., Luthi, F., Jolles, B.M., Siegrist, O., Najafi, B., Aminian, K., 2006. A new
448 ambulatory system for comparative evaluation of the three-dimensional knee
449 kinematics, applied to anterior cruciate ligament injuries. *Knee Surgery, Sports
450 Traumatology, Arthroscopy* 14, 592-604.
- 451 Ferber, R.R., 2001. Gait perturbation response in anterior cruciate ligament
452 deficiency and surgery. PhD. thesis, University of Oregon, Eugene.
- 453 Ferber, R.R., Osternig, L.R., Woollacott, M.H., Wasielewski, N.J., Lee, J., 2004.
454 Bilateral accommodations to anterior cruciate ligament deficiency and surgery.
455 *Clinical Biomechanics* 19, 136-144.

- 456 Gardinier, E.S., 2013. Changes in knee joint loading after ACL injury: effects of
457 rehabilitation and influence of patient factors. PhD. thesis, University of Delaware,
458 Newark.
- 459 Gardinier, E S, Manal, K, Buchanan, T S, Snyder-Mackler, L, 2012. Gait and
460 neuromuscular asymmetries after acute ACL rupture. *Med. Sci. Sports Exerc.* 44,
461 1490–1496.
- 462 Georgoulis, A.D., Papadonikolakis, A., Papageorgiou, C.D., Mitsou, A., Stergiou, N.,
463 2003. Three-dimensional tibiofemoral kinematics of the anterior cruciate ligament-
464 deficient and reconstructed knee during walking. *The American Journal of Sports*
465 *Medicine* 31, 75-79.
- 466 Gokalp, O., Akkaya, S., Akkaya, N., Buker, N., Gungor, H.R., Ok, N., Yorukoglu, C.,
467 2016. Preoperative and postoperative serial assessments of postural balance and
468 fall risk in patients with arthroscopic anterior cruciate ligament reconstruction.
469 *Journal of Back and Musculoskeletal Rehabilitation* 29, 343-350.
- 470 Goon, A.M., Gupta, M.K., Dasgupta, B., 1968. *Fundamentals of Statistics (Vol. 1)*.
471 The World Press Private Ltd, Calcutta.
- 472 Grindem, H., Eitzen, I., Engebretsen, L., Snyder-Mackler, L., Risberg, M.A., 2014.
473 Nonsurgical or surgical treatment of ACL injuries: knee function, sports participation,
474 and knee reinjury: the Delaware-Oslo ACL cohort study. *The Journal of Bone and*
475 *Joint Surgery* 96, 1233-1241.
- 476 Hart, H.F., Culvenor, A.G., Collins, N.J., Ackland, D.C., Cowan, S.M., Machotka, Z.,
477 Crossley, K.M., 2016. Knee kinematics and joint moments during gait following
478 anterior cruciate ligament reconstruction: a systematic review and meta-analysis.
479 *British Journal of Sports Medicine* 50, 597-612.

- 480 Hartigan, E.H., 2009. Knee function after ACL rupture and reconstruction effects of
481 neuromuscular training. PhD. thesis, University of Delaware, Newark.
- 482 Hartigan, E.H., Axe, M.J., Snyder-Mackler, L., 2009. Perturbation training prior to
483 ACL reconstruction improves gait asymmetries in non-copers. *Journal of*
484 *Orthopaedic Research* 27, 724-729.
- 485 Hartigan, E.H., Zeni, J.A., Di Stasi, S.L., Axe, M.J., Snyder-Mackler, L., 2012.
486 Preoperative predictors for noncopers to pass return to sports criteria after ACL
487 reconstruction. *Journal of Applied Biomechanics* 28, 366-373.
- 488 Hedges, L.V., Olkin, I., 1985. *Statistical Methods for Meta-Analysis*. Academic Press,
489 San Diego.
- 490 Heijne, A., Werner, S., 2007. Early versus late start of open kinetic chain quadriceps
491 exercises after ACL reconstruction with patellar tendon or hamstring grafts: a
492 prospective randomized outcome study. *Knee Surgery, Sports Traumatology,*
493 *Arthroscopy* 15, 402-414.
- 494 Hemmerich, A., van der Merwe, W., Batterham, M., Vaughan, C.L., 2011. Double-
495 bundle ACL surgery demonstrates superior rotational kinematics to single-bundle
496 technique during dynamic task. *Clinical Biomechanics* 26, 998-1004.
- 497 Higgins, J.P.T., Altman, D.G., Gøtzsche, P.C., Jüni, P., Moher, D., Oxman, A.D.,
498 Savović, J., Schulz, K.F., Weeks, L., Sterne, J.A.C., 2011. The Cochrane
499 Collaboration's tool for assessing risk of bias in randomised trials. *British Medical*
500 *Journal* 343, 5928.
- 501 Isaac, D.L., Beard, D.J., Price, A.J., Rees, J., Murray, D.W., Dodd, C.A.F., 2005. In-
502 vivo sagittal plane knee kinematics: ACL intact, deficient and reconstructed knees.
503 *The Knee* 12, 25-31.

- 504 Jurevičienė, V., Skurvydas, A., Belickas, J., Bušmanienė, G., Kielė, D., Česnaitis, T.,
505 2012. The analysis of proprioception alteration during first five months after anterior
506 cruciate ligament reconstruction. *Baltic Journal of Sport and Health Sciences* 84, 8-
507 14.
- 508 Keays, S.L., Bullock-Saxton, J.E., Newcombe, P., Keays, A.C., 2003. The
509 relationship between knee strength and functional stability before and after anterior
510 cruciate ligament reconstruction. *Journal of Orthopaedic Research* 21, 231-237.
- 511 Kessler, M.A., Behrend, H., Henz, S., Stutz, G., Rukavina, A., Kuster, M.S., 2008.
512 Function, osteoarthritis and activity after ACL-rupture: 11 years follow-up results of
513 conservative versus reconstructive treatment. *Knee Surgery, Sports Traumatology,*
514 *Arthroscopy* 16, 442-448.
- 515 Kim, D.-K., Park, W.-H., 2009. Effects of pre-operative exercise training on knee
516 strength and proprioceptive functions after anterior cruciate ligament reconstruction.
517 *Medicine and Science in Sports and Exercise* 41, 533.
- 518 Knoll, Z., Kiss, R.M., Kocsis, L., 2004a. Gait adaptation in ACL deficient patients
519 before and after anterior cruciate ligament reconstruction surgery. *Journal of*
520 *Electromyography and Kinesiology* 14, 287-294.
- 521 Knoll, Z., Kocsis, L., Kiss, R.M., 2004b. Gait patterns before and after anterior
522 cruciate ligament reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy*
523 12, 7-14.
- 524 Kowalk, D.L., Duncan, J.A., McCue 3rd, F.C., Vaughan, C.L., 1997. Anterior cruciate
525 ligament reconstruction and joint dynamics during stair climbing. *Medicine and*
526 *Science in Sports and Exercise* 29, 1406-1413.

- 527 Kumar, D., Su, F., Wu, D., Pedoia, V., Heitkamp, L., Ma, C.B., Souza, R.B., Li, X.,
528 2018. Frontal plane knee mechanics and early cartilage degeneration in people with
529 anterior cruciate ligament reconstruction: A longitudinal study. *The American Journal*
530 *of Sports Medicine* 46, 378-387.
- 531 Laforest, G., Fuentes, A., Therrien, M., Grimard, G., (2017). Short-term impact of
532 anterior cruciate ligament reconstruction in an adolescent population on 3D knee
533 kinematics. *Orthopaedic Journal of Sports Medicine* 5, 1.
- 534 Lam, M.-H., Fong, D.T.-P., Yung, P.S.-H., Ho, E.P.-Y., Fung, K.-Y., Chan, K.-M.,
535 2010. Excessive tibial rotation is restored after anatomical double bundle anterior
536 cruciate ligament reconstruction. In *Proceedings of the 28th International Conference*
537 *of Biomechanics in Sports*. Northern Michigan University, Marquette.
- 538 Lam, M.-H., Fong, D.T.-P., Yung, P.S.-H., Ho, E.P.-Y., Fung, K.-Y., Chan, K.-M.,
539 2011. Knee rotational stability during pivoting movement is restored after anatomic
540 double-bundle anterior cruciate ligament reconstruction. *The American Journal of*
541 *Sports Medicine* 39, 1032-1038.
- 542 Lephley, A.S., Gribble, P.A., Thomas, A.C., Tevald, M.A., Sohn, D.H., Pietrosimone,
543 B.G., 2016. Longitudinal evaluation of stair walking biomechanics in patients with
544 ACL injury. *Medicine and Science in Sports and Exercise* 48, 7-15.
- 545 Letchford, R., Button, K., Adamson, P., Roos, P., Sparkes, V., Deursen, R., Roos, P.
546 E., van Deursen, R.W.M., 2016. A novel clinical approach for assessing hop landing
547 strategies: a 2D telescopic inverted pendulum (TIP) model. *Knee Surgery, Sports*
548 *Traumatology, Arthroscopy* 24, 279-286.

- 549 Ma, Y., Deie, M., Iwaki, D., Asaeda, M., Fujita, N., Adachi, N., Ochi, M., 2014.
550 Balance ability and proprioception after single-bundle, single-bundle augmentation,
551 and double-bundle ACL reconstruction. *The Scientific World Journal* 2014, 1-8.
- 552 Majewska, J., Szczepanik, M., Szymczyk, D., Bazarnik-Mucha, K., Druzbicki, M.,
553 Snela, S., Jarmuziewicz, A., Pyczuła, R., 2017. Evaluation of selected gait
554 parameters in patients prior to and at 6 months following early anterior cruciate
555 ligament reconstruction. *Ortopedia Traumatologia Rehabilitacja* 19, 271-281.
- 556 Manal, K, Buchanan, T S, 2013. An electromyogram-driven musculoskeletal model
557 of the knee to predict in vivo joint contact forces during normal and novel gait
558 patterns. *J.Biomech. Eng.* 135, 21014.
- 559 McGrath, T.M., Waddington, G., Scarvell, J.M., Ball, N., Creer, R., Woods, K., Smith,
560 D., Adams, R., 2017. An ecological study of anterior cruciate ligament
561 reconstruction, part 2. *Orthopaedic Journal of Sports Medicine* 5, 1-1.
- 562 Mittlmeier, T., Weiler, A., Söhn, T., Kleinhans, L., Mollbach, S., Duda, G., Südkamp,
563 N.P., 1999. Functional monitoring during rehabilitation following anterior cruciate
564 ligament reconstruction. *Clinical Biomechanics* 14, 576-584.
- 565 Moses, B., Orchard, J., Orchard, J., 2012. Systematic review: annual incidence of
566 ACL injury and surgery in various populations. *Research in Sports Medicine* 20, 157-
567 179.
- 568 Moya-Angeler, J., Vaquero, J., Forriol, F., 2017. Evaluation of lower limb kinetics
569 during gait, sprint and hop tests before and after anterior cruciate ligament
570 reconstruction. *Journal of Orthopaedics and Traumatology* 18, 177-184.
- 571 O'Connor, D., Green, S., Higgins, J.P.T., 2011. Defining the review question and
572 developing criteria for including studies. In: Higgins, J.P.T., Green, S. (Eds.),

- 573 Cochrane Handbook for Systematic Reviews of Interventions. The Cochrane
574 Collaboration, London.
- 575 Oberländer, K.D., Brüggemann, G.-P., Höher, J., Karamanidis, K., 2014. Knee
576 mechanics during landing in anterior cruciate ligament patients: a longitudinal study
577 from pre- to 12 months post-reconstruction. *Clinical Biomechanics* 29, 512-517.
- 578 Ogradzka-Ciechanowicz, K., Czechowska, D., Chwala, W., Slusarski, J., Gadek, A.,
579 2018. Stabilometric indicators as an element of verifying rehabilitation of patients
580 before and after reconstruction of anterior cruciate ligament. *Acta of Bioengineering
581 and Biomechanics* 20, 101-107.
- 582 Oliver, G., Portabella, F., Hernandez, J.A., 2019. A comparative study of the
583 neuromuscular response during a dynamic activity after anterior cruciate ligament
584 reconstruction. *European Journal of Orthopaedic Surgery and Traumatology* 29,
585 633-638
- 586 Ordahan, B., Küçükşen, S., Tuncay, İ., Salli, A., Uğurlu, H., 2015. The effect of
587 proprioception exercises on functional status in patients with anterior cruciate
588 ligament reconstruction. *Journal of Back and Musculoskeletal Rehabilitation* 28, 531-
589 537.
- 590 Papadonikolakis, A., Cooper, L., Stergiou, N., Georgoulis, A. D., Soucacos, P. N.,
591 2003. Compensatory mechanisms in anterior cruciate ligament deficiency. *Knee
592 Surgery, Sports Traumatology, Arthroscopy* 11, 235-243.
- 593 Paterno, M.V., Rauh, M.J., Schmitt, L.C., Ford, K.R., Hewett, T.E., 2012. Incidence
594 of contralateral and ipsilateral anterior cruciate ligament (ACL) injury after primary
595 ACL reconstruction and return to sport. *Clinical Journal of Sport Medicine* 22, 116-
596 121.

- 597 Petersen, W., Taheri, P., Forkel, P., Zantop, T., 2014. Return to play following ACL
598 reconstruction: a systematic review about strength deficits. *Archives of Orthopaedic*
599 *and Trauma Surgery* 134, 1417-1428.
- 600 Reider, B., Arcand, M. A., Diehl, L. H., Mroczek, K., Abulencia, A., Stroud, C. C.,
601 Palm, M., Gilbertson, J., Staszak, P., 2003. Proprioception of the knee before and
602 after anterior cruciate ligament reconstruction. *Arthroscopy* 19, 2-12.
- 603 Robbins, S.M.K., Clark, J.M., Maly, M.R., 2011. Longitudinal gait and strength
604 changes prior to and following an anterior cruciate ligament rupture and surgical
605 reconstruction: a case report. *Journal of Orthopaedic and Sports Physical Therapy*
606 41, 191-199.
- 607 Roewer, B.D., Di Stasi, S.L., Snyder-Mackler, L., 2011. Quadriceps strength and
608 weight acceptance strategies continue to improve two years after anterior cruciate
609 ligament reconstruction. *Journal of Biomechanics* 44, 1948-1953.
- 610 Shabani, B., Bytyqi, D., Lustig, S., Cheze, L., Bytyqi, C., Neyret, P., 2015. Gait knee
611 kinematics after ACL reconstruction: 3D assessment. *International Orthopaedics* 39,
612 1187-1193.
- 613 Shidahara, H., Deie, M., Niimoto, T., Shimada, N., Toriyama, M., Adachi, N., Urabe,
614 Y., Ochi, M., 2011. Prospective study of kinesthesia after ACL reconstruction.
615 *International Journal of Sports Medicine* 32, 386-392.
- 616 Smale, K.B., Alkjaer, T., Flaxman, T.E., Krogsgaard, M.R., Simonsen, E. B., Benoit,
617 D.L., 2019a. Assessment of objective dynamic knee joint control in anterior cruciate
618 ligament deficient and reconstructed individuals. *The Knee* 26, 578-585.
- 619 Smale, K.B., Flaxman, T.E., Alkjaer, T., Simonsen, E.B., Krogsgaard, M.R., Benoit,
620 D.L., 2019b. Anterior cruciate ligament reconstruction improves subjective ability but

- 621 not neuromuscular biomechanics during dynamic tasks. *Knee Surgery, Sports*
622 *Traumatology, Arthroscopy* 27, 636-645.
- 623 Tagesson, S., Kvist, J., 2016. Greater fear of re-injury and increased tibial translation
624 in patients who later sustain an ACL graft rupture or a contralateral ACL rupture: a
625 pilot study. *Journal of Sports Sciences* 34, 125-132.
- 626 Tagesson, S., Öberg, B., Kvist, J., 2010. Tibial translation and muscle activation
627 during rehabilitation exercises 5 weeks after anterior cruciate ligament
628 reconstruction. *Scandinavian Journal of Medicine and Science in Sports* 20, 154-
629 164.
- 630 Tagesson, S., Öberg, B., Kvist, J., Öberg, B., 2015. Static and dynamic tibial
631 translation before, 5 weeks after, and 5 years after anterior cruciate ligament
632 reconstruction. *Knee Surgery, Sports Traumatology, Arthroscopy* 23, 3691-3697.
- 633 Teng, H.-L., Wu, D., Su, F., Pedoia, V., Souza, R.B., Ma, C.B., Li, X., 2017. Gait
634 characteristics associated with a greater increase in medial knee cartilage T1 ρ and
635 T2 relaxation times in patients undergoing anterior cruciate ligament reconstruction.
636 *The American Journal of Sports Medicine* 45, 3262-3271.
- 637 Thomas, B.H., Ciliska, D., Dobbins, M., Micucci, S., 2004. A process for
638 systematically reviewing the literature: providing the research evidence for public
639 health nursing interventions. *Worldviews on Evidence-Based Nursing* 1, 176-184.
- 640 Tsigoulis, S.D., Tzagarakis, G.N., Papagelopoulos, P.J., Koulalis, D., Sakellariou,
641 V.I., Kampanis, N.A., Chlouverakis, G.I., Alpantaki, K.I., Nikolaou, P.K., Katonis,
642 P.G., 2011. Pre-operative versus post-operative gait variability in patients with acute
643 anterior cruciate ligament deficiency. *The Journal of International Medical Research*
644 39, 580-593.

645 Tuğcu, I., Tok, F., Yilmaz, B., Taşkınatan, M.A., Göktepe, A.S., MÖhür, H.,
646 Yazıcıođlu, K., Özgöl, A., 2013. The gulhane anterior cruciate ligament rehabilitation
647 protocol following anterior cruciate ligament reconstruction surgery. Turkish Journal
648 of Physical Medicine and Rehabilitation 59, 117-122.

649 von Porat, A., Roos, E.M., Roos, H., 2004. High prevalence of osteoarthritis 14 years
650 after an anterior cruciate ligament tear in male soccer players: a study of
651 radiographic and patient relevant outcomes. Annals of the Rheumatic Diseases 63,
652 269-273.

653 Wan, X., Wang, W., Liu, J., Tong, T., 2014. Estimating the sample mean and
654 standard deviation from the sample size, median, range and/or interquartile range.
655 BMC Medical Research Methodology 14, 1-13.

656 Wellsandt, E., Gardinier, E.S., Manal, K., Axe, M.J., Buchanan, T.S., Snyder-
657 Mackler, L., 2016. Decreased knee joint loading associated with early knee
658 osteoarthritis after anterior cruciate ligament injury. The American Journal of Sports
659 Medicine 44, 143-151.

660 Wellsandt, E., Zeni, J.A., Axe, M.J., Snyder-Mackler, L., 2017. Hip joint
661 biomechanics in those with and without post-traumatic knee osteoarthritis after
662 anterior cruciate ligament injury. Clinical Biomechanics 50, 63-69.

663

664 **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

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

667

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)

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

672 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 x 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

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

ACCEPTED MANUSCRIPT

674 **Table 4.** Cohen's *d* effect sizes (ES) and 95% confidence intervals (95%CI) of
 675 kinematic changes during stair ascent and descent due to anterior cruciate ligament
 676 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	

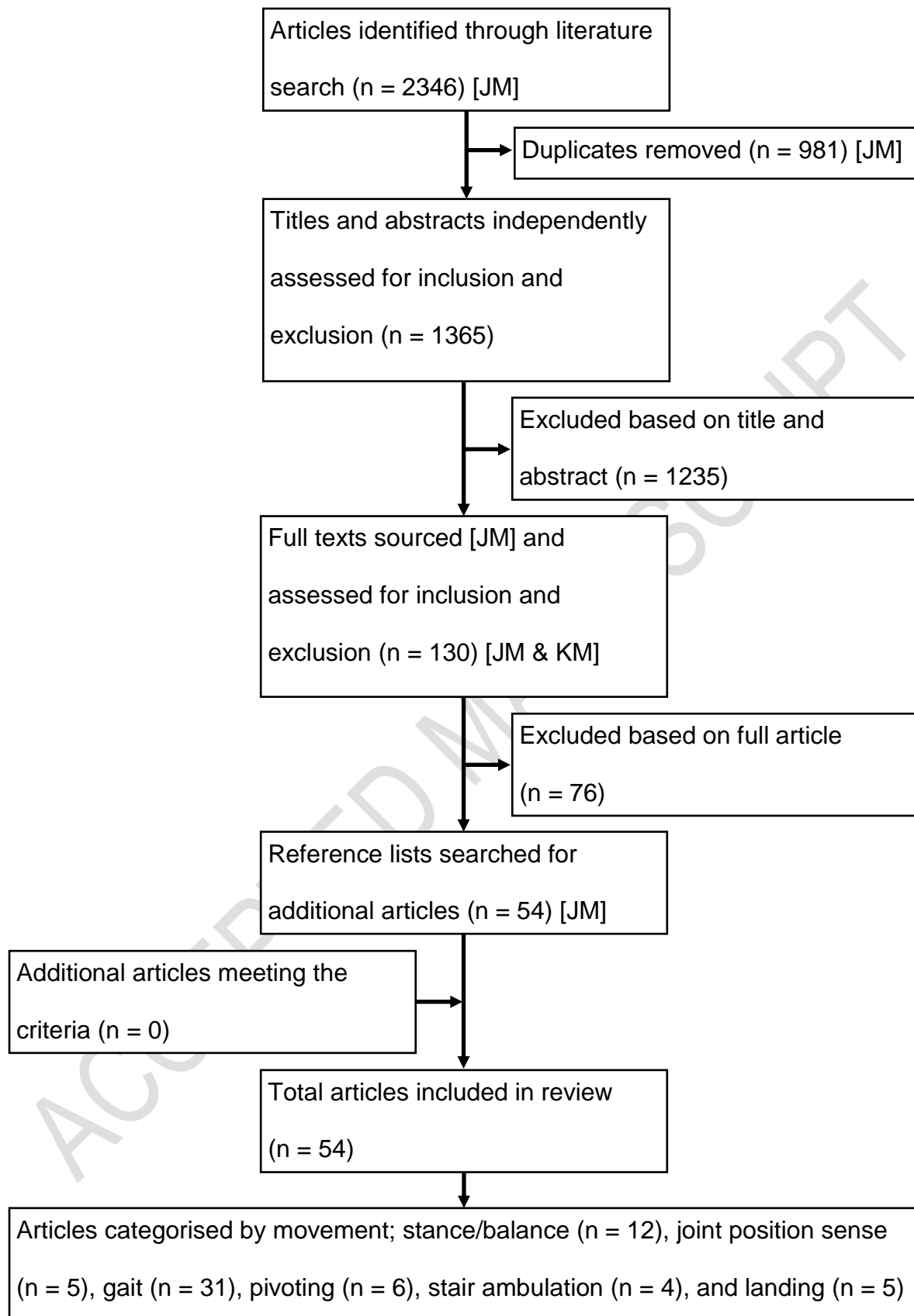
^aClaes et al. (2011); ^bKowalk et al. (1997); ^cLepley et al. (2016). Initial contact (IC)

677

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

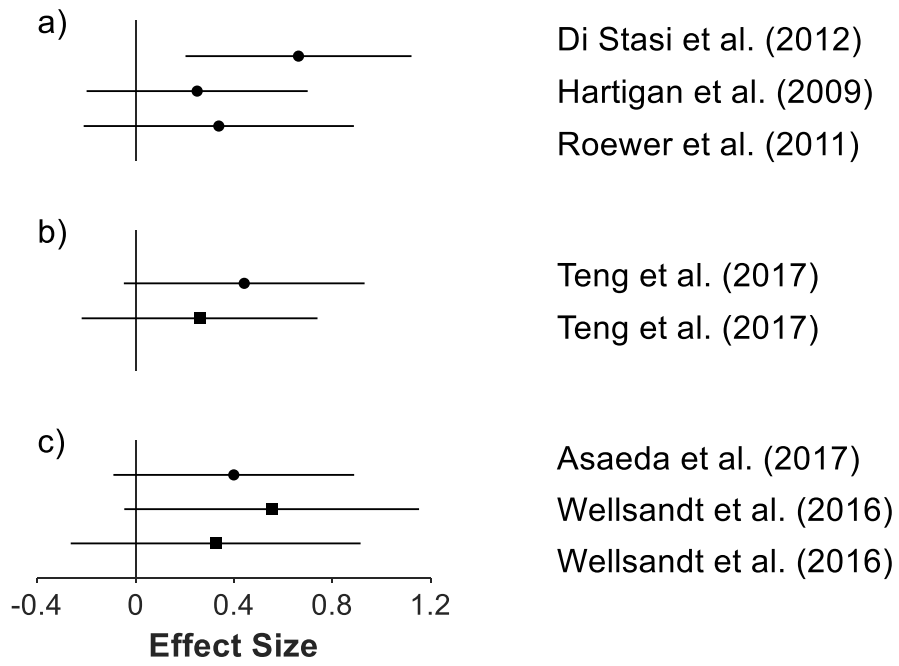
	Participants	Withdrawals	Study design	Intervention integrity	Data collection	Overall rating
Asaeda et al. (2017)	1	3	1	1	1	2
Bartels et al. (2019)	1	2	3	1	1	2
Beard et al. (2001)	1	3	1	3	1	3
Claes et al. (2011)	1	1	1	3	1	2
Devita et al. (1997)	1	3	1	1	1	2
Di Stasi et al. (2012)	1	2	1	3	1	2
Di Stasi et 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
Tsigoulis 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

680 1 = strong; 2 = moderate; 3 = weak



681

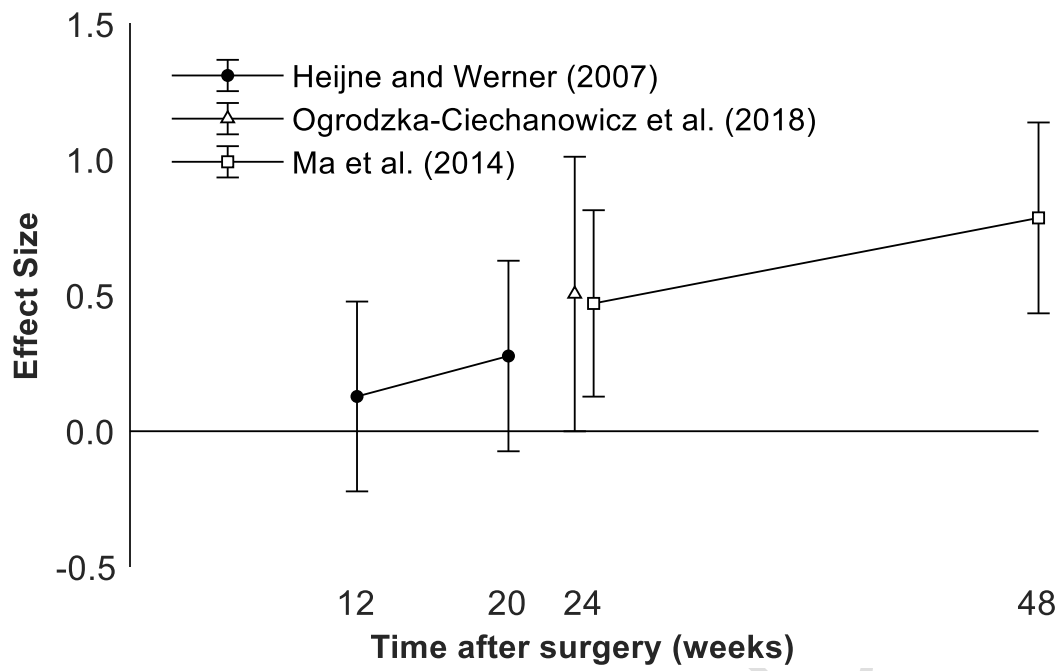
682 **Figure 1**



683

684 **Figure 2**

ACCEPTED MANUSCRIPT

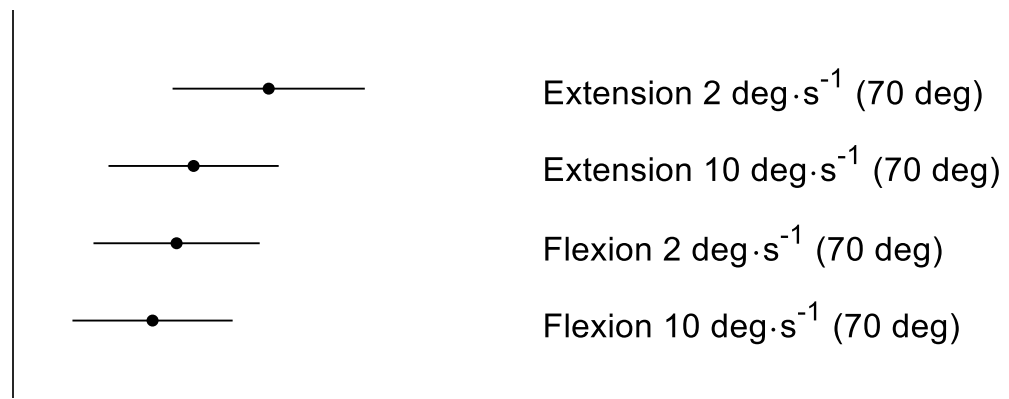


685

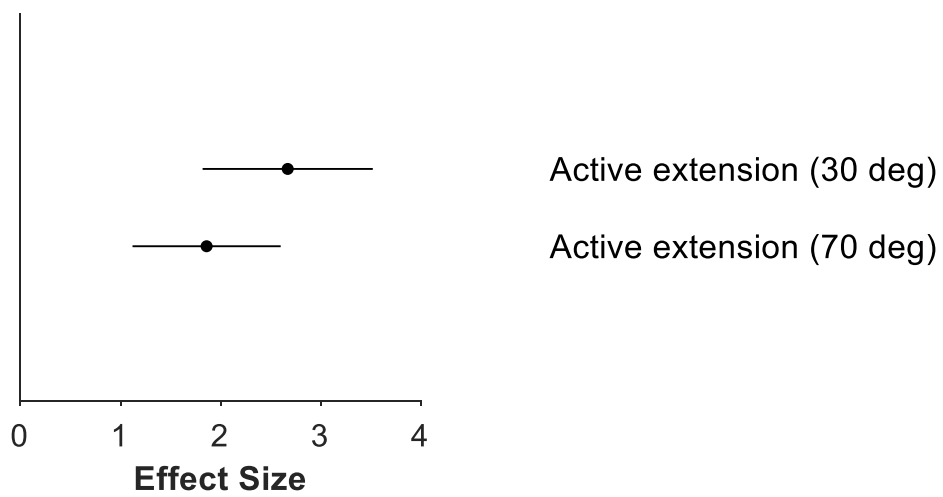
686 **Figure 3**

ACCEPTED MANUSCRIPT

a)



b)



687

688 **Figure 4**

ACCEPTED

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

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

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

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