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Miles, JJ and King, E and Falvey, EC and Daniels, KAJ (2019) Patellar and hamstring autografts are associated with different jump task loading asymmetries after ACL reconstruction. *Scandinavian Journal of Medicine and Science in Sports*, 29 (8). pp. 1212-1222. ISSN 0905-7188

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**Downloaded from:** <https://e-space.mmu.ac.uk/626441/>

**Version:** Accepted Version

**Publisher:** Wiley

**DOI:** <https://doi.org/10.1111/sms.13441>

Please cite the published version

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1 **Title:**

2 Patellar and hamstring autografts are associated with different jump task loading  
3 asymmetries after ACL reconstruction

4

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12

13 **Running head:**

14 Graft type and impulse asymmetries after ACLR

15

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32 **ABSTRACT**

33 After anterior cruciate ligament reconstruction (ACLR) there is a higher re-injury rate  
34 to the contralateral limb in athletes who undergo surgery using a bone-patellar-  
35 tendon-bone (BPTB) autograft than using a semitendinosus and gracilis hamstring  
36 tendon (HT) autograft. This may be influenced by differing lower-limb loading  
37 asymmetries present when athletes of each graft type return to play. The aim of this  
38 study was to compare bilateral countermovement jump (CMJ) phase-specific  
39 impulse asymmetries between athletes with BPTB and HT autografts nine months  
40 post-ACLR, and to identify the relationship between impulse and isokinetic strength  
41 asymmetries. Male field sport athletes with a BPTB (n=22) or HT (n=22) autograft  
42 were tested approximately nine months post-ACLR. An uninjured control group  
43 (n=22) was also tested on a single occasion. Phase-specific bilateral absolute  
44 impulse asymmetries were calculated during the CMJ and compared between  
45 groups using Kruskal-Wallis and post-hoc testing. A linear regression model was  
46 used to assess the relationship between impulse asymmetries and isokinetic  
47 concentric knee extensor strength asymmetries. BPTB athletes demonstrated  
48 greater impulse asymmetries than HT athletes during the eccentric ( $p=0.01$ ) and  
49 concentric ( $p=0.008$ ) phases of the jump. Isokinetic strength asymmetry was a  
50 significant predictor of CMJ concentric impulse asymmetry in both BPTB ( $r^2=0.39$ )  
51 and HT athletes ( $r^2=0.18$ ) but not eccentric impulse asymmetry in any group. The  
52 greater loading asymmetries demonstrated by BPTB than HT athletes nine months  
53 after ACLR may contribute to the differing incidence rates of contralateral ACL injury.  
54 The findings suggest that graft-specific loading asymmetries should be targeted  
55 during rehabilitation prior to return to play.

56

57 **Key words:** biomechanics, isokinetic dynamometry, IKDC, counter-movement jump, phase-specific,  
58 impulse, ground reaction force

## 59 INTRODUCTION

60 Anterior cruciate ligament (ACL) rupture is a severe knee injury with incidence rates  
61 ranging from 0.03-3.67% per year in field sports.<sup>1</sup> The most common treatment is  
62 surgical anterior cruciate ligament reconstruction (ACLR), most-often using either a  
63 bone-patellar-tendon-bone (BPTB) or a semitendinosus and gracilis hamstring  
64 tendon (HT) autograft.<sup>2</sup> Athletes who have had a previous ACLR are at a greater risk  
65 of re-injury, with ACL re-injury risk ranging from 6-26% on the operated limb (graft  
66 rupture) and from 2-20.5% on the contralateral limb, depending on the follow up time  
67 scale.<sup>3-5</sup> Many studies have evaluated the difference in ACL re-injury rates between  
68 BPTB and HT grafts.<sup>4,6,7</sup> Thompson et al.<sup>7</sup> prospectively studied 180 ACLR athletes  
69 with a 20-year follow up and found a significantly greater contralateral ACL injury  
70 rate in BPTB (30%) than HT (14%). Other studies have reported similar findings,<sup>4</sup>  
71 although differentiation of re-injury rate is not always evident when the sample size is  
72 low.<sup>6</sup> It has been suggested that graft type may also influence the risk of  
73 contralateral re-injury when athletes return to high level activity after ACLR.<sup>8</sup>

74

75 After ACLR, the injury itself and the disruption at the graft harvest site result in  
76 reduced strength and other neuromuscular qualities such as power on the ACLR  
77 side, causing an increase in between-limb asymmetry.<sup>9,10</sup> Rehabilitation goals  
78 include restoration of inter-limb symmetry in neuromuscular function and strength to  
79 the pre-injury level.<sup>11</sup> Large inter-limb asymmetries are associated with poorer knee  
80 function and increase the risk of sustaining a second ACL injury after Return To Play  
81 (RTP),<sup>12</sup> with ACLR athletes demonstrating greater knee extensor and flexor  
82 isokinetic strength asymmetries than healthy controls.<sup>9</sup> Graft donor site has been  
83 shown to influence observed strength asymmetries.<sup>13</sup> BPTB athletes were reported  
84 to have a greater knee extensor strength deficit and a lower knee flexor strength

85 deficit than HT athletes in the majority of studies.<sup>13</sup> These deficits may be related to  
86 morbidity caused during the harvest of the graft.<sup>14,15</sup>

87

88 Strength asymmetries have been shown to contribute towards asymmetries in  
89 functional performance, Ground Reaction Force (GRF) variables and knee  
90 mechanics during sporting movements in ACLR athletes.<sup>16,17</sup> Differences in knee  
91 extensor and flexor strength between graft types might hence be expected to  
92 translate to GRF asymmetries during jumping and landing activities. Previous studies  
93 have found a moderate positive relationship between asymmetries in leg muscle  
94 mass and asymmetries in both strength and in GRF variables during bilateral  
95 countermovement jumps (CMJ) in ACLR athletes,<sup>18</sup> which may increase the risk of a  
96 subsequent ACL injury.<sup>19</sup>

97

98 Gold standard measures such as isokinetic dynamometry accurately measure  
99 strength asymmetry but in a uniplanar controlled manner.<sup>20</sup> Jumping and landing are  
100 key components of multi-directional field sports performance, so unilateral and  
101 bilateral CMJ tests are often used to assess lower-limb performance in ACLR  
102 athletes during rehabilitation.<sup>21</sup> ACLR athletes demonstrate greater asymmetries in  
103 single limb vertical and horizontal jump performance than controls.<sup>9</sup> Dynamic joint  
104 loading during a landing task has been reported to differ between graft types, with  
105 BPTB athletes found to land with their operated leg in a more-extended position and  
106 with a greater peak vertical GRF (GRFv) than HT athletes.<sup>22</sup> Studies investigating  
107 asymmetry during bilateral drop jump landings in adolescent cohorts revealed that  
108 BPTB athletes have greater asymmetry than HT in external knee flexion moments  
109 and knee sagittal plane energy absorption.<sup>23</sup> An advantage of assessing bilateral  
110 instead of unilateral movements is to enable analysis of the athlete's choice of

111 loading strategy to achieve motor tasks. For example, the athlete may offload the  
112 operated leg due to fear of knee collapse or pain,<sup>24</sup> increasing the risk of sustaining a  
113 second ACL injury.<sup>12</sup>

114

115 Force platforms alone may be used to measure GRFv during a CMJ, without the  
116 requirement for position sensors to be tracked (as for calculation of joint angles,  
117 moments, etc.). When analysing data from the CMJ, single discrete points such as  
118 peak GRFv are commonly reported to quantify load<sup>16,17,22</sup> but this approach  
119 disregards potentially important information from the majority of the force-time curve.

120 An alternative approach incorporating GRF over the entire movement is to use  
121 impulse, the first integral of the GRF-time curve, to quantify loading during CMJ take-  
122 off and landing. The jump can then be subdivided into eccentric and concentric  
123 movements and impulse assessed within these specific phases to isolate differing  
124 muscle actions (Figure 1).<sup>18</sup> Jordan et al.<sup>18</sup> found that elite post-ACLR skiers  
125 demonstrated greater phase-specific inter-limb asymmetries than controls during the  
126 concentric phase of a CMJ. Athletes scoring lower in the International  
127 Documentation Committee subjective form (IKDC) approximately 31 months post-  
128 ACLR demonstrated greater eccentric deceleration asymmetries than higher-scoring  
129 athletes during unilateral and bilateral CMJs.<sup>25</sup> The influence of graft type on phase-  
130 specific impulse asymmetries has not been examined and is potentially of particular  
131 interest at the critical time point of 9 months post-surgery, when athletes typically  
132 RTP.<sup>8</sup> Graft-specific differences identified could then be targeted during rehabilitation  
133 to improve symmetry outcomes prior to RTP.

134

135 The primary aim of this study was to compare CMJ phase-specific impulse and  
136 isokinetic strength asymmetries in athletes with a BPTB or HT autograft at 9 months

137 post-ACLR and controls. The secondary aim was to assess the relationship between  
138 knee extensor strength asymmetries and both eccentric deceleration impulse and  
139 concentric impulse asymmetries in BPTB and HT patients. We hypothesised that:

140

141 1) Phase-specific impulse asymmetries during a CMJ at 9 months post-ACLR  
142 would be greater for BPTB and HT patients than controls. BPTB patients  
143 would have greater phase-specific impulse asymmetries than HT patients  
144 during the CMJ.

145

146 2) Eccentric deceleration and concentric impulse asymmetries during the CMJ  
147 would be positively related to knee extensor strength asymmetries in both  
148 BPTB and HT patients.

149

## 150 **METHODS**

151

### 152 *Participants*

153 Power analysis (G\*Power, version 3.1.9.2, Universität Düsseldorf, Germany)  
154 indicated a required sample size of 22 participants in each group to achieve 90%  
155 statistical power with an alpha level of 0.05 for the impulse outcome variables, based  
156 on pilot data with 10 participants. We employed a smallest worthwhile effect of 10%  
157 in the power calculation because 10% asymmetry in GRF variables is commonly  
158 used as an RTP criterion after ACLR.<sup>10</sup> Currently no experimental evidence, i.e.  
159 normative data or established relationships with outcome measures, suggests a  
160 more-appropriate alternative value.<sup>26</sup>

161

162 Forty-four eligible ACLR athletes who had a BPTB (n=22) or HT (semitendinosus  
163 and gracilis; n=22) autograft from the ipsilateral side were consecutively recruited  
164 prior to ACLR from the caseload of two orthopaedic knee consultants at Sports  
165 Surgery Clinic, Dublin, Ireland. Inclusion criteria were male, multidirectional field  
166 sport athletes aged between 18 and 35 years with the intention to RTP at the same  
167 level of participation as prior to the injury. As part of their clinical assessment, the  
168 athletes completed a testing session at 8-10 months post-ACLR between July 2015  
169 and July 2017. Rehabilitation was not controlled in the time period between surgery  
170 and assessment. Athletes with multiple ligament reconstructions and previous ACL  
171 injuries were excluded from the study. Meniscal tears and chondral lesions are  
172 common secondary injuries to ACL rupture,<sup>27</sup> therefore athletes with these  
173 pathologies were included in the study. 14 BPTB and 12 HT athletes presented for  
174 surgery with meniscal tears and 9 BPTB and 5 HT athletes, presented with chondral  
175 lesions. A control group (n=22) meeting the same inclusion criteria as the ACLR  
176 athletes (male multidirectional field sport athletes aged between 18-35 years) with no  
177 previous lower-limb injury actively managed within the previous two years were  
178 recruited by word of mouth from the local sporting population and completed a single  
179 testing session. Participants were primarily involved in Gaelic sports (Gaelic football  
180 and hurling; 66%), soccer (24%) and rugby (10%) and their anthropometric data is  
181 reported in Table 1. Participants gave informed written consent prior to testing and  
182 the study received ethical approval from Sports Surgery Clinic Hospital Ethics  
183 Committee.

184

### 185 *Testing Procedures*

186 Height and body mass were measured immediately prior to testing. At the start of  
187 each testing session, participants were instructed to complete a warm up consisting



188 of a two minute jog and five body-weight squats. Participants then performed two  
189 familiarisation CMJs where they were instructed to maintain hands placed on iliac  
190 crests and to jump as high as they could with knees extended during the flight  
191 phase. Participants were then asked to complete three maximal-height CMJs on a  
192 frame mounted dual force platform system (BP400600, AMTI, USA) that recorded  
193  $GRF_v$  at a sampling frequency of 1000 Hz. If any of the jumps deviated from the  
194 required technique (e.g. hands removed from iliac crests) they were excluded and  
195 the jump was repeated. Jump variables were calculated as a mean of the three  
196 jumps. Participants then continued with a battery of vertical and horizontal jumps and  
197 multidirectional cutting for clinical testing. This consisted of three bilateral jumps,  
198 twelve unilateral jumps on each leg and twelve 90° running change-of-direction  
199 (cutting) manoeuvres.

200

201 After a ten minute break following completion of laboratory testing, concentric knee  
202 extensor and flexor strength were measured using an isokinetic dynamometer  
203 (Cybex Humac NORM, CSMI, Massachusetts, USA). All testing sessions were  
204 completed following protocol recommendations to assess isokinetic strength after  
205 ACLR.<sup>20</sup> Participants were set up in a seated position, with stabilisation belts placed  
206 across the thigh and shank on the tested limb. Knee range of motion was set from  
207 full extension (0°) to 100° flexion. Participants completed two maximal sets of 5  
208 concentric knee extension and flexion repetitions on each limb at a speed of 60 °/s  
209 with verbal encouragement, following a submaximal warm up set. A correction for  
210 the gravitational effect on the shank was applied and torque was recorded  
211 continuously at 100 Hz. The uninvolved leg was tested first for the ACLR athletes  
212 and the dominant limb (self-reported preferred kicking limb) was tested first for the

213 controls. Each ACLR athlete completed the IKDC questionnaire to assess subjective  
214 knee function.<sup>28</sup>

215

### 216 *Data Processing*

217 Jump height was calculated from the vertical velocity of the centre of body mass  
218 (CoM) at take-off, as derived from the impulse-momentum relationship.<sup>29</sup> Take-off  
219 was defined as the first instant the sum of GRF<sub>v</sub> on both force platforms was less  
220 than 10 N and landing was defined as the first instant the sum of GRF<sub>v</sub> on both force  
221 platforms was greater than 10 N after take-off. CoM vertical velocity was used to  
222 define phases of interest: The eccentric deceleration phase was defined as the time  
223 interval from maximum negative velocity to zero velocity (lowest CoM position); the  
224 concentric phase was defined from zero velocity to the instant of take-off; the landing  
225 phase was defined as the time interval from landing to zero velocity (lowest CoM  
226 position) (Figure 1). Impulse was calculated separately for the left and right limb for  
227 all phases as the first integral of the force-time curve and divided by body mass to  
228 allow comparison between groups. All impulse variables were extracted using  
229 custom MATLAB scripts (version 2015a, Mathworks Inc., Massachusetts, USA).

230

231 The isokinetic dynamometer set with the highest peak knee extension torque and a  
232 repetition peak torque coefficient of variation of less than 0.1 was used for analysis.  
233 Peak torque relative to body mass during knee extension and flexion was extracted  
234 from this set.

235

### 236 *Asymmetry Calculation*

237 An asymmetry index (AI) along with the absolute value (AAI) were calculated for  
238 each impulse phase and for isokinetic peak torque in flexion and extension for all

239 groups (BPTB, HT, Controls). AI was used for linear regression modelling in order to  
 240 preserve information regarding the direction of the asymmetry. AAI was used in all  
 241 between-group comparisons to remove direction from the calculation, as the  
 242 reference value used in control groups is arbitrary but affects the results of group  
 243 comparisons.<sup>30</sup>

244

#### 245 *Control Group*

$$246 \quad AI = \frac{(\text{Dominant limb} - \text{Non dominant limb})}{\text{Maximum of dominant and non dominant}} \times 100$$

247 [1]

248 Dominance was defined as the self-reported limb the participant would use to kick a  
 249 ball.<sup>31</sup> A positive AI indicated that the value of the parameter was greater for the  
 250 dominant limb and a negative AI indicated that the value of the parameter was  
 251 greater for the non-dominant limb.

252

#### 253 *BPTB and HT Groups*

$$254 \quad AI = \frac{(\text{Uninjured limb} - \text{ACLR limb})}{\text{Maximum of uninjured and ACLR limb}} \times 100$$

255 [2]

256 A positive AI indicated that the value of the parameter was greater for the uninjured  
 257 limb and a negative AI indicated that the value of the parameter was greater for the  
 258 injured limb.

259

260 For all groups, AAI was calculated for all impulse and isokinetic strength parameters  
 261 as

$$262 \quad AAI = \sqrt{AI^2}$$

263 [3]

#### 264 *Statistical Analysis*

265 Shapiro-Wilk tests were used to determine whether kinetic impulse AAI, isokinetic  
266 strength AAI, jump height, IKDC scores, time from injury to surgery and time from  
267 surgery to testing session were normally distributed for all groups.

268  
269 Kruskal-Wallis tests and non-parametric post-hoc testing (Mann-Whitney U tests with  
270 Bonferroni-Holm correction for multiple comparisons) were used for between-group  
271 comparisons (BPTB, HT and controls) in impulse AAIs for each phase of the CMJ  
272 (eccentric deceleration, concentric and landing) and knee extensor and flexor  
273 strength AAIs. Friedman tests and non-parametric post-hoc testing (Wilcoxon tests  
274 with Bonferroni-Holm correction for multiple comparisons) were used for within-group  
275 comparisons in impulse AAIs for each phase of the CMJ. A one-way ANOVA and  
276 Tukey HSD post-hoc testing were used for between-group comparisons in jump  
277 height. Time from injury to surgery and time from surgery to testing session were  
278 compared between BPTB and HT using Mann Whitney U tests. Two tailed  
279 independent Student's t-tests were used to compare IKDC scores between BPTB  
280 and HT.

281  
282 A chi-squared goodness of fit test was used to test whether the proportion of  
283 participants for which each limb (ACL or uninjured; dominant or non-dominant)  
284 produced the greatest magnitude in the kinetic parameter (impulse or torque)  
285 differed from that which would be expected if asymmetry direction were random. A  
286 linear regression model was used to assess the relationship between eccentric  
287 deceleration AI or concentric impulse AI and knee extensor strength AI in all groups.

288  
289 To determine magnitude of differences, Cohen's *d* effect size (ES) was calculated  
290 and interpreted using the following thresholds:  $ES > 0.2$  = small;  $ES > 0.5$  = moderate;

291 ES>0.8=large.<sup>32</sup> Statistical analyses were performed using IBM SPSS 2016 version  
292 24 for Mac (IBM Inc, Chicago, IL, USA). All summary statistics are reported as mean  
293  $\pm$  standard deviation (SD). Significance was accepted at  $\alpha=0.05$ .

294

## 295 **RESULTS**

296

297 IKDC questionnaire, CMJ height, time from injury to surgery and time from surgery  
298 results are reported in Table 2. A main effect of group on jump height was found  
299 ( $F(2, 63) = 4.083, p=0.02$ ). Post-hoc testing did not identify a difference in jump  
300 height between BPTB and HT ( $p=0.93, ES=0.10$ ). Controls jumped higher than  
301 BPTB ( $p=0.03, ES=1.00$ ) but not than HT ( $p=0.07, ES=0.64$ ). No differences were  
302 found in IKDC scores between BPTB and HT ( $t=-0.97, p=0.34, ES=0.29$ ). Time from  
303 surgery to testing was  $9\pm 14$  days greater for BPTB than HT ( $U=122, p=0.005,$   
304  $ES=1.06$ ). No difference was found in the time from injury to surgery between BPTB  
305 and HT ( $U=-231, p=0.79$ ).

306

### 307 *Phase-Specific Impulse AAls*

308

309 A main effect of group was found for AAI during all phases (eccentric deceleration  
310 phase:  $\chi^2(2)=9.259, p=0.01$ ; concentric phase:  $\chi^2(2)=24.093, p<0.001$ ; landing  
311 phase:  $\chi^2(2)=6.970, p=0.03$ ).

312

313 During the eccentric deceleration phase post-hoc testing revealed that BPTB  
314 demonstrated a greater AAI than HT ( $U=119, p=0.01, ES=0.85$ ). No difference in  
315 impulse AAI were found between BPTB and controls during this phase, although the  
316 difference closely approached significance for BPTB demonstrating greater

317 asymmetries than controls ( $U=150$ ,  $p=0.06$ ,  $ES=0.71$ ). No difference was found in  
318 AAI between HT and controls ( $U=-204$ ,  $p=0.37$ ,  $ES=-0.21$ ).

319

320 During the concentric phase, BPTB demonstrated a greater AAI than HT ( $U=119$ ,  
321  $p=0.008$ ,  $ES=0.94$ ) and controls ( $U=39$ ,  $p<0.001$ ,  $ES=1.84$ ). HT also had a greater  
322 AAI than controls during this phase ( $U=148$ ,  $p=0.03$ ,  $ES=0.77$ ).

323

324 During the landing phase, no differences were found in AAI between BPTB and HT  
325 ( $U=187$ ,  $p=0.30$ ,  $ES=0.37$ ). BPTB demonstrated a greater landing phase AAI than  
326 controls ( $U=132$ ,  $p=0.03$ ,  $ES=0.78$ ). However, no differences were found in AAI  
327 between HT and controls during this phase ( $U=181$ ,  $p=0.30$ ,  $ES=0.39$ ). Phase-  
328 specific impulse AAIs for all groups are illustrated in Figure 2.

329

330 A main effect of impulse phase was found for BPTB ( $\chi^2(2)=7.182$ ,  $p=0.03$ ) and  
331 controls ( $\chi^2(2)=12.091$ ,  $p=0.01$ ) but not HT ( $\chi^2(2)=4.727$ ,  $p=0.09$ ). Post-hoc testing  
332 revealed BPTB demonstrating a greater AAI in the eccentric deceleration phase than  
333 the concentric phase ( $p=0.01$ ,  $ES=0.56$ ). No differences were found in AAI between  
334 concentric and landing phases ( $p=0.05$ ,  $ES=0.71$ ) or between eccentric deceleration  
335 and landing phases in BPTB ( $p=0.32$ ). Controls showed a greater AAI in the  
336 eccentric deceleration and landing phases than the concentric phase ( $p<0.001$ ,  
337  $ES=1.27$ ;  $p=0.03$ ,  $ES=0.86$ ). No difference was found in AAI between the eccentric  
338 deceleration and landing phases in the control group ( $p=0.64$ ).

339

#### 340 *Asymmetry direction*

341 There was a greater number of jumps in which impulse was greater on the uninjured  
342 limb than the ACL limb during all phases of the CMJ in BPTB and HT ( $p<0.001$ ). In

343 controls, there was a greater number of jumps in which impulse was greater on the  
344 dominant limb than the non-dominant limb during all phases ( $p<0.001$ ).

345

### 346 *Isokinetic Strength*

347 A main effect of group on isokinetic knee extensor strength AAI ( $\chi^2(2)=19.060$ ,  
348  $p<0.001$ ) but not on flexor strength AAI ( $\chi^2(2)=5.519$ ,  $p=0.06$ ) was identified. Post-  
349 hoc testing revealed that BPTB had a greater knee extensor strength AAI than HT  
350 ( $U=102$ ,  $p=0.002$ ,  $ES=1.17$ ) and controls ( $U=72$ ,  $p<0.001$ ,  $ES=1.40$ ). No difference  
351 was found between HT and controls in knee extensor strength AAI ( $U=185$ ,  $p=0.18$ ).  
352 Isokinetic knee extensor and flexor strength AI and AAI results are shown in Table 3.

353

354 See Table 4 for relative phase-specific impulses and isokinetic strength for both  
355 limbs in all groups.

356

### 357 *Linear Regression Analysis*

358 There was a positive relationship between isokinetic knee extensor strength AI and  
359 CMJ concentric impulse AI in BPTB ( $p=0.002$ ,  $r^2=0.39$ ), HT ( $p=0.04$ ,  $r^2=0.18$ ) but not  
360 controls ( $p=0.33$ ,  $r^2=0.05$ ). No significant relationship was found between isokinetic  
361 knee extensor strength AI and CMJ eccentric deceleration impulse AI in BPTB  
362 ( $p=0.22$ ,  $r^2=0.07$ ), HT ( $p=0.05$ ,  $r^2=0.18$ ) or controls ( $p=0.67$ ,  $r^2=0.01$ ). Figure 3  
363 illustrates the linear regression model for all groups.

364

## 365 **DISCUSSION**

366

367 When assessed nine months post-ACLR, athletes with a BPTB autograft  
368 demonstrated greater inter-limb impulse asymmetries than athletes with a HT

369 autograft in the eccentric deceleration and concentric phases of the CMJ to achieve  
370 similar jump performance. BPTB athletes also had greater impulse asymmetries than  
371 controls during the concentric and landing phases of the CMJ. HT athletes showed a  
372 greater impulse asymmetry than controls during the concentric phase of the jump  
373 only. Knee extensor strength asymmetry explained 39% (BPTB) and 18% (HT) of the  
374 variation in concentric impulse asymmetry during the CMJ but no significant  
375 relationship was found in controls. Furthermore, no significant relationship was found  
376 between eccentric deceleration impulse asymmetry and knee extensor strength  
377 asymmetry in any groups.

378

### 379 *Direction of Asymmetry*

380 ACLR athletes chose to offload the operated side in this study. This may reflect a  
381 reduced capacity to absorb load on the ACLR side while executing the task, and  
382 results in an adaptive pattern favouring the non ACLR side.<sup>24</sup> It may also demonstrate  
383 a learned behaviour such as fear avoidance. Controls preferentially offloaded their  
384 non-dominant limb.

385

### 386 *Eccentric Deceleration and Landing Phases*

387 In this study, loading asymmetry during the eccentric deceleration and landing  
388 phases demonstrated that the athletes did not absorb energy equally on both limbs  
389 to decelerate their body.<sup>33</sup> These phases are often associated with the ACL injury  
390 mechanism, which occurs most commonly in the early part of eccentric phase.<sup>34</sup>  
391 Mean loading asymmetries of 20% were observed during the eccentric deceleration  
392 phase of the jump in BPTB cohort, which was double the asymmetry demonstrated  
393 in HT cohort (large *ES*: 0.85). In the landing phase, BPTB had a 21% asymmetry,  
394 which was significantly greater than the 12% asymmetry demonstrated by controls



395 (moderate *ES*: 0.78). No significant difference was found in landing impulse  
396 asymmetry between BPTB and HT cohorts. The greater asymmetry measured  
397 during the eccentric deceleration phase compared to the concentric phase  
398 (moderate *ES*: 0.56) in the BPTB cohort, has previously been identified by Paterno  
399 et al.<sup>12</sup> as a risk for both operated and non-operated limb. Larger asymmetries were  
400 found in this study during the eccentric deceleration and landing phases of the CMJ  
401 compared to the concentric phase in BPTB athletes. As the ACL injury mechanism  
402 occurs during these higher risk eccentric phases<sup>34</sup> in which asymmetries are at their  
403 greatest, rehabilitation interventions should additionally target symmetry during these  
404 phases to improve outcomes.

405

#### 406 *Concentric Phase*

407 The concentric phase of the CMJ is related to jump performance (net concentric  
408 impulse mechanically determines jump height) and assesses the athlete's ability to  
409 accelerate their CoM from a squat position to take-off during a powerful extension of  
410 the hip, knee and ankle.<sup>29</sup> The BPTB cohort showed a 14% loading asymmetry  
411 during the concentric phase, which was greater than the 8% and 4% asymmetry  
412 demonstrated by the HT cohort and controls respectively (large *ES*: 0.94; large *ES*:  
413 1.84). Rehabilitation practitioners often use concentric exercises to improve jump  
414 performance after ACLR and much of the existing literature regarding RTP  
415 assessment focuses on jump or hop tests with a concentric emphasis.<sup>35</sup> Our findings  
416 suggest that this should be balanced with specific assessment of eccentric  
417 movements.

418

#### 419 *Isokinetic Strength Results*

420 The BPTB cohort demonstrated a greater knee extensor strength asymmetry than  
421 the HT cohort (large  $ES=1.17$ ) and controls (large  $ES=1.40$ ), which is to be expected  
422 due to the influence that BPTB graft harvest has on the knee extensor mechanism.  
423 This difference concurs with previously-reported findings within a similar time-scale  
424 post-surgery.<sup>9,13</sup> As seen in Figure 3, two (9% of) BPTB athletes counterintuitively  
425 demonstrated greater knee extensor strength on their ACL limb than the  
426 contralateral limb, indicating ACL limb dominance ( $AI=-14$ ;  $AI=-17\%$ ). Jordan et al.  
427 reported a similar result in a study of phase-specific asymmetries in elite skiers, with  
428 one participant out of nine demonstrating a 16% greater knee extensor strength on  
429 their ACLR than uninjured limb.<sup>18</sup> These findings highlight the presence of inter-  
430 subject variation in asymmetry outcome measures and may reflect a focus on  
431 unilateral exercises involving the ACL limb during individual rehabilitation  
432 programmes. In contrast to previous studies, we found no main effect of group on  
433 knee flexor strength asymmetry (although the result approached significance  
434 ( $p=0.053$ )). This may be due to the incorporation of a control group into our statistical  
435 model and hence our use of absolute asymmetry calculations, which reduce  
436 calculated differences between group means when the direction of asymmetry is  
437 modulated by group. See Table 3 for relative knee extensor and flexor isokinetic  
438 strength values for both limbs in all groups.

439

#### 440 *Influence of Quadriceps Strength on Functional Loading Asymmetries*

441 We hypothesised that there would be a relationship between knee extensor strength  
442 asymmetries and phase-specific impulse asymmetries in the CMJ, as previous  
443 research has found a relationship between leg muscle mass and concentric impulse  
444 asymmetries in ACLR athletes.<sup>18</sup> A linear regression model showed that knee  
445 extensor strength asymmetry could explain 39% and 18% of the variation in

446 concentric impulse asymmetry during the CMJ in the BPTB and the HT cohorts  
447 respectively. As a relationship was found within the ACLR athletes but not the control  
448 group, concentric strength appears to be an important focus for ACLR rehabilitation,  
449 especially with BPTB athletes. Knee extensor strength deficits are commonly  
450 reported at and beyond nine months post-surgery<sup>9,13</sup> and, given their relationship to  
451 functional loading deficits as demonstrated here, may warrant greater focus earlier in  
452 the rehabilitation process. In both ACLR cohorts, but particularly the HT cohort, other  
453 neuromuscular factors and rate of GRF<sub>v</sub> development (RFD) may be contributing to  
454 concentric loading asymmetries.

455

456 We found no significant relationship between knee extensor strength asymmetry and  
457 eccentric impulse asymmetry in any group. Previous studies have found that ACLR  
458 athletes demonstrate an improvement in isokinetic knee extensor strength when  
459 managed with rehabilitation programs that include knee concentric strength  
460 exercises.<sup>36</sup> However, our results suggest that concentric strength asymmetry does  
461 not contribute towards loading asymmetries during the eccentric phase. This phase  
462 is when loading is greatest (Table 4) and also when the ACL rupture most frequently  
463 occurs.<sup>34</sup> Our findings suggest that eccentric qualities may need to be specifically  
464 targeted during rehabilitation in addition to concentric strength and the development  
465 of concentric impulse-generation qualities.

466

467 RFD is often used to assess explosive strength capabilities and muscle function after  
468 ACLR.<sup>37</sup> Both knee extensor and flexor isometric RFD delays have been found on  
469 the involved limb when compared to the contralateral limb in BPTB graft athletes<sup>38</sup>.  
470 Although there is limited literature investigating RFD during dynamic movements in  
471 ACLR athletes, it may be that eccentric RFD asymmetries are contributing towards

472 the eccentric loading asymmetries observed here by influencing early-phase  
473 impulse. Other factors such as knee eccentric strength may also have contributed  
474 towards the eccentric impulse asymmetry, although knee eccentric extensor strength  
475 asymmetry has been found to recover more rapidly than concentric strength  
476 asymmetry post-ACLR.<sup>39</sup> Lower-limb inter-segmental and coordination asymmetries  
477 at the hip, knee and ankle may also be contributing towards loading asymmetries by  
478 compensating for the injured joint within and between limbs.<sup>40</sup> Finally, it should be  
479 noted that the GRF is not a direct measure of the force experienced by the  
480 musculoskeletal structures of the limb,<sup>41</sup> although it is strongly correlated to net knee  
481 extensor moment in similar tasks,<sup>42</sup> and tissue loading is also affected by factors  
482 such as muscle contraction and mechanical advantage. Future research should  
483 investigate other potential factors contributing to phase-specific loading  
484 asymmetries.

485

#### 486 *RTP Guidelines*

487 There is a lack of consensus regarding acceptable asymmetries for safe RTP after  
488 ACLR. Asymmetries of <10-15% have been recommended as a framework for safe  
489 RTP during functional tests involving jumping movements,<sup>8,10</sup> although this is  
490 dependent on a number of factors including the movement assessed and the  
491 biomechanical variable selected for analysis.<sup>43</sup> The challenge of obtaining a clinically  
492 meaningful asymmetry criterion for RTP is partially due to the limited availability of  
493 normative values for different cohorts and exercises.<sup>26</sup> In this study we report mean  
494 normative phase-specific impulse asymmetry values of 4-12% in a healthy control  
495 group (see Figure 3). Significant differences with large effect sizes were found  
496 between ACLR athletes and controls, even when the <10-15% inter-limb asymmetry  
497 target was achieved. The <10-15% rehabilitation goal may hence be an overestimate

498 of rehabilitation status and restoration of phase-specific impulse asymmetries to  
499 normative range may be a more appropriate and sensitive target criterion.

500

#### 501 *Methodological Considerations*

502 No significant differences were found in IKDC scores between the BPTB and HT  
503 cohorts at the time of testing. Thus, we interpret the differences found in impulse  
504 asymmetries in this study as relating to the capacity of each limb to produce force  
505 rather than the athlete's confidence in knee function.

506

507 Future research should investigate the effect of defined exercise interventions on  
508 loading asymmetries in BPTB autograft athletes and HT autograft athletes during the  
509 rehabilitation process to restore normal levels of impulse asymmetry throughout all  
510 phases. Many rehabilitation practitioners use bilateral vertical jumps as an objective  
511 RTP test,<sup>10</sup> however little is known regarding whether - and how - phase-specific  
512 impulse asymmetries relate to rehabilitation outcomes. Prospective research should  
513 therefore investigate whether these differences in loading asymmetries influence  
514 outcomes such as pain-free RTP and second ACL injury (to either the operated or  
515 non-operated limb) for both graft types.

516

#### 517 *Conclusion*

518 There was a significant influence of graft donor site on loading asymmetries during a  
519 CMJ in athletes at nine months post-ACLR, although no differences in jump height  
520 performance or subjective knee function were identified. Knee extensor strength  
521 asymmetry was greater for the BPTB than the HT cohort. This strength asymmetry  
522 partially explained concentric but not eccentric impulse asymmetries in both graft  
523 types; however, more research is needed to determine other factors contributing to

524 loading asymmetries for each graft type. Given the results of this study, graft-specific  
525 strength deficits should be targeted during rehabilitation along with a greater focus  
526 on reducing eccentric impulse asymmetries after ACLR for both graft types.

527

## 528 **PERSPECTIVES**

529

530 This is the first study to demonstrate an effect of graft type on phase-specific  
531 impulse asymmetries and to relate these asymmetries to strength asymmetry. We  
532 found that BPTB athletes had greater inter-limb impulse asymmetries than HT in the  
533 eccentric deceleration and concentric phases of the CMJ, although similar jump  
534 heights were achieved. By showing that knee extensor strength asymmetry was a  
535 significant predictor of concentric but not eccentric impulse asymmetries in both graft  
536 types, we contribute to the understanding of strength assessment's role and  
537 limitations in explaining functional asymmetry in performance tasks. Rehabilitation  
538 practitioners commonly use concentric exercises to improve jump performance after  
539 ACLR.<sup>35</sup> However, we identified larger asymmetries during the eccentric deceleration  
540 phase of the CMJ than in the concentric phase in BPTB athletes, suggesting that  
541 specific targeting of eccentric movements may be beneficial during rehabilitation  
542 interventions and monitoring.

543

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