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1 **PATELLOFEMORAL JOINT LOADS IN ACL RECONSTRUCTED ELITE ATHLETES DURING RUNNING AT**
2 **TIME OF RETURN TO SPORT**

3

4 **ABSTRACT**

5 **Background:** Patellofemoral joint pain and degeneration is common in patients who undergo ACL
6 reconstruction (ACLR). The presence of patellofemoral joint pain significantly impacts on the ability
7 to continue to participate in sport and may even have a bearing on participation in activities of daily
8 living. What is currently unclear is the mechanisms behind this process, previous research has
9 identified altered patellofemoral joint loading in individuals with patellofemoral joint pain when
10 running. It is unclear if this process is occurring following ACLR.

11 **Hypothesis/Purpose:** To assess the patellofemoral joint stresses during running in ACLR knees and
12 compare the findings to non-injured knee and matched control knees.

13 **Study Design:** Cohort study

14 **Methods:** Thirty four elite sports practitioners who had undergone ACLR and thirty four age and sex
15 matched controls participated in the study. The participants had their running gait assessed using 3D
16 motion capture, and knee loads and forces calculated using inverse dynamics.

17 **Results:** There was a significance difference in knee extensor moment, knee flexion angles,
18 patellofemoral contact force (around 23% greater), and patellofemoral contact pressure (around
19 27% greater) between the ACLR and non-injured limb ($p \leq 0.04$) and the ACLR and control limb
20 ($p \leq 0.04$), with no significant difference between the non-injured and control limbs ($p \geq 0.44$).

21 **Conclusion:** Significantly greater levels of patellofemoral joint stress and load were found in the
22 ACLR knee compared to the non-injured and control knees.

23 **Clinical Relevance:** Altered levels of patellofemoral stress in the ACLR knee during running may
24 predispose these individuals to patellofemoral joint pain.

25 **Key terms:** patellofemoral joint, stress, running, anterior cruciate ligament

26

27 **What is known about the subject**

28 A large proportion of patients following ACL reconstructive surgery have long term knee symptoms,
29 which have been linked to the development of Osteoarthritis, the mechanism by which this occurs is
30 currently not clear.

31

32 **What this study adds to existing knowledge**

33 The study demonstrates that ACL reconstruction patients despite reaching the end of an intensive
34 rehabilitation have a running pattern which significantly increases load on the patellofemoral joint in
35 a way which could be speculated to be a precursor to damage and degeneration.

36

37

38 **PATELLOFEMORAL JOINT LOADS IN ANTERIOR CRUCIATE LIGAMENT RECONSTRUCTED ELITE**
39 **ATHLETES DURING RUNNING AT TIME OF RETURN TO SPORT**

40 **INTRODUCTION**

41 Patellofemoral osteoarthritis (PFOA) is by no means a rare outcome following Anterior Cruciate
42 Ligament reconstruction (ACLR) surgery; it has been reported to affect approximately 50% of ACLR
43 patients within 10 years of surgery (7). The presence of PFOA appears to be strongly linked to the
44 occurrence of knee symptoms and impaired knee function following ACLR (6, 7). The high rates of
45 PFOA do not appear to be related to the type of graft used in the reconstruction (7). The
46 mechanisms underpinning the development of PFOA following ACLR surgery though remain unclear.

47

48 Patellofemoral pain (PFP) has been defined by pain which occurs as a result of the contact between
49 the articular surfaces of the patella and trochlea of the femur during dynamic activities (3).
50 Patellofemoral pain can be debilitating and may significantly restrict participation in sporting
51 activities (23, 28). Patellofemoral pain has been cited as a potential precursor to the progression of
52 osteoarthritic symptoms in later life (6, 7). A number of biomechanical mechanisms have been linked
53 to the etiology of PFP such as increased internal knee abduction moments and angles and decreased
54 internal knee extensor moments and knee flexion angles during a variety of tasks (29). It is believed
55 that the habitual and excessive contact stresses could develop between the patella and femur could
56 be strongly associated with the initiation of patellofemoral symptoms (14, 17), but there is only
57 limited prospective evidence available to support this hypothesis (29).

58

59 Knee symptoms such as swelling and pain are reported as one of the main limiting factors
60 preventing return to sport following ACLR (20); it is possible that these symptoms are at least in part
61 related to the presence of PFP because of the high incidence of PFP in the first 12 months post ACLR
62 (7). This appears to indicate that there is a need to investigate the loads experienced by the
63 patellofemoral joint in ACLR patients in relation to both the non-injured limb and non-injured

64 individuals in order to gain further insight into the increased incidence of patellofemoral disorders
65 which occur post ACLR.

66

67 Previous research has found decreased internal knee extensor moments and knee flexion angles in
68 both patellofemoral pain (PFP) patients (2) and the ACLR knee (19) during running, but the link
69 between these changes and patellofemoral joint (PFJ) loads is yet to be established during running.
70 Hypothetically the decreased knee flexion angle could be related to a decrease in the PFJ contact
71 area (29) so increasing joint stress; this though may be mitigated by the decreased internal knee
72 extensor moment decreasing the overall load, but the effect of this inter-relationship in PFP patients
73 has yet to be established. Previous studies have also found increased patellofemoral joint stress in
74 patients with PFP during running compared to controls (2) in the presence of decreased knee flexion
75 angles and knee extensor moments. The aim of this study is therefore to describe patella stress
76 during running in ACLR patients and matched controls, specifically to assess if differences exist in the
77 levels of load and stress between injured, non-injured and control knees which could be linked to
78 the future development of PFOA. It is hypothesised that the ACLR knee will present with greater
79 patellofemoral joint contact pressures and forces in comparison to uninjured and control knees.

80

81 **METHOD**

82 **Participants**

83 Thirty four patients who had undergone an ACLR and thirty four age and sex matched controls
84 participated in the study. These patients were recruited via orthopaedic surgeons or directly from
85 the sports teams, following an invitation letter to participate in the study. An initial screening of the
86 volunteers was then undertaken to exclude any individuals who had received more than primary
87 ACL reconstructive surgery. Assessment was performed on all eligible participants who volunteered
88 to participate between the period January 2015-November 2016 (18 months). The control group
89 included 10 females and 24 males, who regularly participated in team sports, physical activity and

90 training (> 6 hours per week) and had no history of lower limb injury, with a mean age of 22.1 (+/-
91 3.6) years, body mass 76.9 (+/-13.2) kg, height 1.70 (+/-0.1)m, there was no significant difference
92 ($p>0.05$) in these variables between the control and patient group. The patient group consisted of 10
93 females and 24 males who had all undergone ACL reconstruction (mean time since surgery 7.8 (+/-
94 1.3) months). All these individuals were full time professional athletes performing at the time of
95 injury at national or international level across a variety of sports (Soccer, Rugby Union, Rugby
96 League, Netball, Basketball and Taekwondo). All these individuals had been medically cleared to
97 return to sport and undertaken and past functional return to play testing and all their rehabilitation
98 had been undertaken on a full time basis within their professional club or elite performance centre
99 environment supervised by a sports physiotherapist, sports physician and Orthopaedic surgeon.
100 Twenty of the 34 had received a hamstring autograft and 14 had received a patella tendon autograft.
101 All surgery had been undertaken by experienced orthopaedic surgeons using standard procedures,
102 with none of the cases having any secondary procedures, beyond the primary ACLR. At the time of
103 surgery none of these athletes had any significant meniscus lesions or chondral damage reported (as
104 assessed either from MRI or by the orthopaedic surgeon at the time of surgery). The patient group
105 had a mean age of 21.8 (+/-3.9) years, body mass 79.9 (+/-16.5) kg, height 1.71 (+/-0.1)m, and a
106 global KOOS questionnaire score of 89.3(+/-8.6) at time of assessment. Ethical approval was
107 provided by the University's ethical committee and written informed consent was attained from all
108 participants.

109

110 **Procedures**

111 **3D motion capture:** The method is based on the procedure previously reported in Alenezi et al (1). A
112 ten-camera motion analysis system (Pro-Reflex, Qualisys, Sweden), sampling at 240 Hz, and a force
113 platform embedded into the floor (AMTI, USA), sampling at 1200 Hz, were used to collect kinematic
114 and kinetic variables during the support stance phase of the running task. Before testing,
115 participants were fitted with the standard training shoes (New Balance, UK) to control shoe-surface

116 interface. Reflective markers (14mm) were attached with self-adhesive tape to the participants'
117 lower extremities over the following landmarks; anterior superior iliac spines, posterior superior iliac
118 spines, iliac crest, greater trochanters, medial and lateral femoral condyles, medial and lateral
119 malleoli, posterior calcanei, and the head of the first, second and fifth metatarsals. The tracking
120 markers were mounted on technical clusters on the thigh and shank with elastic bands. The foot
121 markers were placed on the shoes, and the same individual placed the markers for all participants.
122 The calibration anatomical systems technique (CAST) was employed to determine the six-degree of
123 freedom movement of each segment and anatomical significance during the movement trials. The
124 static trial position was designated as the participants' neutral (anatomical zero) alignment, and
125 subsequent kinematic measures were related back to this position. To orientate participants with
126 the running task, each participant was asked to perform 3 practice trials before data collection.
127 Participants were required to complete five successful running trials.

128

129 **Running task:** All testing took place on an indoor synthetic running surface which was 25m long.
130 Each participant started approximately 10 m behind the first set of timing lights and was ask to run
131 at a comfortable running pace. Some flexibility was allowed for the exact starting point for each
132 participant to allow for the participants differing stride pattern as they approached the force
133 platform, to be able to "hit" the force platform without alteration to normal stride pattern. The
134 participants were instructed to run through the camera capture field until they had passed the
135 second timing gate, average running speed for the ACLR group was 3.5 (+/-0.57) m.sec⁻¹ and for the
136 control group 3.5 (+/-0.58) m.sec⁻¹.

137

138 Visual3D motion (Version 4.21, C-Motion Inc. USA) was used to calculate the joint kinematic and
139 kinetic data. Motion and force plate data were filtered using a Butterworth 4th order bi-directional
140 low-pass filter with cut-off frequencies of 12 Hz and 25 Hz, respectively, with the cut-off frequencies
141 based on a residual analysis (26). All lower extremity segments were modelled as conical frustra,

142 with inertial parameters estimated from anthropometric data (10). Joint kinematic data calculated
 143 using an X–Y–Z Euler rotation sequence. Joint kinetic data were calculated using three-dimensional
 144 inverse dynamics, and the joint moment data were normalized to body mass and presented as
 145 internal moments referenced to the proximal segment. Internal knee extensor moments were
 146 described in this study, with the maximum value during stance phase of running being reported
 147 along with the knee flexion angle at that point.

148

149 **Calculation of Patellofemoral joint force and pressure:** Patella contact force (PCF) during running
 150 was estimated using knee flexion angle (kf) and knee extensor moment (KEM) through the
 151 biomechanical model of Ho et al. (14). This model has been utilised previously to resolve differences
 152 in PCF and patella contact pressure (PCP) (4, 5, 16, 25). The effective moment arm distance of the
 153 quadriceps muscle (QM) was calculated as a function of kf using a non-linear equation, based on
 154 information presented by van Eijden et al. (11):

155

$$156 \quad QM = 0.00008kf^3 - 0.013kf^2 + 0.28kf + 0.046$$

157

158 The force (Newtons) of the quadriceps (FQ) was calculated using the

159 Formula below:

160

$$161 \quad FQ = KEM/QM$$

162

163 Net PCF (Newtons) was estimated using the FQ and a constant (C):

164

$$165 \quad PCF = FQ * C$$

166 C was described in relation to kf using a curve fitting technique based on the non-linear equation

167 described by van Eijden et al. (11):

168

169 $C = (0.462+0.00147xkf^2)/(1-0.0162xkf+0.000155xkf^2-0.000000698xkf^3)$

170

171 PCP (MPa) was calculated using the net PCF divided by the patellofemoral contact area. The contact
 172 area was described using the Ho et al. (14) recommendations by fitting a 2nd order polynomial curve
 173 from the data of Beiser et al (3), Lee et al (18), Powers et al. (21) and Salsich et al (22) to provide
 174 patellofemoral contact areas at varying angles of kf.

175

176 $PCP = PCF/contact\ area$

177

178 **Statistical analyses:** Prior to analysis the data were assessed for normality. The following variables
 179 were analyzed from the control group and the ACLR and non-injured legs of the patient group: peak
 180 internal knee extensor moment (KEM) during stance phase; knee angle at peak KEM; patella contact
 181 force (PCF) and patella contact pressure. For each variable a one-way ANOVA assessed the
 182 differences between limbs (ACLR, non-injured and control) then as appropriate either a paired or
 183 two sample T-test was used for post hoc assessment of the differences with appropriate Bonferroni
 184 adjustment applied.

185

186 **RESULTS**

187 **Table 1: Mean values found during running for each variable across limbs**

	Patella contact pressure (Mpa)			Patella contact force (xBW)			Knee extensor moment (Nm/kg)			Knee angle at peak KEM (degrees)		
	ACLR	ACL NI	Control	ACLR	ACL NI	Control	ACLR	ACL NI	Control	ACLR	ACL NI	Control
Mean	4.87	3.57	3.7	5.92	4.61	4.75	2.87	3.28	3.26	44.76	48.85	49.64
Standard Deviation	1.22	0.46	0.63	3.78	1.51	2.08	0.54	0.56	0.34	6.30	5.52	7.62

188 ACLR = ACL reconstructed limb

189 ACLNI = ACL patient non-injured limb

190

191 There was a significant difference between limbs for all variables ($p < 0.02$, table 1). There was a
 192 significance difference in KEM between the ACLR and non-injured limb ($p = 0.002$) and the ACLR and
 193 control limb ($p = 0.0003$), with no significant difference between the non-injured and control limbs
 194 ($p = 0.44$). There was a significance difference in knee flexion angle between the ACLR and non-
 195 injured limb ($p = 0.003$) and the ACLR and control limb ($p = 0.003$), with no significant difference
 196 between the non-injured and control limbs ($p = 0.31$). There was a significance difference in PCF
 197 between the ACLR and non-injured limb ($p = 0.03$) and the ACLR and control limb ($p = 0.04$), with no
 198 significant difference between the non-injured and control limbs ($p = 0.38$). There was a significance
 199 difference in PCP between the ACLR and non-injured limb ($p = 0.01$) and the ACLR and control limb
 200 ($p = 0.04$), with no significant difference between the non-injured and control limbs ($p = 0.37$) (Table
 201 1). All other kinematic (hip adduction and internal rotation: knee abduction and rotation) angles and
 202 kinetics (hip adduction and internal rotation: knee abduction and rotation) presented no significant
 203 differences between the ACLR, non-injured and control limbs.

204 **DISCUSSION**

205 This study has demonstrated significantly increased patella contact pressures in the ACLR knee of
 206 patients compared to their contralateral knee or the knee of matched controls. They also
 207 demonstrated significantly increased patella contact forces whilst having significant reductions in
 208 knee extensor moments and knee flexion angles during running. The levels of contact pressures and
 209 forces for the control and non-injured limb were in a range similar to those previously reported (2,
 210 27), however, the levels found in the ACL reconstructed knee were higher. As there is an elevated
 211 risk of PFOA and PFP in this group these findings may justify the formulation of a hypothesis as the
 212 possible mechanisms behind the occurrence of these problems. It is believed that the habitual and
 213 excessive contact stresses between the patella and femur could be associated with the initiation of
 214 patellofemoral symptoms (14, 17). This study has shown the presence of increased patella stress in
 215 an asymptomatic group of ACLR knees, 6-9 months post-ACLR surgery. While this time period is still
 216 relatively early to develop PFJ OA symptoms (7), the possibility exists. Currently this group was

217 asymptomatic and had a higher than average KOOS score for this stage (13) and were deemed fit to
218 return to sport having participated in full time rehabilitation programmes. However, despite these
219 advantages and high levels of performance they developed a movement strategy that could be
220 exposing their PFJ to excessive load.

221

222 It is not uncommon for ACLR patients to demonstrate both decreased knee extensor moments and
223 knee flexion angles across a variety of tasks such as running, walking and single leg landing tasks
224 (15), the findings of this study align with the findings of these others (19). Furthermore, Culvenor et
225 al (9) found that during a forward hopping task ACLR patients with early PFOA had reduced knee
226 flexion angles, despite hopping similar distances. What has not been previously calculated is the
227 effect of these biomechanical changes on PFJ load and stress in the ACLR group, so direct
228 comparison of our findings is not possible. Why the increased stress is occurring could be related to
229 the decreased knee flexion angle which leads to a decrease in the PFJ contact area (29) so increased
230 joint stress. This increase in stress may be mitigated by the decreased knee extensor moment
231 decreasing the overall load; the effect of this inter-relationship though would appear to have been
232 an increased stress per unit area of contact.

233

234 It might be speculated that the increased stress could then create an imbalance in the underlying
235 tissue homeostasis with stress exceeding the cartilage and subchondral bone mechanic-biological
236 thresholds (29). This could in turn lead to the patellar articular cartilage then becoming thinner and
237 less elastic which may lead to more focal loads being transmitted to the highly innervated
238 subchondral bone (12) resulting in pain. Increasing loading may then result in elevated bone
239 metabolic activity and patellar water content which can predict the progressive cartilage loss of
240 PFOA (24). The changes in patella stress could therefore be very significant in the development of a
241 cascade of events progressing through PFP to PFOA.

242

243 This study was limited to a specific homogenous group of elite sportspeople examined immediately
244 prior to return to full unrestricted sporting activity. They had all completed full time fully supervised
245 rehabilitation programs, alongside this, their baseline strength and physical capabilities are likely to
246 exceed those of normal ACLR patients. Therefore the findings are not representative of the general
247 ACLR population. Due to the intensive rehabilitation these individuals received, it might be expected
248 that their results would be superior. A number of studies have shown decreased knee flexion angles
249 and internal knee extensor moments in patients at various time points post ACLR (15) including up to
250 two years post operation (9). In light of the findings of this study, it is likely that all these individuals
251 would show increased relative levels of patella stress. The increased patella stress may be a source
252 of the continued knee symptoms reported in the group (20) and play a role in the development of
253 PFOA (7, 8).

254

255 There are at least two limitations of the model used in this study. Firstly it only incorporated joint
256 angles and moments from the sagittal plane. The mechanics in the frontal and transverse planes
257 could also have a prominent effect on the contact area between the patella and the femur. The
258 model does not take into account asymmetrical loading of the PFJ across the other planes. As this
259 study found no significant differences between limbs or groups for the motion and moments in the
260 transverse and frontal plane, it is likely to have had to influence on the results. Another limitation
261 was that the model may have underestimated the quadriceps muscle force in comparison to models
262 that account for co-contraction of the muscles that surround the knee joint (30). This means the
263 absolute values provided in this paper may have underestimated the PFJ contact forces.

264 **CONCLUSION**

265 The ACLR knee exhibits significantly greater patella stress compared to either the uninjured knee or
266 the knee of control group during running. Given the proposed relationship between patella joint
267 loading and patellofemoral pathology, the current study provides some insight into why ACLR
268 patients may have a higher incidence of patellofemoral pain.

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