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

ABSTRACT

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

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

Study Design: Cohort study

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

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

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

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

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

What is known about the subject

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

What this study adds to existing knowledge

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

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

INTRODUCTION

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

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

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

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

METHOD

Participants

Thirty four patients who had undergone an ACLR and thirty four age and sex matched controls participated in the study. These patients were recruited via orthopaedic surgeons or directly from the sports teams, following an invitation letter to participate in the study. An initial screening of the volunteers was then undertaking to exclude any individuals who had received more than primary ACL reconstructive surgery. Assessment was performed on all eligible participants who volunteered to participate between the period January 2015-November 2016 (18 months). The control group included 10 females and 24 males, who regularly participated in team sports, physical activity and training (> 6 hours per week) and had no history of lower limb injury, with a mean age of 22.1 (+/-3.6) years, body mass 76.9 (+/-13.2) kg, height 1.70 (+/-0.1)m, there was no significant difference (p>0.05) in these variables between the control and patient group. The patient group consisted of 10 females and 24 males who had all undergone ACL reconstruction (mean time since surgery 7.8 (+/-1.3) months). All these individuals were full time professional athletes performing at the time of injury at national or international level across a variety of sports (Soccer, Rugby Union, Rugby League, Netball, Basketball and Taekwondo). All these individuals had been medically cleared to return to sport and undertaken and past functional return to play testing and all their rehabilitation had been undertaken on a full time basis within their professional club or elite performance centre environment supervised by a sports physiotherapist, sports physician and Orthopaedic surgeon. Twenty of the 34 had received a hamstring autograft and 14 had received a patella tendon autograft. All surgery had been undertaken by experienced orthopaedic surgeons using standard procedures, with none of the cases having any secondary procedures, beyond the primary ACLR. At the time of surgery none of these athletes had any significant meniscus lesions or chondral damage reported (as assessed either from MRI or by the orthopaedic surgeon at the time of surgery). The patient group 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 global KOOS questionnaire score of 89.3(+/-8.6) at time of assessment. Ethical approval was provided by the University's ethical committee and written informed consent was attained from all participants.

Procedures

3D motion capture: The method is based on the procedure previously reported in Alenezi et al (1). A ten-camera motion analysis system (Pro-Reflex, Qualisys, Sweden), sampling at 240 Hz, and a force platform embedded into the floor (AMTI, USA), sampling at 1200 Hz, were used to collect kinematic and kinetic variables during the support stance phase of the running task. Before testing, participants were fitted with the standard training shoes (New Balance, UK) to control shoe-surface interface. Reflective markers (14mm) were attached with self-adhesive tape to the participants' lower extremities over the following landmarks; anterior superior iliac spines, posterior superior iliac spines, iliac crest, greater trochanters, medial and lateral femoral condyles, medial and lateral malleoli, posterior calcanei, and the head of the first, second and fifth metatarsals. The tracking markers were mounted on technical clusters on the thigh and shank with elastic bands. The foot markers were placed on the shoes, and the same individual placed the markers for all participants. The calibration anatomical systems technique (CAST) was employed to determine the six-degree of freedom movement of each segment and anatomical significance during the movement trials. The static trial position was designated as the participants' neutral (anatomical zero) alignment, and subsequent kinematic measures were related back to this position. To orientate participants with the running task, each participant was asked to perform 3 practice trials before data collection. Participants were required to complete five successful running trials.

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

Visual3D motion (Version 4.21, C-Motion Inc. USA) was used to calculate the joint kinematic and kinetic data. Motion and force plate data were filtered using a Butterworth 4th order bi-directional low-pass filter with cut-off frequencies of 12 Hz and 25 Hz, respectively, with the cut-off frequencies based on a residual analysis (26). All lower extremity segments were modelled as conical frustra, with inertial parameters estimated from anthropometric data (10). Joint kinematic data calculated using an X–Y–Z Euler rotation sequence. Joint kinetic data were calculated using three-dimensional inverse dynamics, and the joint moment data were normalized to body mass and presented as internal moments referenced to the proximal segment. Internal knee extensor moments were described in this study, with the maximum value during stance phase of running being reported along with the knee flexion angle at that point.

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

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

The force (Newtons) of the quadriceps (FQ) was calculated using the Formula below:

$$FQ = KEM/QM$$

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

$$PCF = FQ*C$$

C was described in relation to kf using a curve fitting technique based on the non-linear equation described by van Eijden et al. (11):

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

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

PCP = PCF/contact area

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

RESULTS

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

ACLR = ACL reconstructed limb
ACLNI = ACL patient non-injured limb

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

DISCUSSION

This study has demonstrated significantly increased patella contact pressures in the ACLR knee of patients compared to their contralateral knee or the knee of matched controls. They also demonstrated significantly increased patella contact forces whilst having significant reductions in knee extensor moments and knee flexion angles during running. The levels of contact pressures and forces for the control and non-injured limb were in a range similar to those previously reported (2, 27), however, the levels found in the ACL reconstructed knee were higher. As there is an elevated risk of PFOA and PFP in this group these findings may justify the formulation of a hypothesis as the possible mechanisms behind the occurrence of these problems. It is believed that the habitual and excessive contact stresses between the patella and femur could be associated with the initiation of patellofemoral symptoms (14, 17). This study has shown the presence of increased patella stress in an asymptomatic group of ACLR knees, 6-9 months post-ACLR surgery. While this time period is still relatively early to develop PFJ OA symptoms (7), the possibility exists. Currently this group was asymptomatic and had a higher than average KOOS score for this stage (13) and were deemed fit to return to sport having participated in full time rehabilitation programmes. However, despite these advantages and high levels of performance they developed a movement strategy that could be exposing their PFJ to excessive load.

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

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

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

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

CONCLUSION

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

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