Biomechanical Analysis After Anterior Cruciate Ligament Reconstruction at the Return-to-Sport Time Point

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Background: Biomechanical alterations after anterior cruciate ligament reconstruction (ACLR) may increase the risk of knee reinjury. Furthermore, individuals may experience persistent biomechanical differences in the lower limbs after finishing the rehabilitation program and being ready to return to sport, which may lead to an increase in the risk of reinjury. Limited data exist on individuals after ACLR and biomechanical alterations during running in elite athletes.

Purpose: To measure kinetic and kinematic data during overground running 6 to 8 months after ACLR in an elite sports cohort.

Study Design: Controlled laboratory study.

Methods: Three-dimensional motion capture tested the running gait of the participants. A total of 34 elite sports professionals who underwent ACLR and were cleared to return to sport and 34 noninjured high-level athlete participants matched by age and sex participated as the control group in this study.

Results: A significant reduction was identified in internal knee extensor moment and knee flexion angles between the ACLR limb and the contralateral side (P = .01, .02) and between the ACLR limb and the control limb (P = .01, .01). The external knee adduction moment was increased significantly between the ACLR and control limbs (P = .01). No other differences were seen in the knee or hip kinetics and kinematics.

Conclusion: After ACLR, the elite participants demonstrated altered knee joint kinematics and kinetics at the time of being cleared to return to sport. These biomechanical deficits suggest that, despite being cleared, the athletes may not have been fully prepared for a safe return to sport, potentially increasing the risk of knee reinjury.

Clinical Relevance: Alterations in kinematics and kinetics in the sagittal plane of the ACLR knee observed during running may predispose participants to joint-related issues, such as patellofemoral pain. Similarly, increased knee adduction moments in the affected limb may indicate unresolved biomechanical deficits. These findings suggest that the elite population may not be fully prepared to resume high-level activity within the 6-month time frame outlined in current rehabilitation protocols. A longer recovery period may be necessary to restore joint kinematics and kinetics to levels more consistent with a safe return to sport.

Keywords: anterior cruciate ligament; running; patellofemoral pain syndrome; elite; osteoarthritis

Anterior cruciate ligament injury (ACL) is considered one of the most devastating injuries and is among the most common sports injuries.[21] ACL reconstruction (ACLR) is a standard surgical procedure for restoring knee stability and potentially minimizing the risk of future degenerative changes.[14] Most patients undergo a surgical procedure to reconstruct the ACL, followed by an intensive rehabilitation program, before being expected to return to sporting activities.[14]

Running is usually prescribed during rehabilitation[17,39] and is required for most sports.[30] Running is a high-impact activity characterized by large ground-reaction forces and increased lower extremity angular velocities, resulting in increased power absorption during loading throughout early to midstance, which requires eccentric control and greater muscular demand compared with low-impact activities.[34,39] Although several studies have highlighted changes in kinetics and kinematics after ACLR during walking,[9,17,18] investigating running may be more

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important because safe running is important to the clinical success of any pivoting and cutting athlete aiming to return to preinjury level. Moreover, the cyclic repetition involved in high-impact activities such as running may exacerbate biomechanical deficits, underscoring the need for further investigation into these patterns.[30]

Interestingly, the load distribution in the knee is influenced by the joint moment and angle, and any changes may increase the risk of joint dysfunction or injury. Supporting evidence showed that less than half of individuals with ACLR return to the preinjury level[13] and the risk of reinjury reaches 29.5%.[32] A systematic review and meta-analysis found strong evidence of reduced knee flexion angle (KFA) and internal knee extensor moment (KEM) during running compared with the contralateral limb 3 months to 5 years after ACLR.[30] However, there is inconclusive evidence related to impact and peak vertical ground-reaction forces. In the frontal plane, some studies show no difference in the external adduction moment,[22,35] while others show a reduction[27] or fluctuation over time.[17] However, previous studies have focused on the general population or recreational sports and have not investigated changes in elite populations.

Professional athletes depend on their performance to be as high as possible to earn money; therefore, any ACL injury can devastate their career financially and may affect the whole team's performance,[37] such impacts will be higher on the elite athletes. Interestingly, previous studies show that elite athletes are more likely to return to sport (83%)[23] than nonelites (60%),[2] which may be due to psychological, physical, and social differences. A literature review reported that 6 months after surgery is the most common time to assess readiness to return to activity after ACLR.[1,24] However, there is no current consensus on defining readiness to return to activity.[5] The result of the previous paper revealed that 32% of the studies used the time postoperative as a return-to-sport criteria, 15% of the studies used the time pulse subjective criteria, 40% of the studies failed to provide any criteria, and 13% of the studies provided objective criteria.

Many studies exploring kinematic and kinetic data alterations after ACLR have used small sample sizes, treadmill-based testing, and relatively slow running speeds.[27,31,33,34] Furthermore, these studies have been limited to individuals with average fitness.[27,31,33,34] Only 1 study[20] on elite athletes focused on calculating joint loading during running after ACLR. However, while the study highlights an interesting finding (higher knee loading), only the peak KFA and internal KEM are presented. Therefore, there is a need for a study that reports the outcomes of hip and knee (frontal) kinetics and kinematics in elite athletes after ACLR.[20] It is important to investigate if elite athlete patients are ready to return to sport after the rehabilitation program and if there are any biomechanical alterations that may potentially lead to an increased risk of knee injury and future pathology if they persist. Hence, this study aimed to measure kinematics and kinetics during overground running after 6 to 8 months of reconstruction in patients from an elite sports cohort. It was hypothesized that the ACLR individuals would demonstrate differences in knee kinematics and kinetics between the ACLR limb and uninjured limbs and between the ACLR side and a matched control group.

METHODS

Participants

Orthopaedic surgeons and sports team coaches were approached and asked to identify potential patients and noninjured participants for this study. Inclusion criteria for the patient group included being full-time elite athletes with a history of ACLR surgery who were, at the time of rupture, performing at the international or national level in different sports (rugby union, soccer, rugby league, basketball, taekwondo, and netball); being cleared medically to return to full training and had passed sport lead functional testing; and had undergone a full-time physical rehabilitation program monitored by a professional sports physical therapist and a sports doctor, as well as an orthopaedic surgeon. The lead functional testing is single-leg squat, single-leg hop, and triple crossover hop for distance and isokinetic quadriceps strength. The exclusion criteria for participants included a history of >1 ACLR surgery or any other secondary orthopaedic procedures or a history of any other orthopaedic or neurological conditions that affected the participant's ability to perform the tasks in the current study. All the orthopaedic surgeons (4 surgeons, 2 of which were based within the same group) who

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performed the surgeries had years of experience (range of years in practice, 16-29 years) utilizing standard surgical ACLR techniques. All patients were assessed for and cleared of having signs of significant meniscal or chondral injury. A significant meniscal or chondral injury was defined as one that required specific surgical management, such as repair, or, in the surgeon's view, would interfere with standard rehabilitation. The orthopaedic surgeon typically assessed these injuries through clinical evaluation, imaging studies (eg, magnetic resonance imaging), and arthroscopic or intraoperative findings.

Sports team coaches also identified age-matched individuals with no history of ACLR surgery as the control group. The control group's inclusion criteria included being a high-level athlete (regularly participating in physical activity, team sports and training for >6 hours a week) with no history of orthopaedic or neurological conditions or surgeries or previous history of lower limb injury. All eligible individuals were sent a letter inviting them to participate in the study. All individuals who agreed to participate in the study completed a 3-dimensional (3D) motion capture running analysis and a clinical questionnaire from January 2015 until November 2016 (for a period of 23 months). The ethics committees of the Salford University and the National Health Service approved the study, and informed consent was obtained from each participant before starting the trials. The determination of sample size, utilizing a 1-tail hypothesis with a significance level of $\alpha = .05$ and a power of $(1-\beta)$ 0.90 using the G*Power program (University of Düsseldorf), revealed that a minimum of 34 patients per group was necessary. To calculate the power, the effect size of the primary outcome (KEM) was taken from our pilot study, which showed an effect size of 3.8. This estimation aligns with the sample size in a previous study.[31]

Procedures

A cross-sectional study measured the data (kinematic and kinetic) using a gait analysis system (Qualisys) with a 12-camera (240 Hz) synchronized with 3 force platforms (BP600900, 1200Hz; AMTI) placed along a 25-m indoor running track. The participants wore standard New Balance training shoes to control the interaction between shoes and the surface. Before testing, 14-mm reflective markers were attached to the skin using hypoallergenic sticky tape on the posterior superior iliac spine; anterior superior iliac spine; iliac crest; greater trochanters; lateral and medial femoral condyles; lateral and medial malleoli; calcaneus; and the head of the fifth, second, and first metatarsals. Tracking markers were also placed onto technical clusters on the shank and thigh using elastic bands. Foot markers were positioned on the shoes, adopting the CAST protocol,[10] as described in Herrington et al.[20] A static standing trial position was assumed. Individuals were asked to practice 3 static trials before the actual data collection and recording.

Running Task: The participants were requested to complete 5 successful speed running trials with valid kinetic data (ie, contacting the force platform with ≥1 foot) for each side. To control the speed during the task, the Brower timing gate system (TCI; Brower Timing Systems) was used, and the speed was controlled at +/−5% of the self-selected speed during running. Five minutes of cycling and 5 practical trials were conducted before collecting the actual trial. The testing was conducted on a 25 m–long indoor synthetic running track. Each participant began approximately 10 m behind the first set of timing lights and was instructed to run at a comfortable pace. To accommodate variations in stride patterns, the exact starting point for each participant was adjusted to ensure each could naturally step onto the force platform without modifying his or her normal running stride. Participants were directed to continue running through the camera's capture area and past the second timing gate.

Visual 3D (V3D; C-Motion Inc) software was utilized to process kinetic and kinematic data (Version 4.21; C-Motion Inc). A low-pass filter (bidirectional fourth-order Butterworth) was used to filter the data with 25 Hz and 12 Hz as the cutoff for kinetic data (motion) and kinematics data (force plate data), respectively.[20] The lower extremities' segment was modeled as a conical shape, with inertial characteristics anticipated from anthropometric data.[19] Euler rotation sequence of *x-y-z* was utilized to compute joint kinematics, whereby *x* represented sagittal plane rotation (flexion-extension), *y* represented coronal plane rotation (abduction-adduction/varus-valgus), and *z* represented transverse plane rotation (internal-external rotation). Moments were presented as internal moments, except for the knee adduction moment, which was presented as an external moment. The kinetics data were computed using inverse dynamic theory, and then the moments were normalized to body mass.

Outcome Measures

Based on the outcome measurements for ACL, patellofemoral pain syndrome, and osteoarthritis reported in the literature, discrete kinetic and kinematic variables for the hip frontal plane (peak adduction angle and peak adduction moment), hip transverse plane (peak internal rotation angle and peak internal rotation moment), knee sagittal plane (peak flexion angle and peak internal extensor moment), and knee frontal plane (peak adduction angle, peak external adduction moment) were computed during the first half of the stance phase, from 0% to 50 % (early stance) for each trial. The Knee injury and Osteoarthritis Outcome Score (KOOS) outcomes were also reported.

Statistical Analysis

Mean and standard deviation values for all variables of interest have been reported. A Kolmogorov-Smirnov test was used to investigate normality. Comparisons were made between the injured limb and the ACLR group's non-injured limb. In addition, comparisons were made between the injured limb of the ACLR group and the control group

TABLE 1
Comparison Between the Reconstructed Limb and Contralateral Limb and Between the Reconstructed Limb and Control Group During Running[a]

Variables	ACLR	ACLN	P	ACLR	Control	P
Joint Angles, deg						
Hip adduction	11.15 (5.59)	10.16 (4.44)	.30	11.15 (5.59)	11.69 (4.48)	.66
Hip internal rotation	7.14 (6.94)	4.74 (6.02)	.07	7.14 (6.94)	4.39 (5.85)	.08
Knee adduction	5.82 (5.01)	4.85 (4.48)	.28	5.82 (5.01)	7.20 (3.54)	.19
Knee flexion	44.67 (6.30)	48.85 (5.52)	.02[b]	44.67 (6.30)	49.64 (7.62)	.01[b]
Moments, Nm/kg						
Hip adduction	2.00 (0.57)	2.07 (0.54)	.37	2.00 (0.58)	1.89 (0.54)	.58
Hip internal rotation	0.73 (0.20)	0.77 (0.27)	.21	0.73 (0.21)	0.72 (0.22)	.66
Knee adduction	0.88 (0.37)	0.79 (0.36)	.36	0.88 (0.37)	0.69 (0.36)	.01[b]
Knee extensor	2.87 (0.54)	3.28 (0.56)	.01[b]	2.87 (0.54)	3.26 (0.34)	.01[b]

[a]Data are presented as mean (SD). ACLN, noninjured limb of patients with ACLR; ACLR, anterior cruciate ligament reconstruction.
[b]Indicates statistical significance (P).

and between the ACLR group's noninjured limb and the control group. Graft type was not included in the analysis as a factor because a previous study showed no significant difference, and current study data may not be enough to conduct this analysis.[16] To identify any significant difference, the paired-sample t test (within participants) or independent-sample t test (between participants) was used when the assumptions were met, and the Wilcoxon signed-rank test or Mann-Whitney U test was used when assumptions were not met.[40] The significant level was set to be ≤.05. Data were analyzed using SPSS (Version 25; SPSS Inc). The effect size was calculated using the Cohen d equation as the following Cohen d = (M2-M1)/SD pooled and interpreted as small (0.2-0.49), medium (0.5-0.79), and large (0.8-1).[11]

RESULTS

In total, 34 patients (sex, 10 female/24 male; body mass, 79.9 kg [±16.5 kg]; age, 21.8 years [±3.9 years]; height, 1.71 m [±0.1 m]) with a history of primary ACLR surgery (mean postsurgery time of 7.8 months [±1.3 months; range, 6-8 months]) were included in the study. Study participants had ≤1 month from injury to surgery (minimum-maximum, 10 days-1 month). ACLR was performed utilizing standard surgical techniques in all surgeries. At the time of assessment, the patient group reported a global KOOS score of 89.3 (±8.6). Twenty individuals from the patient group had a hamstring tendon autograft, whereas the rest (14 participants) had a patellar tendon autograft. The study group consisted of 6 rugby union players, 19 soccer players, 4 rugby league players, 1 basketball player, 2 taekwondo players, and 2 netball players.

Likewise, a total of 34 age and sex-matched individuals with no history of ACLR or other orthopaedic or neurological conditions were included in the study (sex, 10 female/24 male; body mass, 76.9 kg (±13.2 kg); age, 22.1 years (±3.6 years); height, 1.70 m (±0.1 m); and KOOS, 96.1 (±6)). The individuals in this group engaged actively in team sports, physical exercise, and training (>6 hours a week) and had no lower limb injury history. No significant difference ($P > .05$) between the patients and the control group was detected in anthropometric and demographic characteristics. Also, there were no significant differences in running speed between the groups, with a mean of 3.5 m/s^{-1} (±0.57 m/s^{-1}) for the ACLR group and 3.5 m/s^{-1} (±0.58 m/s^{-1}) for the control group.

Kinematic and kinetic results for the reconstructed and contralateral limb for the ACLR group and the control group's limb are presented in Tables 1 and 2. A significant reduction was observed in the peak KFA in the ACLR limb compared with the control group (P = .01; Cohen d = 0.63) and the contralateral limb (noninjured limb) for the ACLR group (P = .02; effect size, 0.64). The internal KEM was significantly reduced in the ACLR limb compared with the contralateral side (noninjured limb) for the ACLR group (P = .01; Cohen d = 0.77) and the control group (P = .01; Cohen d = 1.17). No significant difference was observed between limbs in the ACLR group's external knee adduction moment (P = .36). In contrast, there was a significant increase in the external knee adduction moment for the ACLR limb compared with the control group (P = .01; Cohen d = 0.52). No significant difference was identified in the other kinematic and kinetic data in the hip and the knee, either within the participant or between groups ($P > .05$). No significant difference was identified in any outcome between the contralateral limb in the reconstructed group and the control group.

DISCUSSION

This study identified altered knee and hip kinematics and kinetics during running in elite athletes after ACLR, compared with the control athletes group, at the return-to-sport time point. The participants in this study were asymptomatic during testing, with KOOS scores exceeding mean values for this stage of recovery,[36,42] and having engaged in full-time rehabilitation programs. Despite

TABLE 2
Comparison Between the Contralateral Limb in the Reconstructed Group and Control Group During Running[a]

Variables	Groups		
	ACLN	Control	P
Joint Angle, deg			
Hip adduction	10.16 (4.44)	11.69 (4.48)	.16
Hip internal rotation	3.39 (7.04)	4.39 (5.85)	.54
Knee adduction	5.92. (3.03)	7.20. (3.54)	.11
Knee flexion	48.95 (6.40)	49.64 (7.62)	.62
Moment, Nm/kg			
Hip adduction	2.06 (0.54)	1.89 (0.54)	.30
Hip internal rotation	0.77 (0.27)	0.72 (0.22)	.25
Knee adduction	0.76 (0.38)	0.69 (0.36)	.14
Knee extensor	3.32 (0.70)	3.26 (0.34)	.17

[a]Data are presented as mean (SD). ACLN, noninjured limb of patients with anterior cruciate ligament reconstruction.

being cleared for full training and participation in high-performance sports, these elite athletes exhibited biomechanical differences, including reduced peak KFA, reduced internal KEM, and increased external knee adduction moment during running, highlighting persistent deficits that may require targeted interventions to ensure safe and effective return to sport.

Running places significant demands on the knee,[15] and research has shown that alterations in biomechanical running variables could be linked to increased risk of reinjury and conditions of overuse.[6] Similar to previous studies carried out with nonelite athletes, this study shows that elite athletes presented a reduction in internal KEM[4,30,33,39] and KFA[4,30,31] after ACLR during running at the return-to-sport time. The reduction in internal KEM and KFA might be a strategy adopted to minimize patellofemoral compressive forces and quadriceps contraction (ie, quadriceps avoidance)[7] to reduce pain.[12] Such stress prevention strategies could also help protect the ACL from injury by avoiding the potential anterior tibial translation from strong quadriceps contraction to counter the moment in relatively small KFAs. Quadriceps avoidance, however, may restrict the distribution of patellofemoral loads across the contact area, potentially altering the contact location within the tibiofemoral joint. This could lead to increased contact stress on smaller regions of the patellofemoral joint, thereby elevating the risk of patellofemoral disease[8,20] and the knee's long-term health.[17] These findings reinforce the importance of understanding and improving the strength[4] and neuromuscular control[37] of the knee flexors and extensors during rehabilitation after ACLR.

Larger external knee adduction moments may result in altered knee joint contact and loading patterns, potentially promoting tibiofemoral knee osteoarthritis progression if persisting for a long time.[28,41] The previous claim is supported by evidence that reveals a 6-fold increased risk in tibiofemoral knee osteoarthritis progression when the peak external knee adduction moment increases by 1%.[28] This highlights the importance of such a moment in the load distribution between the medial and lateral condyles. The current study's findings regarding the external knee adduction moment contradict previous studies, which showed no difference between the ACLR and the control group.[22,35] Another study showed a lower knee adduction moment in the ACL-reconstructed leg compared with the control group.[27] However, a direct comparison cannot be made due to the difference in population characteristics, as the current study involved an elite population. The previous study only included male patients and measured kinematics and kinetics after 4- to 6-year follow-up after ACLR. The minimum rehabilitation protocol length was 1 year.

Moreover, a study found that elite athletes may exhibit a greater ability to keep the knee robust than nonathletes while performing side-hopping.[25] In addition, these differences may be related to the time between surgery and postoperative assessment. One study[17] found lower external knee adduction moments in the early stages (6-24 months after ACLR), no difference in the midgroup (2-5 years after ACLR), and a significant increase in the late group (5-15 years after ACLR). This highlights that >6 months may be needed postoperatively to achieve baseline joint health and function, with some authors proposing >1 year after ACLR surgery for athletes to fully return to sport.[3,29]

Muscle strength is vital in the rehabilitation process after ACLR surgery. A previous study[4] aimed to determine the relationship between knee muscle strength and running knee biomechanical patterns at 6 and 12 months after ACLR. The study found significantly reduced KFA at 6 months, and KEM was significantly lower at 6 and 12 months.[4] They also identified a significant correlation between KEM and maximal knee extension/flexion peak torque. Asaeda et al also found that knee joint kinematics were restored at 12 months after surgery.[4] The authors suggested that strengthening knee extensors and flexors could help restore knee kinetic patterns during running. Spencer et al[38] carried out a study where a group of 28 patients had quadriceps strength testing, along with knee flexion range of excursion measurements during 3D running analysis, where they found that ACLR limbs had an altered quadriceps strength/knee flexion excursion relationship in the ACLR limbs when compared with the contralateral side. They hypothesized that this relationship could indicate an altered neuromuscular control pattern within the ACLR limb that manifests in abnormal kinematic patterns.[38]

Limitations

This study has limitations. While the biomechanical model and motion capture system used in this study are consistently used in the literature, the marker set is based on clusters prone to soft tissue artefacts affecting primarily frontal and transverse plane kinematics, which can affect kinetic calculations.[26] It is also unclear whether altered biomechanics would be maintained during field performance as measured in the laboratory. Future research should include taking the findings from standardized investigations and carrying out more ecologically valid loading and injury risk evaluations by replicating real-life sporting environments and training sessions as accurately as possible. There is a need for longitudinal studies assessing knee kinematic and kinetic patterns, along with psychometric evaluations at different stages during and after rehabilitation post-ACLR surgery, as these patterns are likely to change over time and differ for each individual.

CONCLUSION

This study has examined the knee and hip kinetics and kinematics of elite athletes returning to full unrestricted training during running after ACLR surgery. Based on the current study's results, the elite population is potentially not fully ready to return to activity at 6 months as set out in the current rehabilitation protocol. Perhaps >6 months is needed to restore the joint kinematics and kinetics to normal values. The biomechanical alterations observed in the current study may predispose athletes to an increased risk of knee reinjury.

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DATA ACCESSIBILITY STATEMENT

The data underlying this scientific publication are available upon request. Interested parties may contact the corresponding author to access the data set, which will foster transparency and promote further scientific collaboration. Open access to the data will contribute to the advancement of research and facilitate the validation and replication of findings reported in this publication.

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