



**Knee moments of anterior cruciate ligament reconstructed and control participants during normal and inclined walking.**

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## Abstract

### Background

Prior injury to the knee, particularly anterior cruciate ligament (ACL) injury is known to predispose to premature osteoarthritis (OA). The study sought to explore if there was a biomechanical rationale for this process by investigating changes to knee function during routine daily activities.

### Methods

Twelve subjects who had undergone ACL reconstruction (ACLR) and 12 volunteers with no history of knee trauma or injury were recruited into this study. Gait was assessed during flat (normal and slow speed), and uphill and downhill walking using a bespoke inclined walkway with an embedded Kistler Force plate (Kistler Instrumented AG, Winterthur, Switzerland), and a ten camera Vicon motion capture system.

### Results

No significant difference was observed in the peak knee adduction moment between ACLR and control participants however, in further analysis, a one way ANOVA revealed that ACLR participants with an additional meniscal tear or collateral ligament damage (7 subjects) had a significantly higher adduction moment ( $0.33 \pm 0.12$  Nm/kg.m) when compared to those with isolated ACLR (5 subjects,  $0.1 \pm 0.057$  Nm/kg.m) during normal gait ( $p < 0.05$ ). A similar, but non-significant trend was seen in all the other activities.

## Conclusion

Subjects with an isolated ACLR had a reduced adductor moment rather an increased moment, thus questioning prior theories on OA development. In contrast those subjects who had sustained associated trauma to other key knee structures were observed to have an increased adduction moment. This fits with the theory that it is additional injury following ACL rupture that has a higher predisposition to osteoarthritis rather than isolated ACL deficiency alone.

## Article summary

### Strengths and limitations of this study

- To our knowledge this is the first report looking at external moments during inclined and declined walking for ACL reconstruction participants.
- In addition to looking into the external moments of the affected and unaffected knee, this study also looked at the effect of gait speed on external moments and differences in knee osteoarthritis outcome score (KOOS) for each group.
- This study provides an explanation for the disparity seen in previous studies looking into peak knee adduction moment in ACLR and matched control subjects.
- This study suggests that injuries to other key knee structures may play a bigger part in inducing osteoarthritis than ACL injury alone.
- One limitation to this study is the small sample size, in particular after dividing our ACLR group into ACLR + and ACLR – groups.

## Introduction

Anterior Cruciate Ligament (ACL) injuries are common, exceeding 100,000 annual cases in the United States.(1) The majority are sports related injuries, and lead to knee instability as a result of increased anterior tibial translation and anterolateral rotation.(2) ACL reconstruction (ACLR) is the primary treatment for an ACL rupture and permits return to a range of high-level activities including sport. It is accepted that people with ACL injuries, including those who undergo surgical reconstruction, are prone to further knee degeneration(3) and early OA.(4,5) Lohmander et al. (2007) reviewed 127 publications and determined that the overall mean incidence of developing OA after an ACL injury with/without reconstruction to be over 50%(3) with the majority noting radiographic signs of OA 10 years after injury.(3) Gait biomechanics are considered to play a vital part in knee joint degeneration, (5, 6) with altered kinematics and kinetics changing the distribution of mechanical load on the knee. (7) This in turn is postulated to lead to cartilage wear(5 - 7) and eventually knee osteoarthritis.

There is consensus amongst researchers that ACL deficient patients employ different gait strategies.(8) In vivo studies have found reduced knee flexion,(5) increased internal tibial rotation(5, 9) and increased knee adduction moment(10) during level walking, to be the three main changes in external knee moments following an ACL rupture. Furthermore, research has indicated that ACL reconstruction does not restore normal knee mechanics. Berchuck et al. in 1990(11) noted reduced knee flexion during normal gait indicating a coping strategy called quadriceps avoidance gait. Anterior displacement of tibia through the contraction of quadriceps is balanced by the ACL when the knee is at an angle of 0 to 45 degrees.(11) People with ACL rupture and/or reconstruction may

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3 involuntarily avoid quadriceps activation(12) to prevent further ACL damage. Gait  
4 adaptations in the sagittal plane can lead to knee joint instability and ligament laxity.(13)  
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8 This may result in osteoarthritis initiation and progression.(13)  
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11 High moments in frontal and transverse planes of the knee have been linked to OA.(5)  
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13 ACLR has been shown to restore rotational stability,(9, 14) however high knee  
14 adduction moments (KAM) after reconstruction have been observed (15) but such  
15 changes are not universally agreed(16, 17) This is of importance since a 1% increase in  
16 adduction of moment at the knee is thought to increase the risk of knee OA by 6.5  
17 times.(18) Hence in this study we aim to gain a better understanding of peak knee  
18 moments in the sagittal and frontal plane. Our primary aim is to compare peak knee  
19 moments in the sagittal and frontal plane of ACLR participants to healthy controls on  
20 sloped surfaces. We additionally investigated the effect of speed on peak moments.  
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## 36 **Methods**

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39 This cross-sectional study explored peak knee moments between ACLR and healthy  
40 control subjects during slope walking. The study was approved by Imperial College  
41 Research Ethics Committee.  
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47 A total number of 24 subjects participated in this study and written informed consent  
48 obtained, details are provided in Table 1; 12 (9 male and 3 female) ACLR participants  
49 (age,  $24.83 \pm 8.81$  year; weight  $75 \pm 11.13$  kg; height  $1.76 \pm 0.13$  m); and 12 (9 male  
50 and 3 female) control participants (age,  $30.5 \pm 8.68$  year; weight  $71.6 \pm 11.2$  kg; height  
51  $1.73 \pm 0.11$ ). The ACLR inclusion criteria were; aged between 18 – 60 years, Body mass  
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3 index (BMI) < 30kg/m<sup>2</sup>, a complete, unilateral ACL rupture followed by a single bundle  
4 hamstring auto graft reconstruction that was performed at least one-year ago, no history  
5 of knee trauma or injury to their contralateral leg. Subjects who were unable to walk  
6 comfortably on a 10-degree incline walkway were also excluded. The control group did  
7 not have any muscular or neurological lower limb pathology and were matched to the  
8 ACLR subjects with respect to height, weight and their dominant leg (leg preference for  
9 kicking). All subject completed the Knee injury and Osteoarthritis Outcome Score  
10 (KOOS)(19).  
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23 A three-dimensional motion analysis system (Vicon MX™ T-20 System, Vicon, Oxford)  
24 was used to collect kinematic data for normal, slow, upslope and downslope gait. This  
25 software used 10 motion capture cameras to pick up 35 reflective markers at a sampling  
26 rate of 100Hz. The reflective markers were placed bilaterally on the head of 2<sup>nd</sup>  
27 metatarsal, head of 5<sup>th</sup> metatarsal, head of 2<sup>nd</sup> tarsal, calcaneal tuberosity, medial and  
28 lateral malleolus, medial and lateral femoral epicondyle, anterior superior iliac spine,  
29 posterior superior iliac spine, acromion and one single marker on the manubrium.  
30 Marker clusters were affixed bilaterally to the calf and thigh. Kinetic data (ground  
31 reaction force) were collected using portable force plates (Kistler Instruments AG,  
32 Winterthur, Switzerland) at a sampling rate of 1000 Hz and was synchronised with the  
33 camera data.  
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49 The subjects were asked to walk barefoot. A 5 minute self-directed warm up allowed the  
50 subjects to familiarise themselves with each task.  
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3 A 7-meter long walkway was used, 2.5-meters of which could be raised to form a ramp,  
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5 at an incline of 10 degrees. It was constructed from a steel frame and covered with  
6  
7 plywood, with one portable force plate embedded in the centre (Figure 1). Participants  
8  
9 were asked to walk at a self-selected pace both uphill and downhill. The ramp was then  
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11 removed to create a level walkway. All the participants were asked to walk at a self-  
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13 selected pace and at a pace, which they consider to be slow. Each task was repeated  
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15 until both feet made complete contact with the middle of the force plate at least three  
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17 times.  
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23 All data was time normalised to one gait cycle. The data was analysed from the stance  
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25 phase of the gait cycle; when the ground reaction force reached more than 40N (heel  
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27 strike) to when it dropped to less than 40N (toe off). A fourth order Butterworth Filter at a  
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29 cut off (12 Hz) was used to reduce noise. Joint angles and moments were calculated  
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31 from the position of the reflective markers and the ground reaction force data using a  
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33 custom model written in body builder software.(20-22) Peak moments in the sagittal and  
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35 frontal planes of the knee were extracted using MATLAB (R2013b) software.  
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40 Paired Student's t-tests were used to determine any significant differences in  
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42 demographics between ACLR and control group. A one-Way ANOVA was used to  
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44 calculate significant differences in all other parameters. Holm-Sidak approach was used  
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46 to establish significance, with the alpha value set at 0.05. All statistics were carried out  
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48 using SigmaPlot 11.0 on Windows.  
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## Results

The ACLR group was significantly older than the control group ( $p < 0.05$ ). A multiple linear regression was carried out which showed that age ( $p = 0.65$ ) did not have a significant effect on ACLR peak adduction moment. There were no significant differences between groups in height, weight and Tegner Activity Scale (Table 1). The mean time since reconstruction surgery was 4 years and 6 months.

**Table 1** Subject characteristics, activity level and time since surgery. 12 participants in ACLR group and 12 in control group

	ACLR (SD)	Control (SD)	Paired T-test
Age (yr)	30.5 (8.68)	24.8 (8.81)	$P = 0.011$
Height (m)	1.76 (0.13)	1.73 (0.11)	$P = 0.078$
Weight (kg)	75 (11.13)	71.6 (11.2)	$P = 0.535$
Tegner Activity Scale	6.25 (1.82)	6.08 (1.93)	$P = 0.755$
Time since surgery (yr)	4.5 (3.5)	NA	

ACLR, Anterior cruciate ligament reconstruction

We further divided our ACLR group into two; subjects that had additional cartilage, meniscus or ligament damage in their ACLR leg (ACLR + group; 7 subjects) and subjects with isolated ACL injuries (ACLR – group; 5 subjects). The additional knee injuries to the ACL rupture are meniscal tear (3 participants), cartilage damage (3 participants) and torn MCL (1 participant).

The control group had significantly higher scores in all of the KOOS domains apart from activities of daily life compared to the ACLR group (Table 2). No significant KOOS differences were seen between ACLR + and ACLR – groups. Table 3 shows that there were no significant differences in gait speed in normal or slow walking between any groups.

**Table 2** Knee osteoarthritis outcome score (KOOS) with standard deviation (SD) for each domain recorded for each group.

KOOS Outcome	ACLR (SD) (n=12)	Control (SD) (n=12)	ACLR + (SD) (n=7)	ACLR - (SD) (n=5)	P-value	Post-hoc analysis
Pain	88.4 (9.32)	99.1 (3.2)	87.5 (8.83)	89.4 (10.8)	P = 0.006	Control vs ACLR; Control vs ACLR +
Symptoms	83.1 (11.4)	98.2 (3.19)	85.1 (12.7)	80.7 (10.6)	P = 0.001	Control vs all other groups
Activities of daily life	96.3 (5.63)	100 (0)	98 (3)	94.4 (7.7)	P = 0.090	
Sport and recreation	83.8 (16.9)	99.6 (1.4)	89.1 (7.4)	77.4 (23)	P = 0.010	Control vs ACLR; Control vs ACLR -
Knee related QOL	64.5 (23.2)	100 (0)	64.6 (23.3)	70 (26.7)	P = 0.001	Control vs all other groups

ACLR, Anterior cruciate ligament reconstruction; ACLR +, subjects with other knee injuries in their ACLR leg; ACLR -, subjects with isolated ACL injuries.  
Data are mean (SD).

**Table 3** Gait speed during normal and slow, level walking tasks.

	ACLR	Control	ACLR +	ACLR -	P = value
Gait normal speed	1.17 (0.13)	1.20 (0.11)	1.18 (0.15)	1.16 (0.11)	P = 0.916
Gait slow speed	0.76 (0.13)	0.75 (0.11)	0.78 (0.16)	0.74 (0.09)	P = 0.946

ACLR, Anterior cruciate ligament reconstruction; ACLR +, subjects with other knee injuries in their ACLR leg; ACLR -, subjects with isolated ACL injuries.  
Data are mean (SD).

No statistically significant differences were found in peak knee adduction moment between ACLR and control participants during normal, slow, uphill and downhill gait.

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3 Further analysis revealed that ACLR participants with meniscal tear, cartilage damage  
4 or medial collateral ligament damage (ACLR +) had significantly higher knee adduction  
5 moment ( $0.33 \pm 0.12$  Nm/kg.m) during normal gait compared to those participants with  
6 an isolated ACL injury (ACLR -,  $0.1 \pm 0.057$  Nm/kg.m),  $p = 0.042$  (Figure 2).  
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12 This was not the case for data collected in the sagittal plane. There was a tendency for  
13 the contralateral (unaffected) knee of ACLR participants to show a higher mean knee  
14 flexion moment in all activities compared to ACLR affected knees and control knees  
15 (Figure 3). The difference was not found to be statistically significant.  
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## 27 Discussion

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30 ACL injury is often accompanied by other knee injuries.(23) Prevalence of associated  
31 meniscal damage and chondral lesions at the time of ACL injury can be as high as 65%  
32 and 23% respectively.(24) Associated knee injuries are thought to increase the  
33 incidence of OA from 0 – 13% in isolated ACL injury to 21 – 48%.(23) This may be  
34 because key knee structures such as menisci prevent cartilage wear by distributing  
35 loads and functioning as a shock absorber.(13) Our results suggest that high knee  
36 adduction moments may be a relevant risk factor in OA incidence in ACLR subjects only  
37 when associated knee injuries are present.  
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50 Three other studies have looked at peak knee adduction moment in ACLR and matched  
51 control subjects. Butler et al. found the ACLR group to have a higher peak knee  
52 adduction moment to controls.(15) This was also seen by our ACLR + group. Whereas  
53 the studies that followed, Webster et al. and Zabala et al. found the ACLR group to have  
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3 a reduced peak knee adduction moment to controls.(16, 17) This was seen by our ACLR  
4 - group. This disparity in studies may be a consequence of different exclusion criteria for  
5 ACLR subjects. Butler et al. did not exclude ACLR subjects with other knee injuries,(15)  
6 while the other two studies excluded subjects with ligament damage(16, 17) and also  
7 those with >25% of menisci loss.(17) We suggest that associated knee injuries are  
8 related to increased knee adduction moments in ACLR participants.  
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10 We found the difference between peak KAM in ACLR + and ACLR – to be statistically  
11 significant only during normal gait. We expected the difference to be higher during  
12 sloped walking, as it is more challenging than level walking. Change in terrain, muscle  
13 weakness, gait deficit and balance deficit are primary risk factors for falling.(25, 26) This  
14 suggests that ACLR participants need to adopt a conservative gait strategy while  
15 walking on a sloped surface to ensure safety. During challenging tasks such as downhill  
16 walking healthy participants increased their metabolic activity and implemented a  
17 conservative gait strategy to reduce the risk of falling.(25) This principle may also be  
18 applied by ACLR participants to ensure safety.  
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20 Both uphill and downhill walking require greater use of quadriceps muscle than on a  
21 level walkway.(26, 27) However in our study no statistically significant differences were  
22 observed between ACLR, ACLR +, ACLR – and control group in peak knee flexion and  
23 extension moments.  
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25 Two years after an ACLR surgery, differences in quadriceps strength between limbs are  
26 no longer seen.(25) All of the ACLR subjects had undergone reconstruction at least 1  
27 year before taking part in this study, with an average of 4.5 years. This indicates that all  
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3 subjects may have had sufficient time to restore their quadriceps strength. Even though  
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5 sagittal instability is thought to increase joint loads and lead to joint failure,(13, 28) it may  
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7 not play a significant role in OA induction and progression after reconstruction.  
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11 An unexpected finding was the tendency for the contralateral knees of ACLR  
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13 participants to have higher peak knee flexion and lower peak knee extension moment  
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15 compared to the ACLR and control knee in all activities. This may be an adaptation to  
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17 reduce loading on their ACLR knee. Patients with advanced knee OA also display this  
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19 adaptation to reduce loading on their injured leg.(29) Even though this may present as a  
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21 mechanism to slow the progression of OA, there are harmful implications associated  
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23 with the contralateral leg. Weight bearing asymmetry may induce OA in the contralateral  
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25 leg;(30) 37% (24/65 female patients) showed signs of radiographic OA in their  
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27 contralateral leg, 12 years after ACL reconstruction.(31) This suggests that in this  
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29 population unilateral injury changes joint function bilaterally.  
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36 In addition to our primary investigations we also investigated differences in KOOS and  
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38 walking speed. There was no significant difference in Knee Osteoarthritis Outcome  
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40 Score or gait speed between ACLR + and ACLR -. This indicates that high peak knee  
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42 adduction moment in the injured leg does not affect our subjects' pain outcome,  
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44 symptoms, activities of daily life, sport and recreation, knee related quality of life and gait  
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46 speed. Thereby patient reported outcome measures and gait speed might not provide  
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48 the clinician with any information about different gait adaptations.  
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53 Mundermann et al (2004) found a 10.2% reduction in maximum knee adduction moment  
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55 when people with less severe OA reduced their walking speed from 1.2 meters/second  
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57 to 0.8 meters per second.(32) However in this study the difference in peak knee  
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3 moments between normal (1.17 m/s) and slow gait speed (0.76 m/s) were not  
4 statistically significant. This may be due to our small sample size.  
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9 It is important to note that different knee injuries, rehabilitation protocols and time  
10 between injury and reconstruction are all thought to influence joint moments.(17) These  
11 are limitations that should be considered when examining the results presented here. In  
12 our study the difference in age between ACLR and control group was statistically  
13 significant. A multiple linear regression was carried out to show that age ( $p = 0.65$ ) did  
14 not have a significant effect on ACLR knee adduction moment. Another limitation was  
15 our small sample size, in particular after dividing our ACLR group into ACLR + and  
16 ACLR – groups.  
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28 The ramp was set at an incline of 10 degrees because the transition from a level to  
29 slope walking strategy is thought to be around 5.5 degrees(27) and after the incline of  
30 10 degrees no kinematic differences are seen in healthy participants.(27)  
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36 With regards to Vicon Motion capture system different skin marker placement and skin  
37 motion artifacts are thought to increase error.(6) We tried to reduce the effects of  
38 different skin marker placement by having only one researcher place all markers on  
39 each individual. In addition we used a model that used clusters to reduce the effects of  
40 skin motion artefacts.(22)  
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## 52 **Conclusion**

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55 In conclusion, this study looked at peak moments in the sagittal and frontal plane during  
56 level and sloped walking for ACLR participants (subdivided into ACLR + and ACLR –)  
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3 and their contralateral legs. We found individuals who have other knee injuries  
4 associated with their ACLR knee exhibit higher peak adduction moments. This suggests  
5 that injuries to other key knee structures may play a bigger part in inducing OA than ACL  
6 injury alone. Contralateral knees appear to be functioning in such a way to reduce high  
7 moments in the ACLR knees, which may be relevant in the risk of OA development in  
8 both knees. These findings warrant a longitudinal study comparing the knee adduction  
9 moment between isolated ACLR injury and ACLR with additional knee injuries and the  
10 prevalence of premature OA.  
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23 **Data sharing** - no additional data available  
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34  
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40 **Contributorship Statement** - All authors helped with the study design. Raghav K  
41 Varma carried out data collection, statistical analysis and analysis of the data produced.  
42 He also drafted and revised the paper. He is guarantor. Lynsey D Duffell attained ethical  
43 approval, determined the methodology, helped with data analysis and drafted and  
44 revised the paper. Dinesh Nathwani helped with data collection and drafted and revised  
45 the paper. Alison H McGregor monitored the data collection for the whole trial, provided  
46 the data collection tools and drafted and revised the paper. Robert Weinert-Aplin  
47 designed the data collection tool.  
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## References

1. Lyman S, Koulouvaris P, Sherman S et al. Epidemiology of anterior cruciate ligament reconstruction: trends, readmissions, and subsequent knee surgery. *J Bone Joint Surg Am* 2009;91:2321-8.
2. Matsumoto H, Suda Y, Otani T et al. Roles of the anterior cruciate ligament and the medial collateral ligament in preventing valgus instability. *J Orthop Sci* 2001;6:28-32.
3. Lohmander LS, Englund PM, Dahl LL et al. The long-term consequence of anterior cruciate ligament and meniscus injuries: osteoarthritis. *Am J Sports Med* 2007;35:1756-69.
4. Porat A, Roos EM, Roos H. High prevalence of osteoarthritis 14 years after an anterior cruciate ligament tear in male soccer players: a study of radiographic and patient relevant outcomes. *Ann Rheum Dis* 2004;63:269-73.
5. Andriacchi TP, Mündermann A. The role of ambulatory mechanics in the initiation and progression of knee osteoarthritis. *Curr Opin Rheumatol* 2006;18:514-8.
6. Stergiou N, Ristanis S, Moraiti C et al. Tibial rotation in anterior cruciate ligament (ACL)-deficient and ACL-reconstructed knees: a theoretical proposition for the development of osteoarthritis. *Sports Med* 2007;37:601-13.
7. Andriacchi TP, Mündermann A, Smith RL et al. A framework for the in vivo pathomechanics of osteoarthritis at the knee. *Ann Biomed Eng* 2004;32:447-57.
8. Hart JM, Ko JW, Konold T et al. Sagittal plane knee joint moments following anterior cruciate ligament injury and reconstruction: a systematic review. *Clin Biomech* 2010;25:277-83.



- 1  
2  
3 9. Georgoulis AD, Papadonikolakis A, Papageorgiou CD et al. Three-dimensional  
4 tibiofemoral kinematics of the anterior cruciate ligament-deficient and  
5 reconstructed knee during walking. *Am J Sports Med* 2003;31:75-9.  
6  
7
- 8  
9  
10 10. Noyes FR, Schipplein OD, Andriacchi TP et al. The anterior cruciate ligament-  
11 deficient knee with varus alignment. An analysis of gait adaptations and dynamic  
12 joint loadings. *Am J Sports Med* 1992;20:707-16.  
13  
14
- 15  
16  
17 11. Berchuck M, Andriacchi TP, Bach BR et al. Gait adaptations by patients who  
18 have a deficient anterior cruciate ligament. *J Bone Joint Surg Am* 1990;72:871-7.  
19  
20
- 21  
22 12. Urbach D, Nebelung W, Becker R et al. Effects of reconstruction of the anterior  
23 cruciate ligament on voluntary activation of quadriceps femoris a prospective  
24 twitch interpolation study. *J Bone Joint Surg Br* 2001;83:1104-10.  
25  
26  
27
- 28  
29 13. Roos EM. Joint injury causes knee osteoarthritis in young adults. *Curr Opin*  
30 *Rheumatol* 2005;17:195-200.  
31  
32
- 33  
34 14. Papageorgiou CD, Gil JE, Kanamori A et al. The biomechanical interdependence  
35 between the anterior cruciate ligament replacement graft and the medial  
36 meniscus. *Am J Sports Med* 2001;29:226-31.  
37  
38  
39
- 40  
41 15. Butler RJ, Minick KI, Ferber R et al. Gait mechanics after ACL reconstruction:  
42 implications for the early onset of knee osteoarthritis. *Br J Sports Med*  
43 2009;43:366-70.  
44  
45  
46
- 47  
48 16. Webster KE, Feller JA. The knee adduction moment in hamstring and patellar  
49 tendon anterior cruciate ligament reconstructed knees. *Knee Surg Sports*  
50 *Traumatol Arthrosc* 2012;20:2214-9.  
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3 17. Zabala ME, Favre J, Scanlan SF et al. Three-dimensional knee moments of ACL  
4 reconstructed and control subjects during gait, stair ascent, and stair descent. *J*  
5 *Biomech* 2013;46:515-20.  
6  
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9  
10 18. Miyazaki T, Wada M, Kawahara H et al. Dynamic load at baseline can predict  
11 radiographic disease progression in medial compartment knee osteoarthritis. *Ann*  
12 *Rheum Dis* 2002;61:617-22.  
13  
14  
15 19. Roos EM, Roos HP, Lohmander LS et al. Knee Injury and Osteoarthritis Outcome  
16 Score (KOOS)— development of a self-administered outcome measure. *J Orthop*  
17 *Sports Phys Ther* 1998;28:88–96.  
18  
19  
20 20. Cleather DJ, Bull AM Influence of inverse dynamics methods on the calculation of  
21 inter-segmental moments in vertical jumping and weightlifting. *Biomed Eng*  
22 *Online* 2010;9:74  
23  
24  
25 21. Cleather DI, Bull AM Lower-extremity musculoskeletal geometry affects the  
26 calculation of patellofemoral forces in vertical jumping and weightlifting. *Proc Inst*  
27 *Mech Eng H* 2010;224:1073-1083  
28  
29  
30  
31 22. Hope, N., Duffell, L. D., and McGregor, A. H. Validation of a new model to  
32 calculate joint kinematics during gait. *European Society of Biomechanics*  
33 *Conference Proceedings* 1-7-2012.  
34  
35  
36  
37 23. Claes S, Hermie L, Verdonk R et al. Is osteoarthritis an inevitable consequence of  
38 anterior cruciate ligament reconstruction? A meta- analysis. *Knee Surg Sports*  
39 *Traumatol Arthrosc* 2013;21:1967-76.  
40  
41  
42  
43 24. Louboutin H, Debarge R, Richou J et al. Osteoarthritis in patients with anterior  
44 cruciate ligament rupture: a review of risk factors. *Knee* 2009;16:239-44.  
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25. Monsch ED, Franz CO, Dean JC. The effects of gait strategy on metabolic rate and indicators of stability during downhill walking. *J Biomech* 2012;45:1928-33.
26. Mizner RL, Snyder-Mackler L. Altered loading during walking and sit-to-stand is affected by quadriceps weakness after total knee arthroplasty. *J Orthop Res* 2005;23:1083-90.
27. A.N. Lay, C.J. Hass, R.J. Gregor. The effects of sloped surfaces on locomotion: a kinematic and kinetic analysis. *Journal of Biomechanics* 2006;39:1621–1628
28. Gottschall JS, Nichols TR. Neuromuscular strategies for the transitions between level and hill surfaces during walking. *Philos Trans R Soc Lond B Biol Sci* 2011;366:1565-79.
29. Creaby MW, Bennell KL, Hunt MA. Gait differs between unilateral and bilateral knee osteoarthritis. *Arch Phys Med Rehabil* 2012;93(5):822-7.
30. Christiansen CL, Stevens-Lapsley JE. Weight-bearing asymmetry in relation to 378 measures of impairment and functional mobility for people with knee osteoarthritis. *Arch Phys Med Rehabil* 2010;91:1524-8.
31. Lohmander, L.S., Ostenberg, A., Englund, M. et al. High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. *Arthritis and Rheumatology* 2004;50:3145–3152.
32. Mündermann A, Dyrby CO, Hurwitz DE et al. Potential strategies to reduce medial compartment loading in patients with knee osteoarthritis of varying severity: reduced walking speed. *Arthritis Rheum* 2004;50:1172-8.

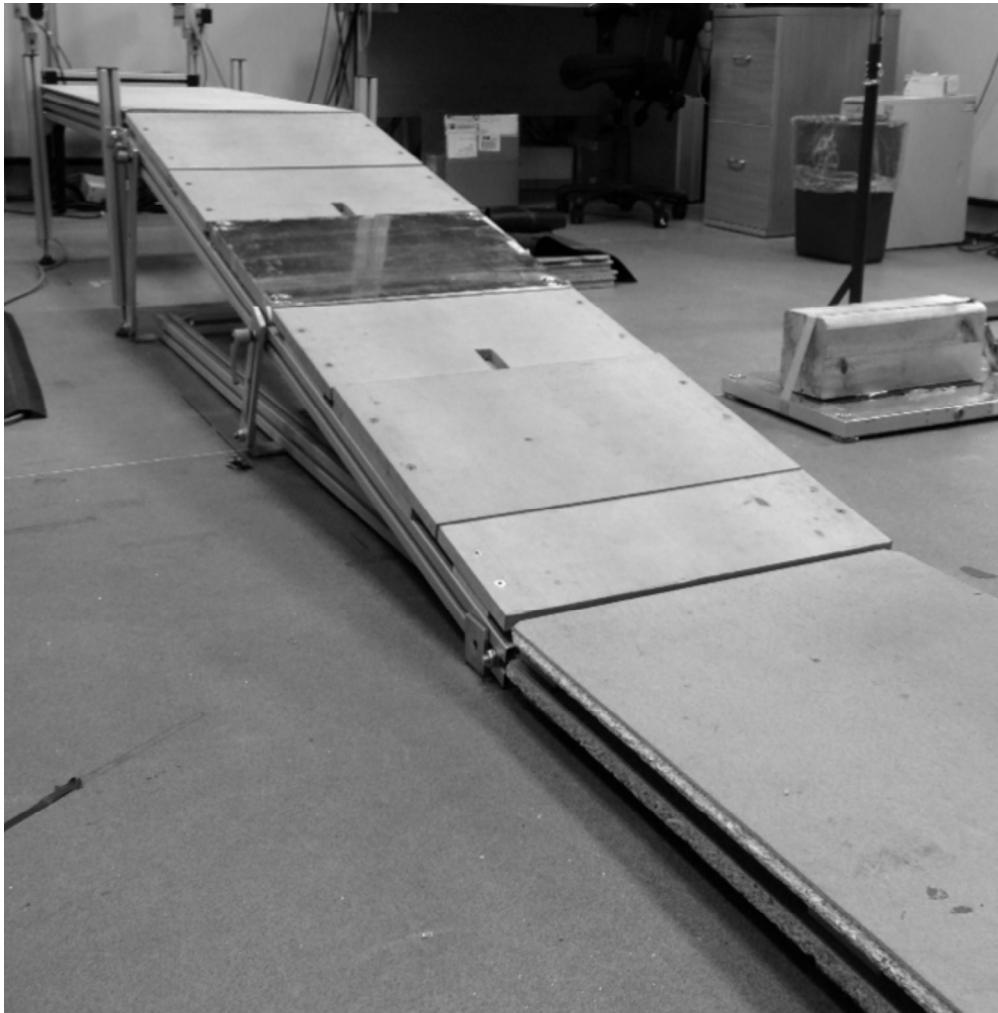
## Figures

**Fig. 1** Steel framed ramp covered in plywood, set an incline of 10 degrees.

**Fig. 2** Peak adduction moments in **a)** level walking and **b)** slope walking for ACLR, ACLR +, ACLR – and control group. Asterisk indicates significance ( $p = 0.042$ ).

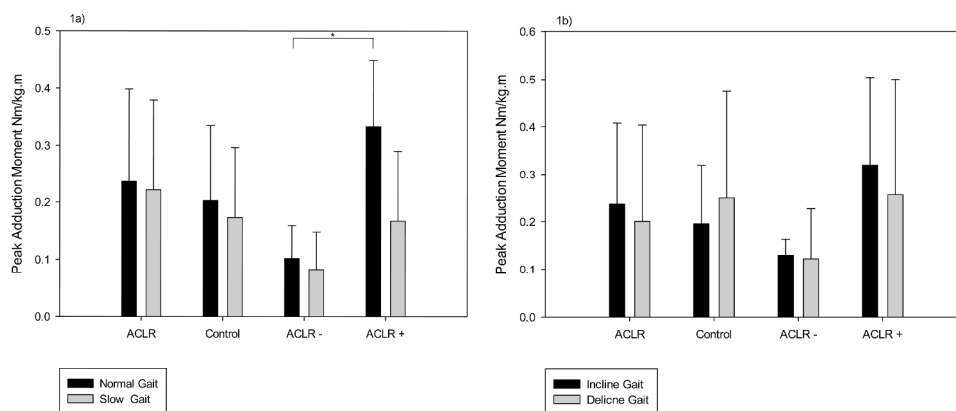
**Fig. 3, a)** Peak flexion moment in all activities for ACLR, contralateral and control group. § represents decline gait to be significantly higher than all other activities ( $p < 0.01$ ). Asterisk indicates significance,  $p < 0.05$  **b)** Peak extension moment in all activities for ACLR, contralateral and control group. ~ represents decline gait to be significantly lower than normal and incline gait,  $p < 0.05$

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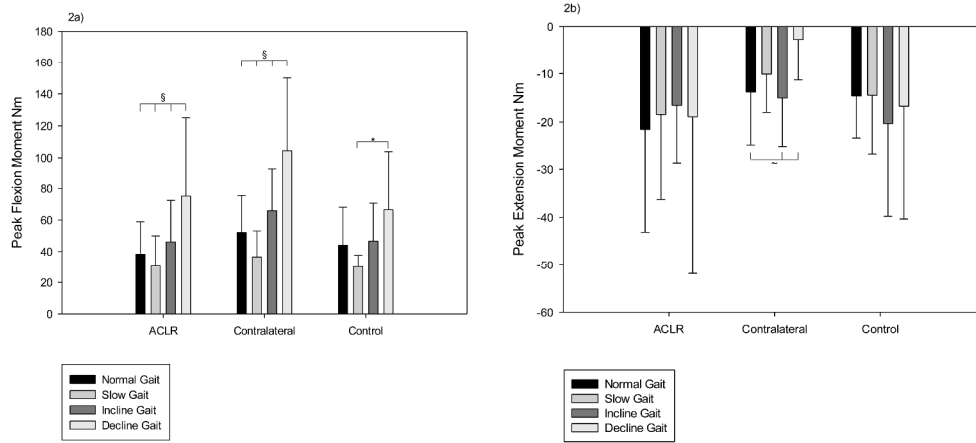
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Peak adduction moments in a) level walking and b) slope walking for ACLR, ACLR +, ACLR - and control group. Asterisk indicates significance ( $p = 0.042$ ).  
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a) Peak flexion moment in all activities for ACLR, contralateral and control group. § represents decline gait to be significantly higher than all other activities ( $p < 0.01$ ). Asterisk indicates significance,  $p < 0.05$  b) Peak extension moment in all activities for ACLR, contralateral and control group. ~ represents decline gait to be significantly lower than normal and incline gait,  $p < 0.05$

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## STROBE Statement—checklist of items that should be included in reports of observational studies

	Item No	Recommendation
<b>Title and abstract</b>	1	(a) Indicate the study's design with a commonly used term in the title or the abstract (b) Provide in the abstract an informative and balanced summary of what was done and what was found
<b>Introduction</b>		
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported
Objectives	3	State specific objectives, including any prespecified hypotheses
<b>Methods</b>		
Study design	4	Present key elements of study design early in the paper
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection
Participants	6	(a) <i>Cohort study</i> —Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up <i>Case-control study</i> —Give the eligibility criteria, and the sources and methods of case ascertainment and control selection. Give the rationale for the choice of cases and controls <i>Cross-sectional study</i> —Give the eligibility criteria, and the sources and methods of selection of participants (b) <i>Cohort study</i> —For matched studies, give matching criteria and number of exposed and unexposed <i>Case-control study</i> —For matched studies, give matching criteria and the number of controls per case
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group
Bias	9	Describe any efforts to address potential sources of bias
Study size	10	Explain how the study size was arrived at
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why
Statistical methods	12	(a) Describe all statistical methods, including those used to control for confounding (b) Describe any methods used to examine subgroups and interactions (c) Explain how missing data were addressed (d) <i>Cohort study</i> —If applicable, explain how loss to follow-up was addressed <i>Case-control study</i> —If applicable, explain how matching of cases and controls was addressed <i>Cross-sectional study</i> —If applicable, describe analytical methods taking account of sampling strategy (e) Describe any sensitivity analyses

Continued on next page



**Results**

Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed (b) Give reasons for non-participation at each stage (c) Consider use of a flow diagram
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders (b) Indicate number of participants with missing data for each variable of interest (c) <i>Cohort study</i> —Summarise follow-up time (eg, average and total amount)
Outcome data	15*	<i>Cohort study</i> —Report numbers of outcome events or summary measures over time <i>Case-control study</i> —Report numbers in each exposure category, or summary measures of exposure <i>Cross-sectional study</i> —Report numbers of outcome events or summary measures
Main results	16	(a) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included (b) Report category boundaries when continuous variables were categorized (c) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses

**Discussion**

Key results	18	Summarise key results with reference to study objectives
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence
Generalisability	21	Discuss the generalisability (external validity) of the study results

**Other information**

Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based
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\*Give information separately for cases and controls in case-control studies and, if applicable, for exposed and unexposed groups in cohort and cross-sectional studies.

**Note:** An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at <http://www.plosmedicine.org/>, Annals of Internal Medicine at <http://www.annals.org/>, and Epidemiology at <http://www.epidem.com/>). Information on the STROBE Initiative is available at [www.strobe-statement.org](http://www.strobe-statement.org).

# BMJ Open

## Knee moments of anterior cruciate ligament reconstructed and control participants during normal and inclined walking.

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<b>Primary Subject Heading</b>:	Sports and exercise medicine
Secondary Subject Heading:	Rehabilitation medicine, Sports and exercise medicine
Keywords:	Knee < ORTHOPAEDIC & TRAUMA SURGERY, Orthopaedic sports trauma < ORTHOPAEDIC & TRAUMA SURGERY, SPORTS MEDICINE

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3 Title: Knee moments of anterior cruciate ligament reconstructed and control  
4 participants during normal and inclined walking.  
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9 Authors: Raghav K Varma<sup>1</sup>, Lynsey D Duffell<sup>1</sup>, Dinesh Nathwani<sup>1</sup> & Alison H  
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49 Word count: 3056  
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53 Key words: Anterior cruciate ligament reconstruction, inclined walkway, adduction  
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55 moment and gait analysis.  
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## Abstract

### Objectives

Prior injury to the knee, particularly anterior cruciate ligament (ACL) injury is known to predispose to premature osteoarthritis (OA). The study sought to explore if there was a biomechanical rationale for this process by investigating changes in external knee moments between people with a history of ACL injury and uninjured subjects during walking; i) on different surface inclines and; ii) at different speeds. In addition we assessed functional differences between the groups.

### Participants

Twelve subjects who had undergone ACL reconstruction (ACLR) and 12 volunteers with no history of knee trauma or injury were recruited into this study. Peak knee flexion and adduction moments were assessed during flat (normal and slow speed), uphill and downhill walking using a inclined walkway with an embedded Kistler Force plate, and a ten camera Vicon motion capture system. Knee osteoarthritis outcome score (KOOS) was used to assess function. MANOVA was used to examine statistical differences in gait and KOOS outcomes.

### Results

No significant difference was observed in the peak knee adduction moment between ACLR and control participants however, in further analysis, MANOVA revealed that ACLR participants with an additional meniscal tear or collateral ligament damage (7 subjects) had a significantly higher adduction moment ( $0.33 \pm 0.12$  Nm/kg.m) when compared to those with isolated ACLR (5 subjects,  $0.1 \pm 0.057$  Nm/kg.m) during gait at

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3 their normal speed ( $p < 0.05$ ). A similar (non-significant) trend was seen during slow,  
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5 uphill and downhill gait.  
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## 8 9 Conclusion

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11 Subjects with an isolated ACLR had a reduced adductor moment rather an increased  
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13 moment, thus questioning prior theories on OA development. In contrast those subjects  
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15 who had sustained associated trauma to other key knee structures were observed to  
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17 have an increased adduction moment. Additional injury concurrent with an ACL rupture  
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19 may lead to a higher predisposition to osteoarthritis than isolated ACL deficiency alone.  
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## 27 Article summary

### 28 29 Strengths and limitations of this study

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- 33 • To our knowledge this is the first report looking at external moments during inclined and  
34 declined walking for ACL reconstruction participants.  
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  - 37 • In addition to looking into the external moments of the affected and unaffected knee, this  
38 study also looked at the effect of gait speed on external moments and differences in knee  
39 osteoarthritis outcome score (KOOS) for each group.  
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  - 45 • This study provides a potential explanation for the disparity seen in previous studies  
46 looking into peak knee adduction moment in ACLR and matched control subjects.  
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  - 50 • This study suggests that injuries to other key knee structures may play a bigger part in  
51 inducing osteoarthritis than ACL injury alone.  
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- One limitation to this study is the small sample size, in particular after dividing our ACLR group into ACLR + and ACLR – groups.

## Introduction

Anterior Cruciate Ligament (ACL) injuries are common, exceeding 100,000 annual cases in the United States.(1) The majority are sports related injuries, and lead to knee instability as a result of increased anterior tibial translation and anterolateral rotation.(2) ACL reconstruction (ACLR) is the primary treatment for an ACL rupture and permits return to a range of high-level activities including sport. It is accepted that people with ACL injuries, including those who undergo surgical reconstruction, are prone to further knee degeneration(3) and early OA.(4,5) Lohmander et al. (2007) reviewed 127 publications and determined that the overall mean incidence of developing OA after an ACL injury with/without reconstruction to be over 50%(3) with the majority noting radiographic signs of OA 10 years after injury.(3) Gait biomechanics are considered to play a vital part in knee joint degeneration, (5, 6) with altered kinematics and kinetics changing the distribution of mechanical load on the knee. (7) This in turn is postulated to lead to cartilage wear(5 - 7) and eventually knee osteoarthritis.

There is consensus amongst researchers that ACL deficient patients employ different gait strategies.(8) In vivo studies have found reduced knee flexion,(5) increased internal tibial rotation(5, 9) and increased knee adduction moment(10) during level walking, to be the three main changes in external knee moments following an ACL rupture. Furthermore, research has indicated that ACL reconstruction does not restore normal knee mechanics(11). Berchuck et al. in 1990(12) noted reduced knee flexion during

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3 normal gait, indicating a coping strategy termed quadriceps avoidance gait. Anterior  
4 displacement of tibia through the contraction of quadriceps is balanced by the ACL when  
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8 the knee is at an angle of 0 to 45 degrees.(12) People with ACL rupture and/or  
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10 reconstruction are found to have quadriceps activation deficits(13), which may be due to  
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12 a central regulatory mechanism to avoid further joint damage by these muscle groups.  
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14 Gait adaptations in the sagittal plane can lead to knee joint instability and ligament  
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16 laxity.(14) This may result in osteoarthritis initiation and progression.(14)  
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20 High moments in frontal and transverse planes of the knee have been linked to OA.(5)  
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22 ACLR has been shown to restore rotational stability,(9, 15) however high knee  
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24 adduction moments (KAM) after reconstruction have been observed(16) but such  
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26 changes are not universally agreed.(17, 18) This is of particular importance since a 1%  
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28 increase in adduction moment at the knee is thought to increase the risk of knee OA by  
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30 6.5 times.(19) The discrepancies in previous studies may be due to different walking  
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32 speeds, and higher KAM may only be evident during more challenging tasks. Hence in  
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34 this study we aimed to gain a better understanding of peak knee moments in the frontal  
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36 and sagittal plane during gait at different speeds and inclines. Our primary aim is to  
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38 compare peak knee moments in the sagittal and frontal plane of ACLR participants to  
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40 healthy controls on sloped surfaces, with a view to exploring the biomechanical basis for  
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42 the observation that ACL injury predisposes to OA. Our secondary aim was to  
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44 investigate the effect of speed on peak moments. Finally, we compared functional  
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46 outcome scores between groups using the Knee injury and Osteoarthritis Outcome  
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48 Score (KOOS).  
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## Methods

This cross-sectional study explored peak knee moments between ACLR and healthy control subjects during slope walking. The study was approved by Imperial College Research Ethics Committee. We used the STROBE statement as a checklist for our observational study. (20)

A total number of 24 subjects participated in this study and written informed consent obtained, details are provided in Table 1. The ACLR inclusion criteria were; aged between 18 – 60 years, Body mass index (BMI) < 30kg/m<sup>2</sup>, a complete, unilateral ACL rupture followed by a single bundle hamstring auto graft reconstruction that was performed at least one-year ago with no history of knee trauma or injury to their contralateral leg. Subjects who were unable to walk comfortably on a 10-degree incline walkway were also excluded. The control group did not have any muscular or neurological lower limb pathology and were matched to the ACLR subjects with respect to gender, activity, height, weight and their dominant leg (leg preference for kicking). All subject completed the Knee injury and Osteoarthritis Outcome Score (KOOS)(21). We measured the subject's activity levels using Tegner Activity scale (22).

A three-dimensional motion analysis system (Vicon MX™ T-20 System, Vicon, Oxford) was used to collect kinematic data for normal, slow, upslope and downslope gait. This software used 10 motion capture cameras to pick up 35 reflective markers at a sampling rate of 100Hz. The reflective markers were placed bilaterally on the head of 2<sup>nd</sup> metatarsal, head of 5<sup>th</sup> metatarsal, head of talus, calcaneal tuberosity, medial and lateral malleolus, medial and lateral femoral epicondyle, anterior superior iliac spine, posterior superior iliac spine, acromion and one single marker on the manubrium. Marker clusters



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3 (3 reflective markers on each) were affixed bilaterally to the calf and thigh. Kinetic data  
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5 (ground reaction force) were collected using portable force plates (Kistler Instruments  
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8 AG, Winterthur, Switzerland) at a sampling rate of 1000 Hz and was synchronised with  
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10 the camera data.

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13 The subjects were asked to walk barefoot. A 5 minute self-directed warm up allowed the  
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15 subjects to familiarise themselves with each task.

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18 A 7-meter long walkway was used, 2.5-meters of which could be raised to form a ramp,  
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20 at an incline of 10 degrees. It was constructed from a steel frame and covered with  
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22 plywood, with one portable force plate embedded in the centre (Figure 1). Participants  
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24 were asked to walk at a self-selected pace both uphill and downhill. The ramp was then  
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26 removed to create a level walkway. All the participants were asked to walk at a self-  
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28 selected pace and at a pace, which they consider to be slow. Each task was repeated  
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30 until both feet made complete contact with the middle of the force plate at least three  
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32 times.  
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39 All data was time normalised to one gait cycle. The data was analysed from the stance  
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41 phase of the gait cycle; when the ground reaction force reached more than 40N (heel  
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43 strike) to when it dropped to less than 40N (toe off). A fourth order Butterworth Filter at a  
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45 cut off (12 Hz) was used to reduce noise. Joint angles and moments were calculated  
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47 from the position of the reflective markers and the ground reaction force data using a  
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49 custom model written in body builder software.(23-25) Peak moments in the sagittal and  
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51 frontal planes of the knee were extracted using MATLAB (R2013b) software.  
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Unpaired Student's t-tests were used to determine any significant differences in demographics between ACLR and control group. MANOVA test was used to calculate significant differences in all other parameters. Tukey HSD approach was used to establish significance, with the alpha value set at 0.05. All statistics were carried out using SPSS version 22.

## Results

12 ACLR participants (9 male and 3 female) and 12 control (9 male and 3 female) were recruited for this study. There were no significant differences between groups in age, height, weight and Tegner Activity Scale (Table 1). The mean time since reconstruction surgery was 4 years and 6 months.

**Table 1** Subject characteristics, activity level and time since surgery. 12 participants in ACLR group and 12 in control group

	ACLR (SD)	Control (SD)	Unpaired T-test
Age (yr)	30.5 (8.68)	24.8 (8.81)	P = 0.125
Height (m)	1.76 (0.13)	1.73 (0.11)	P = 0.547
Weight (kg)	75 (11.13)	71.6 (11.2)	P = 0.464
Tegner Activity Scale	6.25 (1.82)	6.08 (1.93)	P = 0.826
Time since surgery (yr)	4.5 (3.5)	NA	

ACLR, Anterior cruciate ligament reconstruction

We further divided our ACLR group into two; subjects that had additional cartilage, meniscus or ligament damage in their ACLR leg (ACLR + group; 7 subjects) and subjects with isolated ACL injuries (ACLR – group; 5 subjects). The additional knee injuries to the ACL rupture are meniscal tear (3 participants), cartilage damage (3 participants) and torn MCL (1 participant).

No statistically significant differences were found in peak knee adduction moment between ACLR and control participants during uphill and downhill gait, and during gait at normal and slow walking speeds on a flat surface (Figure 2). Further analysis revealed that ACLR participants with meniscal tear, cartilage damage or medial collateral ligament damage (ACLR +) had significantly higher knee adduction moment ( $0.33 \pm 0.12$  Nm/kg.m) during gait on a flat surface at a normal walking speed compared to those participants with an isolated ACL injury (ACLR -,  $0.1 \pm 0.057$  Nm/kg.m),  $p = 0.042$  (Figure 2).

This was not the case for data collected in the sagittal plane. There was a tendency for the contralateral (unaffected) knee of ACLR participants to show a higher mean knee flexion moment in all activities compared to ACLR affected knees and control knees (Figure 3). The difference was not found to be statistically significant.

Table 2 shows that there were no significant differences in gait speed in normal or slow walking between any groups. The control group had significantly higher scores in all of the KOOS domains apart from activities of daily life compared to the ACLR group (Table 3). No significant KOOS differences were seen between ACLR + and ACLR – groups.

**Table 2** Gait speed during normal and slow, level walking tasks.

	ACLR	Control	ACLR +	ACLR -	P = value
Gait normal speed	1.17 (0.13)	1.20 (0.11)	1.18 (0.15)	1.16 (0.11)	P = 0.940
Gait slow speed	0.76 (0.13)	0.75 (0.11)	0.78 (0.16)	0.74 (0.09)	P = 0.885

ACLR, Anterior cruciate ligament reconstruction; ACLR +, subjects with other knee injuries in their ACLR leg; ACLR -, subjects with isolated ACL injuries.  
Data are mean (SD).

**Table 3** Knee osteoarthritis outcome score (KOOS) with standard deviation (SD) for each domain recorded for each group.

KOOS Outcome	ACLR (SD) (n=12)	Control (SD) (n=12)	ACLR + (SD) (n=7)	ACLR - (SD) (n=5)	Significant values
Pain	88.4 (9.32)	99.1 (3.2)	87.5 (8.83)	89.4 (10.8)	Control vs ACLR: P = 0.010 Control vs ACLR(+): P = 0.019
Symptoms	83.1 (11.4)	98.2 (3.19)	85.1 (12.7)	80.7 (10.6)	Control vs all other groups: P < 0.05
Activities of daily life	96.3 (5.63)	100 (0)	98 (3)	94.4 (7.7)	No significant differences
Sport and recreation	83.8 (16.9)	99.6 (1.4)	89.1 (7.4)	77.4 (23)	Control vs ACLR: P = 0.006 Control vs ACLR(-): P = .003
Knee related QOL	64.5 (23.2)	100 (0)	64.6 (23.3)	70 (26.7)	Control vs all other groups: P < 0.05

ACLR, Anterior cruciate ligament reconstruction; ACLR +, subjects with other knee injuries in their ACLR leg; ACLR -, subjects with isolated ACL injuries.  
Data are mean (SD).

## Discussion

In the frontal plane we found no statistically significant differences between our ACLR participants and controls. However ACLR subjects who had sustained associated trauma to other key knee structures (meniscal, collateral ligament and chondral damage) were observed to have a higher adduction moment during gait on a flat surface at normal walking speed when compared to subjects with isolated ACLR. In the sagittal

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3 plane there was a tendency for ACLR participants to have higher peak knee flexion  
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5 moment in their contralateral leg during all activities.  
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9 Previous studies that have investigated peak knee adduction moment in ACLR and  
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11 matched control subjects have provided mixed results.(16,17,18) We investigated  
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13 similar and more challenging gait set-ups (by altering incline), as well as the effects of  
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15 differences in walking speed, in order to explore the biomechanical basis for the  
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17 observation that ACL injury predisposes to OA. Our data showed no significant  
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19 differences in KAM between our ACLR participants and control subjects under all  
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21 conditions. This indicates that providing more challenging gait set-ups such as sloped  
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23 walking, where a higher range of motion in the sagittal plane is required, does not  
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25 emphasize differences between ACLR and control subjects. Based on our findings, the  
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27 discrepancies in previous studies appear not to be related to the difficulty of the task or  
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29 differences in walking speed.  
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36 ACL injury is often accompanied by other knee injuries.(26) Prevalence of associated  
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38 meniscal damage and chondral lesions at the time of ACL injury can be as high as 65%  
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40 and 23% respectively.(27) Associated knee injuries are thought to increase the  
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42 incidence of OA from 0 – 13% in isolated ACL injury to 21 – 48%.(28) This may be  
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44 because key knee structures such as menisci prevent cartilage wear by distributing  
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46 loads and functioning as a shock absorber.(14) Our results suggest that people with  
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48 ACLR injuries with associated knee injuries experience higher knee adduction moments  
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50 than people with isolated ACLR injuries.  
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3 Of the three previous studies that have looked at peak KAM in ACLR and matched  
4 control subjects, Butler et al. found the ACLR group to have a higher peak KAM  
5 compared to controls.(16) This was also seen by our ACLR + group. In the studies that  
6 followed, Webster et al. and Zabala et al. found the ACLR group to have a reduced peak  
7 knee adduction moment to controls.(17, 18) This was seen by our ACLR – group (Figure  
8 2). This disparity in studies may therefore be a consequence of different exclusion  
9 criteria for ACLR subjects. Butler et al. did not exclude ACLR subjects with other knee  
10 injuries,(16) while the other two studies excluded subjects with ligament damage(17, 18)  
11 and also those with >25% of menisci loss.(18) We suggest that associated knee injuries  
12 are related to increased knee adduction moments in ACLR participants.  
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28 We found the difference between peak KAM in ACLR + and ACLR – to be statistically  
29 significant only during normal gait. We expected the difference to be higher during  
30 sloped walking, as it is more challenging than level walking. Change in terrain, muscle  
31 weakness, gait deficit and balance deficit are primary risk factors for falling.(29, 30) This  
32 suggests that ACLR participants need to adopt a conservative gait strategy while  
33 walking on a sloped surface to ensure safety. During challenging tasks such as downhill  
34 walking healthy participants increased their metabolic activity and implemented a  
35 conservative gait strategy to reduce the risk of falling.(29) This principle may also be  
36 applied by ACLR participants to ensure safety.  
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50 In the sagittal plane, no statistically significant differences were observed between  
51 ACLR, ACLR +, ACLR – and control group in peak knee flexion and extension moments.  
52 Both uphill and downhill walking require greater use of quadriceps muscle than on a  
53 level walkway.(30, 31) Two years after an ACLR surgery, differences in quadriceps  
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3 strength between limbs are no longer seen.(29) All of the ACLR subjects had undergone  
4 reconstruction at least 1 year before taking part in this study, with an average of 4.5  
5  
6 years. This indicates that all subjects may have had sufficient time to restore their  
7 quadriceps strength. Even though sagittal instability is thought to increase joint loads  
8 and lead to joint failure,(14, 32) it may not play a significant role in OA induction and  
9 progression after reconstruction.  
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18 An unexpected finding was the tendency for the contralateral knees of ACLR  
19 participants to have higher peak knee flexion and lower peak knee extension moment  
20 compared to the ACLR and control knee in all activities. This may be an adaptation to  
21 reduce loading on their ACLR knee. Patients with advanced knee OA also display this  
22 adaptation to reduce loading on their injured leg.(33) Even though this may present as a  
23 mechanism to slow the progression of OA, there are harmful implications associated  
24 with the contralateral leg. Weight bearing asymmetry may induce OA in the contralateral  
25 leg;(34) 37% (24/65 female patients) showed signs of radiographic OA in their  
26 contralateral leg, 12 years after ACL reconstruction.(35) This suggests that in this  
27 population unilateral injury changes joint function bilaterally.  
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42 In addition to our primary investigations we also investigated differences in KOOS and  
43 walking speed. There was no significant difference in KOOS or gait speed between  
44 ACLR + and ACLR -. This indicates that high peak knee adduction moment in the  
45 injured leg does not affect our subjects' pain outcome, symptoms, activities of daily life,  
46 sport and recreation, knee related quality of life and gait speed. Thereby patient reported  
47 outcome measures and gait speed might not provide the clinician with any information  
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60 about different gait adaptations.

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3 Mundermann et al (2004) found a 10.2% reduction in maximum knee adduction moment  
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5 when people with less severe OA reduced their walking speed from 1.2 meters/second  
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7 to 0.8 meters per second.(36) However in the current study the difference in peak knee  
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9 moments between normal (1.17 m/s) and slow gait speed (0.76 m/s) were not  
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11 statistically significant. This may be due to our small sample size.  
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15 It is important to note that different knee injuries, rehabilitation protocols and time  
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17 between injury and reconstruction are all thought to influence joint moments.(18) These  
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19 are limitations that should be considered when examining the results presented here.  
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21 Additionally our participants were not recruited straight after their ACLR, some  
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23 participants may have had further injury or pathological changes within the joint since  
24  
25 the reconstruction. Another limitation was our small sample size, in particular after  
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27 dividing our ACLR group into ACLR + and ACLR – groups.  
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31 The ramp was set at an incline of 10 degrees because the transition from a level to  
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33 slope walking strategy is thought to be around 5.5 degrees(31) and after the incline of  
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35 10 degrees no kinematic differences are seen in healthy participants.(31)  
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39 With regards to Vicon Motion capture system different skin marker placement and skin  
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41 motion artifacts are thought to increase error.(6) We tried to reduce the effects of  
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43 different skin marker placement by having only one researcher place all markers on  
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45 each individual. In addition we used a model that used clusters to reduce the effects of  
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47 skin motion.(25)  
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## Conclusion

In conclusion, this study found no significant differences in peak moments in the frontal and sagittal plane during level and sloped walking for ACLR compared with control participants. However, we noted that individuals who have other knee injuries associated with their ACLR knee exhibit higher peak adduction moments during level walking at their normal speed. This suggests that injuries to other key knee structures may play a bigger part in inducing OA than ACL injury alone, although this requires further investigation with a larger sample size. Our data also suggest that the contralateral knee appears to be functioning in such a way to reduce high moments in the ACLR knees, which may be relevant in the risk of OA development in both knees. These findings warrant a longitudinal study comparing the knee adduction moment between isolated ACLR injury and ACLR with additional knee injuries and the prevalence of premature OA.

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15 Varma carried out data collection, statistical analysis and analysis of the data produced.  
16 He also drafted and revised the paper. He is guarantor. Lynsey D Duffell attained ethical  
17 approval, determined the methodology, helped with data analysis and drafted and  
18 revised the paper. Dinesh Nathwani helped with data collection and drafted and revised  
19 the paper. Alison H McGregor monitored the data collection for the whole trial, provided  
20 the data collection tools and drafted and revised the paper. Robert Weinert-Aplin  
21 designed the data collection tool.  
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34 **Competing interests** - None  
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37 **Data sharing** - No additional data available  
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## References

1. Lyman S, Koulouvaris P, Sherman S et al. Epidemiology of anterior cruciate ligament reconstruction: trends, readmissions, and subsequent knee surgery. *J Bone Joint Surg Am* 2009;91:2321-8.
2. Matsumoto H, Suda Y, Otani T et al. Roles of the anterior cruciate ligament and the medial collateral ligament in preventing valgus instability. *J Orthop Sci* 2001;6:28-32.
3. Lohmander LS, Englund PM, Dahl LL et al. The long-term consequence of anterior cruciate ligament and meniscus injuries: osteoarthritis. *Am J Sports Med* 2007;35:1756-69.
4. Porat A, Roos EM, Roos H. High prevalence of osteoarthritis 14 years after an anterior cruciate ligament tear in male soccer players: a study of radiographic and patient relevant outcomes. *Ann Rheum Dis* 2004;63:269-73.
5. Andriacchi TP, Mündermann A. The role of ambulatory mechanics in the initiation and progression of knee osteoarthritis. *Curr Opin Rheumatol* 2006;18:514-8.
6. Stergiou N, Ristanis S, Moraiti C et al. Tibial rotation in anterior cruciate ligament (ACL)-deficient and ACL-reconstructed knees: a theoretical proposition for the development of osteoarthritis. *Sports Med* 2007;37:601-13.
7. Andriacchi TP, Mündermann A, Smith RL et al. A framework for the in vivo pathomechanics of osteoarthritis at the knee. *Ann Biomed Eng* 2004;32:447-57.
8. Hart JM, Ko JW, Konold T et al. Sagittal plane knee joint moments following anterior cruciate ligament injury and reconstruction: a systematic review. *Clin Biomech* 2010;25:277-83.

- 1  
2  
3 9. Georgoulis AD, Papadonikolakis A, Papageorgiou CD et al. Three-dimensional  
4 tibiofemoral kinematics of the anterior cruciate ligament-deficient and  
5 reconstructed knee during walking. *Am J Sports Med* 2003;31:75-9.  
6  
7
- 8  
9  
10 10. Noyes FR, Schipplein OD, Andriacchi TP et al. The anterior cruciate ligament-  
11 deficient knee with varus alignment. An analysis of gait adaptations and dynamic  
12 joint loadings. *Am J Sports Med* 1992;20:707-16.  
13  
14
- 15  
16  
17 11. Gokeler A, Benjaminse A, van Eck CF, et al. Return of normal gait as an outcome  
18 measurement in acl reconstructed patients. A systematic review. *Int J Sports*  
19 *Phys Ther.* 2013 Aug;8(4):441-51.  
20  
21
- 22  
23  
24 12. Berchuck M, Andriacchi TP, Bach BR et al. Gait adaptations by patients who  
25 have a deficient anterior cruciate ligament. *J Bone Joint Surg Am* 1990;72:871-7.  
26  
27
- 28  
29  
30 13. Urbach D, Nebelung W, Becker R et al. Effects of reconstruction of the anterior  
31 cruciate ligament on voluntary activation of quadriceps femoris a prospective  
32 twitch interpolation study. *J Bone Joint Surg Br* 2001;83:1104-10.  
33  
34
- 35  
36  
37 14. Roos EM. Joint injury causes knee osteoarthritis in young adults. *Curr Opin*  
38 *Rheumatol* 2005;17:195-200.  
39  
40
- 41  
42  
43 15. Papageorgiou CD, Gil JE, Kanamori A et al. The biomechanical interdependence  
44 between the anterior cruciate ligament replacement graft and the medial  
45 meniscus. *Am J Sports Med* 2001;29:226-31.  
46  
47
- 48  
49  
50 16. Butler RJ, Minick KI, Ferber R et al. Gait mechanics after ACL reconstruction:  
51 implications for the early onset of knee osteoarthritis. *Br J Sports Med*  
52 2009;43:366-70.  
53  
54  
55  
56  
57  
58  
59  
60

- 1  
2  
3 17. Webster KE, Feller JA. The knee adduction moment in hamstring and patellar  
4 tendon anterior cruciate ligament reconstructed knees. *Knee Surg Sports*  
5 *Traumatol Arthrosc* 2012;20:2214-9.  
6  
7  
8  
9  
10 18. Zabala ME, Favre J, Scanlan SF et al. Three-dimensional knee moments of ACL  
11 reconstructed and control subjects during gait, stair ascent, and stair descent. *J*  
12 *Biomech* 2013;46:515-20.  
13  
14  
15  
16  
17 19. Miyazaki T, Wada M, Kawahara H et al. Dynamic load at baseline can predict  
18 radiographic disease progression in medial compartment knee osteoarthritis. *Ann*  
19 *Rheum Dis* 2002;61:617-22.  
20  
21  
22  
23  
24 20. von Elm E, Altman DG, Egger M, et al; STROBE Initiative. The Strengthening the  
25 Reporting of Observational Studies in Epidemiology (STROBE) statement:  
26 guidelines for reporting observational studies.  
27 *J Clin Epidemiol*. 2008 Apr;61(4):344-9.  
28  
29  
30  
31  
32  
33 21. Roos EM, Roos HP, Lohmander LS et al. Knee Injury and Osteoarthritis Outcome  
34 Score (KOOS)— development of a self-administered outcome measure. *J Orthop*  
35 *Sports Phys Ther* 1998;28:88–96.  
36  
37  
38  
39  
40  
41 22. Tegner Y, Lysholm J. Rating systems in the evaluation of knee ligament injuries.  
42 *Clin Orthop*. 1985;198:43–49.  
43  
44  
45  
46 23. Cleather DJ, Bull AM. Influence of inverse dynamics methods on the calculation  
47 of inter-segmental moments in vertical jumping and weightlifting. *Biomed Eng*  
48 *Online* 2010;9:74  
49  
50  
51  
52 24. Cleather DI, Bull Am. Lower-extremity musculoskeletal geometry affects the  
53 calculation of patellofemoral forces in vertical jumping and weightlifting. *Proc Inst*  
54 *Mech Eng H* 2010;224:1073-1083  
55  
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49  
50  
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53  
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55  
56  
57  
58  
59  
60
25. Hope, N., Duffell, L. D., and McGregor, A. H. Validation of a new model to calculate joint kinematics during gait. *European Society of Biomechanics Conference Proceedings* 1-7-2012.
26. Claes S, Hermie L, Verdonk R et al. Is osteoarthritis an inevitable consequence of anterior cruciate ligament reconstruction? A meta- analysis. *Knee Surg Sports Traumatol Arthrosc* 2013;21:1967-76.
27. Louboutin H, Debarge R, Richou J et al. Osteoarthritis in patients with anterior cruciate ligament rupture: a review of risk factors. *Knee* 2009;16:239-44.
28. Oiestad BE, Engebretsen L, Storheim K, et al. Knee osteoarthritis after anterior cruciate ligament injury: a systematic review. *Am J Sports Med* 2009;37:1434–1443
29. Monsch ED, Franz CO, Dean JC. The effects of gait strategy on metabolic rate and indicators of stability during downhill walking. *J Biomech* 2012;45:1928-33.
30. Mizner RL, Snyder-Mackler L. Altered loading during walking and sit-to-stand is affected by quadriceps weakness after total knee arthroplasty. *J Orthop Res* 2005;23:1083-90.
31. A.N. Lay, C.J. Hass, R.J. Gregor. The effects of sloped surfaces on locomotion: a kinematic and kinetic analysis. *Journal of Biomechanics* 2006;39:1621–1628
32. Gottschall JS, Nichols TR. Neuromuscular strategies for the transitions between level and hill surfaces during walking. *Philos Trans R Soc Lond B Biol Sci* 2011;366:1565-79.
33. Creaby MW, Bennell KL, Hunt MA. Gait differs between unilateral and bilateral knee osteoarthritis. *Arch Phys Med Rehabil* 2012;93(5):822-7.

- 1  
2  
3 34. Christiansen CL, Stevens-Lapsley JE. Weight-bearing asymmetry in relation to  
4 378 measures of impairment and functional mobility for people with knee  
5  
6 osteoarthritis. *Arch Phys Med Rehabil* 2010;91:1524-8.  
7  
8  
9  
10 35. Lohmander, L.S., Ostenberg, A., Englund, M. et al. High prevalence of knee  
11 osteoarthritis, pain, and functional limitations in female soccer players twelve  
12 years after anterior cruciate ligament injury. *Arthritis and Rheumatology*  
13 2004;50:3145–3152.  
14  
15  
16  
17 36. Mündermann A, Dyrby CO, Hurwitz DE et al. Potential strategies to reduce  
18 medial compartment loading in patients with knee osteoarthritis of varying  
19 severity: reduced walking speed. *Arthritis Rheum* 2004;50:1172-8.  
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## 30 Figures

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33 **Fig. 1** Steel framed ramp covered in plywood, set an incline of 10 degrees.  
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35 **Fig. 2** Peak adduction moments in **a)** level walking and **b)** slope walking for ACLR,  
36 ACLR +, ACLR – and control group. Asterisk indicates significance ( $p = 0.042$ ).  
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38 **Fig. 3, a)** Peak flexion moment in all activities for ACLR, contralateral and control group.  
39 § represents decline gait to be significantly higher than all other activities ( $p < 0.01$ ).  
40 Asterisk indicates significance,  $p < 0.05$  **b)** Peak extension moment in all activities for  
41 ACLR, contralateral and control group. ~ represents decline gait to be significantly lower  
42 than normal and incline gait,  $p < 0.05$   
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3 Title: Knee moments of anterior cruciate ligament reconstructed and control  
4 participants during normal and inclined walking.  
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46 Word count: 3056  
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49 Key words: Anterior cruciate ligament reconstruction, inclined walkway, adduction moment and  
50 gait analysis.  
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## Abstract

### Objectives

Prior injury to the knee, particularly anterior cruciate ligament (ACL) injury is known to predispose to premature osteoarthritis (OA). The study sought to explore if there was a biomechanical rationale for this process by investigating changes in external knee moments between people with a history of ACL injury and uninjured subjects during walking; i) on different surface inclines and; ii) at different speeds. In addition we assessed functional differences between the groups.

### Participants

Twelve subjects who had undergone ACL reconstruction (ACLR) and 12 volunteers with no history of knee trauma or injury were recruited into this study. Peak knee flexion and adduction moments were assessed during flat (normal and slow speed), uphill and downhill walking using an inclined walkway with an embedded Kistler Force plate, and a ten camera Vicon motion capture system. Knee osteoarthritis outcome score (KOOS) was used to assess function. MANOVA was used to examine statistical differences in gait and KOOS outcomes.

### Results

No significant difference was observed in the peak knee adduction moment between ACLR and control participants however, in further analysis, MANOVA revealed that ACLR participants with an additional meniscal tear or collateral ligament damage (7 subjects) had a significantly higher adduction moment ( $0.33 \pm 0.12$  Nm/kg.m) when compared to those with isolated ACLR (5 subjects,  $0.1 \pm 0.057$  Nm/kg.m) during gait at

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3 their normal speed ( $p < 0.05$ ). A similar (non-significant) trend was seen during **slow,**  
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5 **uphill and downhill gait.**  
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## 8 9 Conclusion

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11 Subjects with an isolated ACLR had a reduced adductor moment rather an increased  
12 moment, thus questioning prior theories on OA development. In contrast those subjects  
13 who had sustained associated trauma to other key knee structures were observed to  
14 have an increased adduction moment. Additional injury concurrent with an ACL rupture  
15 **may lead to a** higher predisposition to osteoarthritis than isolated ACL deficiency alone.  
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## 27 Article summary

### 28 Strengths and limitations of this study

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- 33 • To our knowledge this is the first report looking at external moments during inclined and  
34 declined walking for ACL reconstruction participants.  
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  - 37 • In addition to looking into the external moments of the affected and unaffected knee, this  
38 study also looked at the effect of gait speed on external moments and differences in knee  
39 osteoarthritis outcome score (KOOS) for each group.  
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  - 45 • This study provides a **potential** explanation for the disparity seen in previous studies  
46 looking into peak knee adduction moment in ACLR and matched control subjects.  
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  - 49 • This study suggests that injuries to other key knee structures may play a bigger part in  
50 inducing osteoarthritis than ACL injury alone.  
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- One limitation to this study is the small sample size, in particular after dividing our ACLR group into ACLR + and ACLR – groups.

## Introduction

Anterior Cruciate Ligament (ACL) injuries are common, exceeding 100,000 annual cases in the United States.(1) The majority are sports related injuries, and lead to knee instability as a result of increased anterior tibial translation and anterolateral rotation.(2) ACL reconstruction (ACLR) is the primary treatment for an ACL rupture and permits return to a range of high-level activities including sport. It is accepted that people with ACL injuries, including those who undergo surgical reconstruction, are prone to further knee degeneration(3) and early OA.(4,5) Lohmander et al. (2007) reviewed 127 publications and determined that the overall mean incidence of developing OA after an ACL injury with/without reconstruction to be over 50%(3) with the majority noting radiographic signs of OA 10 years after injury.(3) Gait biomechanics are considered to play a vital part in knee joint degeneration, (5, 6) with altered kinematics and kinetics changing the distribution of mechanical load on the knee. (7) This in turn is postulated to lead to cartilage wear(5 - 7) and eventually knee osteoarthritis.

There is consensus amongst researchers that ACL deficient patients employ different gait strategies.(8) In vivo studies have found reduced knee flexion,(5) increased internal tibial rotation(5, 9) and increased knee adduction moment(10) during level walking, to be the three main changes in external knee moments following an ACL rupture. Furthermore, research has indicated that ACL reconstruction does not restore normal knee mechanics(11). Berchuck et al. in 1990(12) noted reduced knee flexion during

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3 normal gait, indicating a coping strategy termed quadriceps avoidance gait. Anterior  
4 displacement of tibia through the contraction of quadriceps is balanced by the ACL when  
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6 the knee is at an angle of 0 to 45 degrees.(12) People with ACL rupture and/or  
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8 reconstruction are found to have quadriceps activation deficits(13), which may be due to  
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10 a central regulatory mechanism to avoid further joint damage by these muscle groups.  
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14 Gait adaptations in the sagittal plane can lead to knee joint instability and ligament  
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16 laxity.(14) This may result in osteoarthritis initiation and progression.(14)  
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20 High moments in frontal and transverse planes of the knee have been linked to OA.(5)  
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22 ACLR has been shown to restore rotational stability,(9, 15) however high knee  
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24 adduction moments (KAM) after reconstruction have been observed(16) but such  
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26 changes are not universally agreed.(17, 18) This is of particular importance since a 1%  
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28 increase in adduction moment at the knee is thought to increase the risk of knee OA by  
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30 6.5 times.(19) The discrepancies in previous studies may be due to different walking  
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32 speeds, and higher KAM may only be evident during more challenging tasks. Hence in  
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34 this study we aimed to gain a better understanding of peak knee moments in the frontal  
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36 and sagittal plane during gait at different speeds and inclines. Our primary aim is to  
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38 compare peak knee moments in the sagittal and frontal plane of ACLR participants to  
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40 healthy controls on sloped surfaces, with a view to exploring the biomechanical basis for  
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42 the observation that ACL injury predisposes to OA. Our secondary aim was to  
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44 investigate the effect of speed on peak moments. Finally, we compared functional  
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46 outcome scores between groups using the Knee injury and Osteoarthritis Outcome  
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48 Score (KOOS).  
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## Methods

This cross-sectional study explored peak knee moments between ACLR and healthy control subjects during slope walking. The study was approved by Imperial College Research Ethics Committee. We used the STROBE statement as a checklist for our observational study. (20)

A total number of 24 subjects participated in this study and written informed consent obtained, details are provided in Table 1. The ACLR inclusion criteria were; aged between 18 – 60 years, Body mass index (BMI) < 30kg/m<sup>2</sup>, a complete, unilateral ACL rupture followed by a single bundle hamstring auto graft reconstruction that was performed at least one-year ago with no history of knee trauma or injury to their contralateral leg. Subjects who were unable to walk comfortably on a 10-degree incline walkway were also excluded. The control group did not have any muscular or neurological lower limb pathology and were matched to the ACLR subjects with respect to gender, activity, height, weight and their dominant leg (leg preference for kicking). All subject completed the Knee injury and Osteoarthritis Outcome Score (KOOS)(21). We measured the subject's activity levels using Tegner Activity scale (22).

A three-dimensional motion analysis system (Vicon MX™ T-20 System, Vicon, Oxford) was used to collect kinematic data for normal, slow, upslope and downslope gait. This software used 10 motion capture cameras to pick up 35 reflective markers at a sampling rate of 100Hz. The reflective markers were placed bilaterally on the head of 2<sup>nd</sup> metatarsal, head of 5<sup>th</sup> metatarsal, head of talus, calcaneal tuberosity, medial and lateral malleolus, medial and lateral femoral epicondyle, anterior superior iliac spine, posterior superior iliac spine, acromion and one single marker on the manubrium. Marker clusters

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3 (3 reflective markers on each) were affixed bilaterally to the calf and thigh. Kinetic data  
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5 (ground reaction force) were collected using portable force plates (Kistler Instruments  
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8 AG, Winterthur, Switzerland) at a sampling rate of 1000 Hz and was synchronised with  
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10 the camera data.

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13 The subjects were asked to walk barefoot. A 5 minute self-directed warm up allowed the  
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15 subjects to familiarise themselves with each task.

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18 A 7-meter long walkway was used, 2.5-meters of which could be raised to form a ramp,  
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20 at an incline of 10 degrees. It was constructed from a steel frame and covered with  
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22 plywood, with one portable force plate embedded in the centre (Figure 1). Participants  
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24 were asked to walk at a self-selected pace both uphill and downhill. The ramp was then  
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26 removed to create a level walkway. All the participants were asked to walk at a self-  
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28 selected pace and at a pace, which they consider to be slow. Each task was repeated  
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30 until both feet made complete contact with the middle of the force plate at least three  
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32 times.  
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39 All data was time normalised to one gait cycle. The data was analysed from the stance  
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41 phase of the gait cycle; when the ground reaction force reached more than 40N (heel  
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43 strike) to when it dropped to less than 40N (toe off). A fourth order Butterworth Filter at a  
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45 cut off (12 Hz) was used to reduce noise. Joint angles and moments were calculated  
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47 from the position of the reflective markers and the ground reaction force data using a  
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49 custom model written in body builder software.(23-25) Peak moments in the sagittal and  
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51 frontal planes of the knee were extracted using MATLAB (R2013b) software.  
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Unpaired Student's t-tests were used to determine any significant differences in demographics between ACLR and control group. MANOVA test was used to calculate significant differences in all other parameters. Tukey HSD approach was used to establish significance, with the alpha value set at 0.05. All statistics were carried out using SPSS version 22.

## Results

12 ACLR participants (9 male and 3 female) and 12 control (9 male and 3 female) were recruited for this study. There were no significant differences between groups in age, height, weight and Tegner Activity Scale (Table 1). The mean time since reconstruction surgery was 4 years and 6 months.

**Table 1** Subject characteristics, activity level and time since surgery. 12 participants in ACLR group and 12 in control group

	ACLR (SD)	Control (SD)	Unpaired T-test
Age (yr)	30.5 (8.68)	24.8 (8.81)	P = 0.125
Height (m)	1.76 (0.13)	1.73 (0.11)	P = 0.547
Weight (kg)	75 (11.13)	71.6 (11.2)	P = 0.464
Tegner Activity Scale	6.25 (1.82)	6.08 (1.93)	P = 0.826
Time since surgery (yr)	4.5 (3.5)	NA	

ACLR, Anterior cruciate ligament reconstruction

We further divided our ACLR group into two; subjects that had additional cartilage, meniscus or ligament damage in their ACLR leg (ACLR + group; 7 subjects) and subjects with isolated ACL injuries (ACLR – group; 5 subjects). The additional knee injuries to the ACL rupture are meniscal tear (3 participants), cartilage damage (3 participants) and torn MCL (1 participant).

No statistically significant differences were found in peak knee adduction moment between ACLR and control participants during uphill and downhill gait, and during gait at normal and slow walking speeds on a flat surface (Figure 2). Further analysis revealed that ACLR participants with meniscal tear, cartilage damage or medial collateral ligament damage (ACLR +) had significantly higher knee adduction moment ( $0.33 \pm 0.12$  Nm/kg.m) during gait on a flat surface at a normal walking speed compared to those participants with an isolated ACL injury (ACLR -,  $0.1 \pm 0.057$  Nm/kg.m),  $p = 0.042$  (Figure 2).

This was not the case for data collected in the sagittal plane. There was a tendency for the contralateral (unaffected) knee of ACLR participants to show a higher mean knee flexion moment in all activities compared to ACLR affected knees and control knees (Figure 3). The difference was not found to be statistically significant.

Table 2 shows that there were no significant differences in gait speed in normal or slow walking between any groups. The control group had significantly higher scores in all of the KOOS domains apart from activities of daily life compared to the ACLR group (Table 3). No significant KOOS differences were seen between ACLR + and ACLR - groups.

**Table 2** Gait speed during normal and slow, level walking tasks.

		ACLR	Control	ACLR +	ACLR -	P = value
Gait speed	normal	1.17 (0.13)	1.20 (0.11)	1.18 (0.15)	1.16 (0.11)	P = 0.940
Gait speed	slow	0.76 (0.13)	0.75 (0.11)	0.78 (0.16)	0.74 (0.09)	P = 0.885

ACLR, Anterior cruciate ligament reconstruction; ACLR +, subjects with other knee injuries in their ACLR leg; ACLR -, subjects with isolated ACL injuries.  
Data are mean (SD).



**Table 3** Knee osteoarthritis outcome score (KOOS) with standard deviation (SD) for each domain recorded for each group.

KOOS Outcome	ACLR (SD) (n=12)	Control (SD) (n=12)	ACLR + (SD) (n=7)	ACLR - (SD) (n=5)	Significant values
Pain	88.4 (9.32)	99.1 (3.2)	87.5 (8.83)	89.4 (10.8)	Control vs ACLR: P = 0.010 Control vs ACLR(+): P = 0.019
Symptoms	83.1 (11.4)	98.2 (3.19)	85.1 (12.7)	80.7 (10.6)	Control vs all other groups: P < 0.05
Activities of daily life	96.3 (5.63)	100 (0)	98 (3)	94.4 (7.7)	No significant differences
Sport and recreation	83.8 (16.9)	99.6 (1.4)	89.1 (7.4)	77.4 (23)	Control vs ACLR: P = 0.006 Control vs ACLR(-): P = .003
Knee related QOL	64.5 (23.2)	100 (0)	64.6 (23.3)	70 (26.7)	Control vs all other groups: P < 0.05

ACLR, Anterior cruciate ligament reconstruction; ACLR +, subjects with other knee injuries in their ACLR leg; ACLR -, subjects with isolated ACL injuries.  
Data are mean (SD).

## Discussion

In the frontal plane we found no statistically significant differences between our ACLR participants and controls. However ACLR subjects who had sustained associated trauma to other key knee structures (meniscal, collateral ligament and chondral damage) were observed to have a higher adduction moment during gait on a flat surface at normal walking speed when compared to subjects with isolated ACLR. In the sagittal

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3 plane there was a tendency for ACLR participants to have higher peak knee flexion  
4 moment in their contralateral leg during all activities.  
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9 Previous studies that have investigated peak knee adduction moment in ACLR and  
10 matched control subjects have provided mixed results.(16,17,18) We investigated  
11 similar and more challenging gait set-ups (by altering incline), as well as the effects of  
12 differences in walking speed, in order to explore the biomechanical basis for the  
13 observation that ACL injury predisposes to OA. Our data showed no significant  
14 differences in KAM between our ACLR participants and control subjects under all  
15 conditions. This indicates that providing more challenging gait set-ups such as sloped  
16 walking, where a higher range of motion in the sagittal plane is required, does not  
17 emphasize differences between ACLR and control subjects. Based on our findings, the  
18 discrepancies in previous studies appear not to be related to the difficulty of the task or  
19 differences in walking speed.  
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36 ACL injury is often accompanied by other knee injuries.(26) Prevalence of associated  
37 meniscal damage and chondral lesions at the time of ACL injury can be as high as 65%  
38 and 23% respectively.(27) Associated knee injuries are thought to increase the  
39 incidence of OA from 0 – 13% in isolated ACL injury to 21 – 48%.(28) This may be  
40 because key knee structures such as menisci prevent cartilage wear by distributing  
41 loads and functioning as a shock absorber.(14) Our results suggest that people with  
42 ACLR injuries with associated knee injuries experience higher knee adduction moments  
43 than people with isolated ACLR injuries.  
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3 Of the three previous studies that have looked at peak KAM in ACLR and matched  
4 control subjects, Butler et al. found the ACLR group to have a higher peak KAM  
5 compared to controls.(16) This was also seen by our ACLR + group. In the studies that  
6 followed, Webster et al. and Zabala et al. found the ACLR group to have a reduced peak  
7 knee adduction moment to controls.(17, 18) This was seen by our ACLR – group (Figure  
8 2). This disparity in studies may therefore be a consequence of different exclusion  
9 criteria for ACLR subjects. Butler et al. did not exclude ACLR subjects with other knee  
10 injuries,(16) while the other two studies excluded subjects with ligament damage(17, 18)  
11 and also those with >25% of menisci loss.(18) We suggest that associated knee injuries  
12 are related to increased knee adduction moments in ACLR participants.  
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28 We found the difference between peak KAM in ACLR + and ACLR – to be statistically  
29 significant only during normal gait. We expected the difference to be higher during  
30 sloped walking, as it is more challenging than level walking. Change in terrain, muscle  
31 weakness, gait deficit and balance deficit are primary risk factors for falling.(29, 30) This  
32 suggests that ACLR participants need to adopt a conservative gait strategy while  
33 walking on a sloped surface to ensure safety. During challenging tasks such as downhill  
34 walking healthy participants increased their metabolic activity and implemented a  
35 conservative gait strategy to reduce the risk of falling.(29) This principle may also be  
36 applied by ACLR participants to ensure safety.  
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50 In the sagittal plane, no statistically significant differences were observed between  
51 ACLR, ACLR +, ACLR – and control group in peak knee flexion and extension moments.  
52 Both uphill and downhill walking require greater use of quadriceps muscle than on a  
53 level walkway.(30, 31) Two years after an ACLR surgery, differences in quadriceps  
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3 strength between limbs are no longer seen.(29) All of the ACLR subjects had undergone  
4 reconstruction at least 1 year before taking part in this study, with an average of 4.5  
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6 years. This indicates that all subjects may have had sufficient time to restore their  
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8 quadriceps strength. Even though sagittal instability is thought to increase joint loads  
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10 and lead to joint failure,(14, 32) it may not play a significant role in OA induction and  
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12 progression after reconstruction.  
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18 An unexpected finding was the tendency for the contralateral knees of ACLR  
19 participants to have higher peak knee flexion and lower peak knee extension moment  
20 compared to the ACLR and control knee in all activities. This may be an adaptation to  
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22 reduce loading on their ACLR knee. Patients with advanced knee OA also display this  
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24 adaptation to reduce loading on their injured leg.(33) Even though this may present as a  
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26 mechanism to slow the progression of OA, there are harmful implications associated  
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28 with the contralateral leg. Weight bearing asymmetry may induce OA in the contralateral  
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30 leg;(34) 37% (24/65 female patients) showed signs of radiographic OA in their  
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32 contralateral leg, 12 years after ACL reconstruction.(35) This suggests that in this  
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34 population unilateral injury changes joint function bilaterally.  
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43 In addition to our primary investigations we also investigated differences in KOOS and  
44 walking speed. There was no significant difference in **KOOS** or gait speed between  
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46 ACLR + and ACLR -. This indicates that high peak knee adduction moment in the  
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48 injured leg does not affect our subjects' pain outcome, symptoms, activities of daily life,  
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50 sport and recreation, knee related quality of life and gait speed. Thereby patient reported  
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52 outcome measures and gait speed might not provide the clinician with any information  
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60 about different gait adaptations.

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3 Mundermann et al (2004) found a 10.2% reduction in maximum knee adduction moment  
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5 when people with less severe OA reduced their walking speed from 1.2 meters/second  
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7 to 0.8 meters per second.(36) However in the current study the difference in peak knee  
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9 moments between normal (1.17 m/s) and slow gait speed (0.76 m/s) were not  
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11 statistically significant. This may be due to our small sample size.  
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15 It is important to note that different knee injuries, rehabilitation protocols and time  
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17 between injury and reconstruction are all thought to influence joint moments.(18) **These**  
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19 **are limitations that should be considered when examining the results presented here.**  
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21 **Additionally our participants were not recruited straight after their ACLR, some**  
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23 **participants may have had further injury or pathological changes within the joint since**  
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25 **the reconstruction.** Another limitation was our small sample size, in particular after  
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27 dividing our ACLR group into ACLR + and ACLR – groups.  
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32 The ramp was set at an incline of 10 degrees because the transition from a level to  
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34 slope walking strategy is thought to be around 5.5 degrees(31) and after the incline of  
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36 10 degrees no kinematic differences are seen in healthy participants.(31)  
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40 With regards to Vicon Motion capture system different skin marker placement and skin  
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42 motion artifacts are thought to increase error.(6) We tried to reduce the effects of  
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44 different skin marker placement by having only one researcher place all markers on  
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46 each individual. In addition we used a model that used clusters to reduce the effects of  
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48 skin motion.(25)  
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## Conclusion

In conclusion, this study found no significant differences in peak moments in the frontal and sagittal plane during level and sloped walking for ACLR compared with control participants. However, we noted that individuals who have other knee injuries associated with their ACLR knee exhibit higher peak adduction moments during level walking at their normal speed. This suggests that injuries to other key knee structures may play a bigger part in inducing OA than ACL injury alone, although this requires further investigation with a larger sample size. Our data also suggest that the contralateral knee appears to be functioning in such a way to reduce high moments in the ACLR knees, which may be relevant in the risk of OA development in both knees. These findings warrant a longitudinal study comparing the knee adduction moment between isolated ACLR injury and ACLR with additional knee injuries and the prevalence of premature OA.

**Data sharing** - no additional data available

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**Competing interests** - None

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**Contributorship Statement** - All authors helped with the study design. Raghav K Varma carried out data collection, statistical analysis and analysis of the data produced. He also drafted and revised the paper. He is guarantor. Lynsey D Duffell attained ethical

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3 approval, determined the methodology, helped with data analysis and drafted and  
4 revised the paper. Dinesh Nathwani helped with data collection and drafted and revised  
5 the paper. Alison H McGregor monitored the data collection for the whole trial, provided  
6 the data collection tools and drafted and revised the paper. Robert Weinert-Aplin  
7 designed the data collection tool.  
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## 14 15 16 **References**

- 17  
18  
19 1. Lyman S, Koulouvaris P, Sherman S et al. Epidemiology of anterior cruciate  
20 ligament reconstruction: trends, readmissions, and subsequent knee surgery. *J*  
21 *Bone Joint Surg Am* 2009;91:2321-8.  
22  
23
- 24  
25  
26 2. Matsumoto H, Suda Y, Otani T et al. Roles of the anterior cruciate ligament and  
27 the medial collateral ligament in preventing valgus instability. *J Orthop Sci*  
28 2001;6:28-32.  
29  
30
- 31  
32  
33 3. Lohmander LS, Englund PM, Dahl LL et al. The long-term consequence of  
34 anterior cruciate ligament and meniscus injuries: osteoarthritis. *Am J Sports Med*  
35 2007;35:1756-69.  
36  
37
- 38  
39  
40 4. Porat A, Roos EM, Roos H. High prevalence of osteoarthritis 14 years after an  
41 anterior cruciate ligament tear in male soccer players: a study of radiographic and  
42 patient relevant outcomes. *Ann Rheum Dis* 2004;63:269-73.  
43  
44
- 45  
46  
47 5. Andriacchi TP, Mündermann A. The role of ambulatory mechanics in the initiation  
48 and progression of knee osteoarthritis. *Curr Opin Rheumatol* 2006;18:514-8.  
49  
50
- 51  
52  
53 6. Stergiou N, Ristanis S, Moraiti C et al. Tibial rotation in anterior cruciate ligament  
54 (ACL)-deficient and ACL-reconstructed knees: a theoretical proposition for the  
55 development of osteoarthritis. *Sports Med* 2007;37:601-13.  
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2  
3 7. Andriacchi TP, Mündermann A, Smith RL et al. A framework for the in vivo  
4 pathomechanics of osteoarthritis at the knee. *Ann Biomed Eng* 2004;32:447-57.  
5  
6
- 7  
8 8. Hart JM, Ko JW, Konold T et al. Sagittal plane knee joint moments following  
9 anterior cruciate ligament injury and reconstruction: a systematic review. *Clin  
10 Biomech* 2010;25:277-83.  
11  
12
- 13 9. Georgoulis AD, Papadonikolakis A, Papageorgiou CD et al. Three-dimensional  
14 tibiofemoral kinematics of the anterior cruciate ligament-deficient and  
15 reconstructed knee during walking. *Am J Sports Med* 2003;31:75-9.  
16  
17
- 18 10. Noyes FR, Schipplein OD, Andriacchi TP et al. The anterior cruciate ligament-  
19 deficient knee with varus alignment. An analysis of gait adaptations and dynamic  
20 joint loadings. *Am J Sports Med* 1992;20:707-16.  
21  
22
- 23 11. Gokeler A, Benjaminse A, van Eck CF, et al. Return of normal gait as an outcome  
24 measurement in acl reconstructed patients. A systematic review. *Int J Sports  
25 Phys Ther.* 2013 Aug;8(4):441-51.  
26  
27
- 28 12. Berchuck M, Andriacchi TP, Bach BR et al. Gait adaptations by patients who  
29 have a deficient anterior cruciate ligament. *J Bone Joint Surg Am* 1990;72:871-7.  
30  
31
- 32 13. Urbach D, Nebelung W, Becker R et al. Effects of reconstruction of the anterior  
33 cruciate ligament on voluntary activation of quadriceps femoris a prospective  
34 twitch interpolation study. *J Bone Joint Surg Br* 2001;83:1104-10.  
35  
36
- 37 14. Roos EM. Joint injury causes knee osteoarthritis in young adults. *Curr Opin  
38 Rheumatol* 2005;17:195-200.  
39  
40
- 41 15. Papageorgiou CD, Gil JE, Kanamori A et al. The biomechanical interdependence  
42 between the anterior cruciate ligament replacement graft and the medial  
43 meniscus. *Am J Sports Med* 2001;29:226-31.  
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16. Butler RJ, Minick KI, Ferber R et al. Gait mechanics after ACL reconstruction: implications for the early onset of knee osteoarthritis. *Br J Sports Med* 2009;43:366-70.
17. Webster KE, Feller JA. The knee adduction moment in hamstring and patellar tendon anterior cruciate ligament reconstructed knees. *Knee Surg Sports Traumatol Arthrosc* 2012;20:2214-9.
18. Zabala ME, Favre J, Scanlan SF et al. Three-dimensional knee moments of ACL reconstructed and control subjects during gait, stair ascent, and stair descent. *J Biomech* 2013;46:515-20.
19. Miyazaki T, Wada M, Kawahara H et al. Dynamic load at baseline can predict radiographic disease progression in medial compartment knee osteoarthritis. *Ann Rheum Dis* 2002;61:617-22.
20. von Elm E, Altman DG, Egger M, Pocock SJ, Gøtzsche PC, Vandenbroucke JP; STROBE Initiative. The Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement: guidelines for reporting observational studies. *J Clin Epidemiol*. 2008 Apr;61(4):344-9.
21. Roos EM, Roos HP, Lohmander LS et al. Knee Injury and Osteoarthritis Outcome Score (KOOS)— development of a self-administered outcome measure. *J Orthop Sports Phys Ther* 1998;28:88–96.
22. Tegner Y, Lysholm J. Rating systems in the evaluation of knee ligament injuries. *Clin Orthop*. 1985;198:43–49.
23. Cleather DJ, Bull AM Influence of inverse dynamics methods on the calculation of inter-segmental moments in vertical jumping and weightlifting. *Biomed Eng Online* 2010;9:74

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24. Cleather DI, Bull AM Lower-extremity musculoskeletal geometry affects the calculation of patellofemoral forces in vertical jumping and weightlifting. *Proc Inst Mech Eng H* 2010;224:1073-1083
25. Hope, N., Duffell, L. D., and McGregor, A. H. Validation of a new model to calculate joint kinematics during gait. *European Society of Biomechanics Conference Proceedings* 1-7-2012.
26. Claes S, Hermie L, Verdonk R et al. Is osteoarthritis an inevitable consequence of anterior cruciate ligament reconstruction? A meta- analysis. *Knee Surg Sports Traumatol Arthrosc* 2013;21:1967-76.
27. Louboutin H, Debarge R, Richou J et al. Osteoarthritis in patients with anterior cruciate ligament rupture: a review of risk factors. *Knee* 2009;16:239-44.
28. Oiestad BE, Engebretsen L, Storheim K, Risberg MA. Knee osteoarthritis after anterior cruciate ligament injury: a systematic review. *Am J Sports Med* 2009;37:1434–1443
29. Monsch ED, Franz CO, Dean JC. The effects of gait strategy on metabolic rate and indicators of stability during downhill walking. *J Biomech* 2012;45:1928-33.
30. Mizner RL, Snyder-Mackler L. Altered loading during walking and sit-to-stand is affected by quadriceps weakness after total knee arthroplasty. *J Orthop Res* 2005;23:1083-90.
31. A.N. Lay, C.J. Hass, R.J. Gregor. The effects of sloped surfaces on locomotion: a kinematic and kinetic analysis. *Journal of Biomechanics* 2006;39:1621–1628
32. Gottschall JS, Nichols TR. Neuromuscular strategies for the transitions between level and hill surfaces during walking. *Philos Trans R Soc Lond B Biol Sci* 2011;366:1565-79.

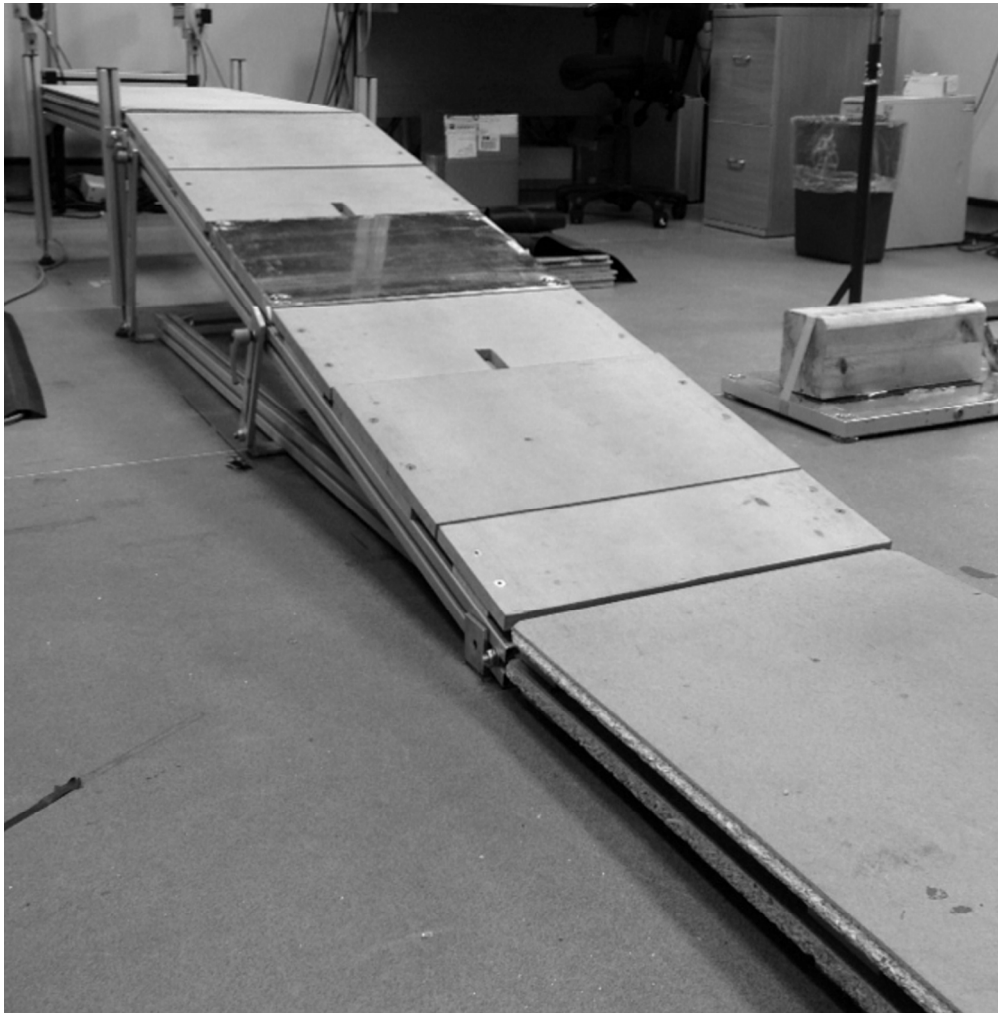
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3 33. Creaby MW, Bennell KL, Hunt MA. Gait differs between unilateral and bilateral  
4 knee osteoarthritis. *Arch Phys Med Rehabil* 2012;93(5):822-7.  
5  
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7  
8 34. Christiansen CL, Stevens-Lapsley JE. Weight-bearing asymmetry in relation to  
9 378 measures of impairment and functional mobility for people with knee  
10 osteoarthritis. *Arch Phys Med Rehabil* 2010;91:1524-8.  
11  
12  
13 35. Lohmander, L.S., Ostenberg, A., Englund, M. et al. High prevalence of knee  
14 osteoarthritis, pain, and functional limitations in female soccer players twelve  
15 years after anterior cruciate ligament injury. *Arthritis and Rheumatology*  
16 2004;50:3145–3152.  
17  
18  
19 36. Mündermann A, Dyrby CO, Hurwitz DE et al. Potential strategies to reduce  
20 medial compartment loading in patients with knee osteoarthritis of varying  
21 severity: reduced walking speed. *Arthritis Rheum* 2004;50:1172-8.  
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## 35 Figures

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38 **Fig. 1** Steel framed ramp covered in plywood, set an incline of 10 degrees.

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40 **Fig. 2** Peak adduction moments in **a)** level walking and **b)** slope walking for ACLR,  
41 ACLR +, ACLR – and control group. Asterisk indicates significance (p = 0.042).  
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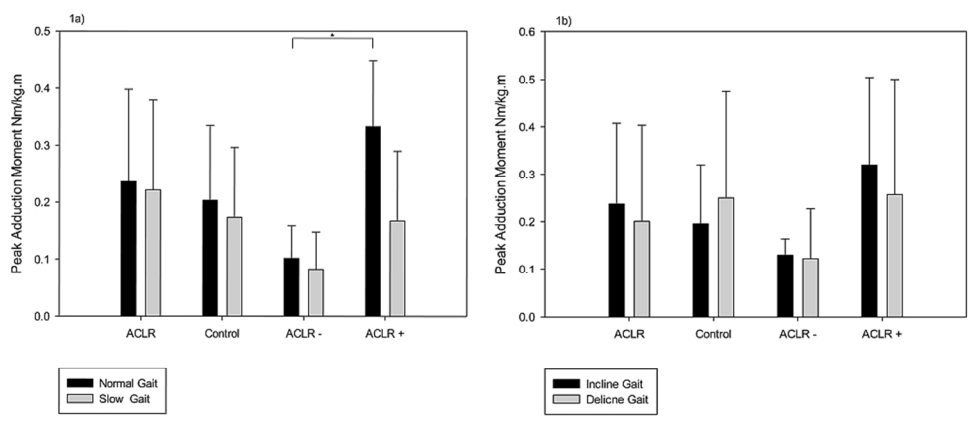
43 **Fig. 3, a)** Peak flexion moment in all activities for ACLR, contralateral and control group.  
44 § represents decline gait to be significantly higher than all other activities (p<0.01).  
45 Asterisk indicates significance, p<0.05 **b)** Peak extension moment in all activities for  
46 ACLR, contralateral and control group. ~ represents decline gait to be significantly lower  
47 than normal and incline gait, p<0.05  
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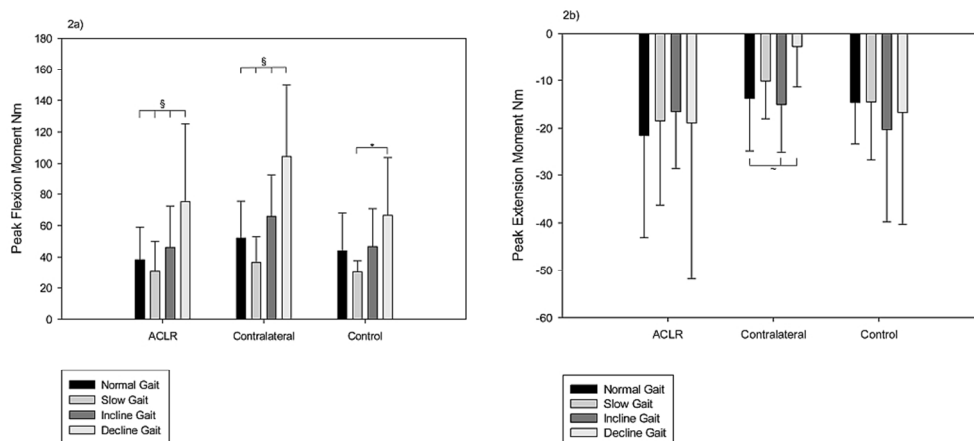
Steel framed ramp covered in plywood, set an incline of 10 degrees.  
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Peak adduction moments in a) level walking and b) slope walking for ACLR, ACLR +, ACLR - and control group. Asterisk indicates significance (p = 0.042).  
90x42mm (300 x 300 DPI)



a) Peak flexion moment in all activities for ACLR, contralateral and control group. § represents decline gait to be significantly higher than all other activities ( $p < 0.01$ ). Asterisk indicates significance,  $p < 0.05$  b) Peak extension moment in all activities for ACLR, contralateral and control group. ~ represents decline gait to be significantly lower than normal and incline gait,  $p < 0.05$

90x44mm (300 x 300 DPI)

review only

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## STROBE Statement—checklist of items that should be included in reports of observational studies

	Item No	Recommendation
<b>Title and abstract</b>	1	(a) Indicate the study's design with a commonly used term in the title or the abstract (b) Provide in the abstract an informative and balanced summary of what was done and what was found
<b>Introduction</b>		
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported
Objectives	3	State specific objectives, including any prespecified hypotheses
<b>Methods</b>		
Study design	4	Present key elements of study design early in the paper
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection
Participants	6	(a) <i>Cohort study</i> —Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up <i>Case-control study</i> —Give the eligibility criteria, and the sources and methods of case ascertainment and control selection. Give the rationale for the choice of cases and controls <i>Cross-sectional study</i> —Give the eligibility criteria, and the sources and methods of selection of participants (b) <i>Cohort study</i> —For matched studies, give matching criteria and number of exposed and unexposed <i>Case-control study</i> —For matched studies, give matching criteria and the number of controls per case
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group
Bias	9	Describe any efforts to address potential sources of bias
Study size	10	Explain how the study size was arrived at
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why
Statistical methods	12	(a) Describe all statistical methods, including those used to control for confounding (b) Describe any methods used to examine subgroups and interactions (c) Explain how missing data were addressed (d) <i>Cohort study</i> —If applicable, explain how loss to follow-up was addressed <i>Case-control study</i> —If applicable, explain how matching of cases and controls was addressed <i>Cross-sectional study</i> —If applicable, describe analytical methods taking account of sampling strategy (e) Describe any sensitivity analyses

Continued on next page

<b>Results</b>		
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed (b) Give reasons for non-participation at each stage (c) Consider use of a flow diagram
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders (b) Indicate number of participants with missing data for each variable of interest (c) <i>Cohort study</i> —Summarise follow-up time (eg, average and total amount)
Outcome data	15*	<i>Cohort study</i> —Report numbers of outcome events or summary measures over time <i>Case-control study</i> —Report numbers in each exposure category, or summary measures of exposure <i>Cross-sectional study</i> —Report numbers of outcome events or summary measures
Main results	16	(a) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included (b) Report category boundaries when continuous variables were categorized (c) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period
Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses
<b>Discussion</b>		
Key results	18	Summarise key results with reference to study objectives
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence
Generalisability	21	Discuss the generalisability (external validity) of the study results
<b>Other information</b>		
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based

\*Give information separately for cases and controls in case-control studies and, if applicable, for exposed and unexposed groups in cohort and cross-sectional studies.

**Note:** An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at <http://www.plosmedicine.org/>, Annals of Internal Medicine at <http://www.annals.org/>, and Epidemiology at <http://www.epidem.com/>). Information on the STROBE Initiative is available at [www.strobe-statement.org](http://www.strobe-statement.org).