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The knee adduction moment in hamstring and patellar tendon anterior cruciate ligament reconstructed knees

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Abstract
Purpose The external knee adduction moment during gait has previously been associated with knee osteoarthritis, and although it has been shown to be greater following anterior cruciate ligament (ACL) reconstruction surgery compared to a control group, it has not been compared between different graft types. Given that the incidence of radiographic knee osteoarthritis appears to be greater following patellar tendon compared to hamstring tendon ACL reconstruction, this study tested the hypothesis that the knee adduction moment would also be increased following patellar tendon ACL reconstruction.
Methods In 48 male participants (16 patellar tendon graft, 16 hamstring graft and 16 controls), the external knee adduction moment was measured during level walking in a gait laboratory at mean of 10 months after surgery.
Results There was no difference in the knee adduction moment between the hamstring and patellar tendon groups, and both patient groups had a significantly reduced knee adduction moment compared to the control group. In the hamstring group, the smaller adduction moment was associated with the patients walking with less knee varus whereas in the patellar tendon group, the smaller moment was associated with the patients walking with a decreased vertical ground reaction force.
Conclusions These results indicate that in male patients during the early stages of recovery from ACL reconstruction, the knee adduction moment is not greater than controls for either hamstring or patellar tendon graft types. Although the knee adduction moment was similar between the two graft types, the overall magnitude of the moment was influenced by different biomechanical factors.
Level of evidence III.

Keywords Gait analysis · ACL · Patellar tendon graft · Hamstring tendon graft · Walking

Introduction

Anterior cruciate ligament (ACL) rupture is common in young athletes. It is typically treated with surgical reconstruction that aims to allow the patient to return to sport participation with normal knee function that does not lead to symptomatic or radiographic evidence of osteoarthritis in later life [20].

Long-term studies have shown that there may be differences in outcomes when the reconstructive surgery is performed using a hamstring tendon graft compared to a patellar tendon graft. Pinczewski et al. have shown significant increases in the incidence of radiographic knee osteoarthritis in a group of patients that received patellar tendon grafts compared to a group that received hamstring tendon grafts at 5, 7 and 10 years after the ACL reconstruction procedure [21, 22, 24]. Fifteen-year outcome data has further shown the incidence of radiographic medial tibiofemoral joint osteoarthritis to be twice that of lateral tibiofemoral and patellofemoral joint osteoarthritis for patients with patellar tendon grafts [12]. However, this does not mean that patients with hamstring grafts are not susceptible to developing knee osteoarthritis. Asano et al. [2] reported the appearance of osteoarthritic changes as

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early as 15 months after hamstring ACL reconstruction in a cohort of 105 patients.

Whilst the mechanisms behind the development of knee osteoarthritis following ACL reconstruction remain to be determined, the persistence of abnormal knee biomechanics during a variety of activities after ACL reconstruction has been suggested as a factor that may increase the risk of long-term joint degeneration [8, 10, 19, 23, 26, 27, 30, 31].

The biomechanical variable most researched for its association with knee osteoarthritis is the adduction moment across the knee. Whilst not extensively researched following ACL reconstruction, Butler et al. [4] reported significantly increased knee adduction moments in a group of patients after ACL reconstruction who had returned to their pre injury level of activity compared to a matched control group. The authors suggested that the increased knee adduction moment may reflect a mechanism for early onset knee osteoarthritis. Graft type was not reported. The knee adduction moment was also recently shown to be greater in female compared to male patients who had undergone hamstring tendon ACL reconstruction surgery [32]. This study did not compare the patients to a control group.

Kinematic and kinetic differences have been reported between patellar tendon and hamstring tendon ACL reconstruction groups in the sagittal plane [31, 33]. Therefore, it should not be assumed that the biomechanical outcomes for one graft type are equivalent to another. Given that patients with patellar tendon ACL reconstruction appear to have a relatively high incidence of medial tibiofemoral joint osteoarthritis [12], it is reasonable to hypothesise that the knee adduction moment may also be increased in patellar tendon ACL-reconstructed knees. If this were the case, it may reflect a potential mechanism for the development of knee osteoarthritis in this group. Therefore, the purpose of this study was to compare the knee adduction moment recorded during level gait between a group of patients with patellar tendon ACL reconstruction, a group with hamstring tendon ACL reconstruction and a control comparison group.

Materials and methods

Two groups of 16 male subjects who had undergone uncomplicated primary ACL reconstruction with either a central third bone patellar tendon bone autograft or a four strand (doubled semitendinosus/doubled gracilis) hamstring autograft participated in the study along with 16 male control subjects with no history of lower limb pathology. Sagittal plane hip, knee and ankle joint kinematic and kinetic data have previously been reported for this group during level walking [33]. Three female subjects that were included in this previous work were excluded from the current study. As we have previously shown the knee adduction moment to differ between men and women (in which a different patient cohort was used [32]), a decision was made to only examine male patients thereby excluding gender as a potential confounding variable. The demographic characteristics of the participants are shown in Table 1.

Table 1 Subject characteristics

	Hamstring tendon graft Mean (SD)	Patellar tendon graft Mean (SD)	Control Mean (SD)
Age (years)	27.5 (6)	23.8 (6)	25.0 (5)
No. of male subjects	16	16	16
Height (cm)	179 (8)	179 (6)	178 (7)
Weight (kg)	79.5 (7)	79.2 (6)	75.9 (12)
Time injury to surgery (weeks)	10.7 (9)	11.9 (11)	
Time since surgery (months)	9.4 (3)	11.2 (2)	

For all ACL-reconstructed subjects, an arthroscopic procedure had been performed by the same experienced knee surgeon at least 6 months (mean 10 months) prior to participation. Apart from the graft type and site of harvest, the surgical technique, including graft fixation, was identical in both groups. Proximal fixation was by means of an EndoButton attached to the graft with a doubled 3-mm polyester tape, and an absorbable interference screw was used for tibial fixation. Postoperatively, all subjects underwent the same rapid rehabilitation protocol that had been previously detailed and includes an emphasis on restoration of vastus medialis function [33]. Running was allowed from 10 weeks and the commencement of sports-specific drills from 3 months. No emphasis was placed on gait retraining.

Subjects underwent physical examination and were to be excluded from the gait analysis if objective signs of laxity were found, as determined by either a KT-1000 arthrometer-measured side to side difference greater than 3 mm at 132 N or a positive pivot shift test. None of the participants were excluded based on this testing.

Procedures

Subjects were informed of the nature of the experiment and gave written consent that was approved by University Ethics Committee. Analysis of each participants gait was conducted over a single test session. Measurements of each subject's pelvis and lower limbs were obtained, and reflective markers were attached to the lower limb using the standard Plug-in-Gait marker set [6, 15].

Data were captured in the central portion of a 10-metre linoleum-covered walkway using a three-dimensional motion analysis system (Vicon, Oxford Metrics Ltd, UK). Ground reaction forces were recorded from a force plate (Kistler, Winterthur, Switzerland) set in the floor of the laboratory. To obtain a reference point for the markers, a static trial was obtained with the subject in quiet standing. For this trial, a knee alignment device was used to determine the centre of the knee joint as previously described [33].

Subjects were asked to walk barefooted up and down the walkway several times at their own pace until they were relaxed and accustomed to the markers. This also enabled a starting point to be identified so that the subject would contact the force plate in normal stride. Subjects were then asked to complete a number of walks at their self-selected comfortable speed whilst data were collected. They were not aware of the presence of the force plates until data collected was completed. Data collection continued until a minimum of three trials with good force plate contact was recorded for both left and right limbs.

Statistical analysis

Vicon Plug-In-Gait (Vicon, Oxford Metrics, Oxford, UK) was used to estimate the position of lower limb joint centres. Plug-In-Gait calculates lower limb joint angles based on the Euler principle where the joint angle is determined by the position of the moving distal segment relative to the proximal fixed segment. Lower limb joint moments were calculated using standard inverse dynamics and are therefore reported as external moments. The dependent variable of interest in this study was the knee adduction moment that was normalised to body mass and height (Nm/kg m). The adduction moment was also expressed as a percentage of body weight and height (%Bw-Ht) to allow for future across study comparisons. As the knee adduction moment is mainly influenced by the product of the ground reaction force and frontal plane lever arm length (the perpendicular distance from the knee joint centre to the ground reaction force) both peak knee adduction (varus) angle and peak vertical ground reaction force (vGRF) were also measured. One-way analysis of variance (ANOVA) was used to test for differences in the knee adduction moment, knee varus angle and vGRF amongst the three groups (hamstring graft, patellar tendon graft and control). In the case of the F ratio being significant ($P < 0.05$), post hoc analysis was performed using t tests with Bonferroni correction. Paired t tests were used to compare between the reconstructed and contralateral knee of the patient groups.

Results

The average walking speed of the subjects was not significantly different between the three groups, $F(2,45) = 2.7$, $P < 0.05$, although the control group walked the fastest at 1.5 ± 0.2 m/s compared to the hamstring and patellar tendon groups at 1.4 ± 0.2 m/s.

The knee adduction moment in the hamstring tendon group was not different from the knee adduction moment in the patellar tendon group (Table 2). The knee adduction moment in both patient groups was significantly smaller than the knee adduction moment in the control group (Fig. 1). A second ANOVA that included speed as a covariate showed that there was still a significant difference in the knee adduction moment between the control and patient groups after accounting for any influence of

Table 2 Descriptive statistics for knee adduction angle, moment and vertical ground reaction force recorded during the stance phase of gait between the hamstring, patellar tendon and control groups

	Hamstring tendon graft Mean (SD)	Patellar tendon graft Mean (SD)	Control Mean (SD)
Peak adduction (varus) angle (°)	3.9 (3.7)*,[a]	6.6 (2.8)	7.7 (2.8)
Peak adduction moment			
Nm/kg m	0.27 (.08)**,[a]	0.28 (.06)**,[b]	0.40 (.08)
%Bw-Ht	2.8 (0.8)**,[a]	2.9 (0.6)**,[b]	4.1 (0.8)
Vertical ground reaction force, N/kg	11.1 (1.2)	10.6 (0.5)*,[b]	11.7 (0.9)

* $P < 0.01$; ** $P < 0.0001$

[a] Hamstring versus Control

[b] Patellar tendon versus Control

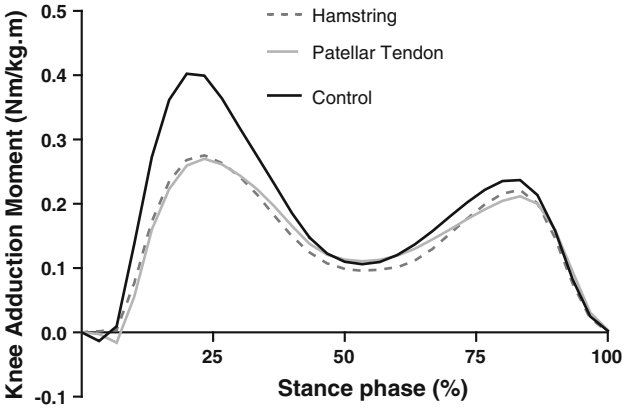

Fig. 1 Mean knee adduction moment pattern for the hamstring, patellar tendon and control groups during the stance phase of level walking

Table 3 The knee adduction moment for operated and contralateral knee in the ACL patient groups

	Hamstring tendon graft		Patellar tendon graft	
	Mean (SD)		Mean (SD)	
	Operated	Contralateral	Operated	Contralateral
Peak adduction moment				
Nm/kg m	0.27 (.08)*	0.31 (.09)	0.28 (.06)	0.28 (.06)
%Bw-Ht	2.8 (0.8)*	3.2 (1.0)	2.9 (0.7)	2.9 (0.6)

* $P = 0.04$

speed. Inspection of individual subject data showed that in both hamstring and patellar tendon groups, 75% (12/16) of patients had a knee adduction moment that was more than one standard deviation below the control group mean.

Inspection of Table 2 also shows that, when compared to the control group, the hamstring group had significantly reduced knee varus during stance ($P < 0.01$) whereas the patellar tendon group had a significantly reduced vGRF ($P < 0.01$). Both knee varus and the vGRF were significantly correlated with the knee adduction moment (varus $r = 0.54$, $P < 0.0001$; vGRF $r = 0.68$, $P < 0.0001$).

The knee adduction moment for the contralateral limb was also significantly greater than the operated knee in the hamstring ($P = 0.04$) but not patellar tendon group (Table 3). The knee adduction moment for the contralateral limb of both patient groups was also significantly smaller than the control group ($P < 0.001$). Post hoc power calculations of all significant ANOVA results showed a power greater than 85%.

Discussion

The most important finding of the present study was that the knee adduction moment recorded during level gait was significantly smaller in a cohort of male subjects who had undergone ACL reconstruction surgery compared to a group of healthy male controls. Contrary to expectation, there was no difference in the knee adduction moment between patients who had undergone hamstring ACL reconstruction compared to patellar tendon ACL reconstruction.

The finding of a smaller knee adduction moment in both ACL patient groups in this study is the opposite of the data previously published by Butler and colleagues who reported a significant increase in the knee adduction moment after ACL reconstruction [4]. It would, however, appear that the disparity relates to the control group data rather than the patient group data. To illustrate this, Table 4 summarises knee adduction moment values for studies that have included an ACL population. From this table, it can be seen that the adduction moment is similar between the two ACL reconstruction studies that have female or mostly female patient groups, [4, 32] and that in these groups, the adduction moment is higher than the two ACL reconstruction studies that have male only patient groups [32]. It is the two control groups that show the greatest variation. In the current study, the control group knee adduction moment is notably higher than the control group in Butler et al. [4].

Table 4 Comparison of knee adduction moment (Nm/kg m) values between studies

	ACL group	Control group
Butler et al. [4]	0.36 (13F; 3M)	0.30 (13F; 3M)
Webster et al. [32]	0.30 (18M) 0.38 (18F)	
Current Study	0.28 (32M)	0.40 (16M)

M males, *F* females

Perhaps, it is not surprising that the knee adduction moment varies between young healthy adults, who have the ability to significantly modify parameters of gait. Whilst the adduction moment for the control group in the current study may appear to be high; there are other studies that report similar values [13, 28]. There are also other studies [16] that report knee adduction moment values similar to that reported by Butler et al. [4]. So what does this mean for interpreting the current results? It would appear that, irrespective of which control group data is used for comparison, male patients do not have increased knee adduction moments in the early phase after ACL reconstruction surgery. However, we feel that more data are required to reach a conclusion for female patients.

It is not clear from the published literature what magnitude of change in the knee adduction moment represents a clinically significant difference. Birmingham and colleagues [3] have shown the minimal detectable change to be 1.0% Bw-Ht in a group with medial compartment osteoarthritis. Although the patient populations are different, the between group difference in our study (1.3%Bw-Ht) is above this value. Based on Birmingham et al. [3], we can be 95% sure that the difference between the patient and control groups in the current study was a true difference.

It would appear that the similarity in the knee adduction moment between patient groups was somewhat coincidental and that different factors contributed to the reduced knee adduction moment in each group. The hamstring group had significantly reduced varus that would have reduced the frontal plane lever arm length that in turn reduces the magnitude of the knee adduction moment. In the patellar tendon group, the reduced knee adduction moment was likely caused by a reduced vertical ground reaction force. Both knee varus and the vertical ground

reaction force were found to be correlated with the knee adduction moment. Although the correlations were statistically significant, the strength of the correlation was as best moderate, which is consistent with other previous research that has also found moderate relationships between knee joint alignment and the knee adduction moment [14, 29]. Other factors that change the way people walk, such as increased medio-lateral trunk sway [18], could also mediate any relationships between the knee adduction moment.

We have previously reported reduced varus during walking with hamstring tendon graft ACL reconstruction [30]. It is possible that this has something to do with the hamstring tendon harvest. As the medial hamstrings contract, there may be a medially directed vector contributing to the net force exerted on the tibia relative to the femur. The medial hamstrings might therefore be expected to contribute to some of the adductor force at the knee, which would be reduced if they are harvested for reconstructive surgery. On the other hand, there is no direct explanation as to why patients with patellar tendon grafts walked with a reduced vertical ground reaction force. Why this should apply to the patellar tendon group and not the hamstring group is unclear.

Overall, there is no direct relationship between the knee adduction moment and the development of knee osteoarthritis following ACL reconstruction. Logically, if an increased knee adduction moment is related to an increased risk for knee osteoarthritis, a reduced/or unchanged moment may relate to a reduced risk. However, this is probably too simplistic, and there are a number of other factors that should be considered. Relevant are the findings from recent studies that show that abnormal biomechanics in the transverse plane may contribute to the development or progression of knee osteoarthritis. Specifically, these studies have reported abnormal tibial rotation movements during the stance phase of both walking [8, 9, 26, 30] and running gait [27] as well as during lunging [19], pivoting [5, 23] and single limb landings [7] in patients who have undergone ACL reconstruction surgery. Rotational shifts in the order of 5 degrees have been suggested to be sufficient to cause the acceleration of cartilage degeneration [1].

It should, however, be emphasised that we are not suggesting that the knee adduction moment is not a relevant outcome variable. Indeed, many studies continue to use the knee adduction moment as a surrogate measure for medial contact force during gait, and it has been shown to be related the progression of radiographic medial compartment knee osteoarthritis [17]. Instead, we would like the current data to be viewed as adding to the limited existing knowledge regarding the knee adduction moment following ACL reconstruction. It is clinically relevant that the knee adduction moment was not increased in a group of male patients that underwent ACL reconstruction as this suggests that the adduction moment is an unlikely contributor to the development of knee osteoarthritis in this group. However, more work is required to better understand what an increased or decreased knee adduction means in this patient group as well as how variation in control group data may impact on the results. The knee adduction moment for the contralateral limb of both patient groups was also smaller than the control group. Again, there is no clear explanation for this result as previous studies have not included data for both the contralateral limb and a separate control group. It may suggest that bilateral adaptations can result from unilateral injury [11, 25], but again, further research is clearly needed, which may need to include both pre- and post-operative measures.

A limitation of this study is the ability to generalise to the wider ACL reconstruction population as the strict selection criteria applied to this study meant that only patients who had relatively acute (<12 months and mean of 11 weeks) ACL ruptures were included. However, this was felt necessary as it reduced the opportunity for gait adaptations to occur before surgery. This may be an important consideration when interpreting the data as changes in sagittal plane joint moments have been shown to be more pronounced as the amount of time after ACL injury increases [34]. It is also relevant to note that having a stable knee was part of the inclusion criteria. This, and the possibility that patients who were not happy with their knee function would be less likely to volunteer, may mean that we only tested patients with a well functioning ACL reconstruction. This criterion is nonetheless consistent with previous studies that have also only included patients with stable knees [26] or who had returned to their previous activity levels [4]. The patients in this study also had normal knee alignment; future studies may wish to examine participants with a varus knee in order to determine whether this is a risk factor in these patients. A further limitation of the current study is the inclusion of only male patients.

Conclusion

The current results showed that in a large cohort of male patients, the knee adduction moment was not increased at a mean of 10 months following ACL reconstruction surgery for either hamstring or patellar tendon graft types. Overall, there is limited data regarding the knee adduction moment following ACL reconstruction despite its association with knee osteoarthritis in other patient populations.

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