

Knee kinematics in anatomic anterior cruciate ligament reconstruction with four- and five-strand hamstring tendon autografts

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Abstract

An alternative to the gold standard four-strand hamstring tendon autograft for anterior cruciate ligament (ACL) reconstruction is the five-strand graft. The rationale for its use is to increase graft width to better restore the anatomical footprint and biomechanical properties of the native ACL when unable to create a four-strand graft of 8 mm in diameter. To date, there are no trials assessing the use of this wider graft and its effect on the kinematics of the knee. The aim of this study was to determine whether the use of a wider five-strand hamstring tendon autograft in ACL reconstructive surgery better replicated the kinematics of a normal non-injured knee than the gold standard four-strand graft. Forty-four patients (27 operative and 17 normal control) were recruited for this study over a 12-month period. Twenty patients underwent anterior cruciate ligament reconstruction with the four-strand hamstring tendon autograft construct and seven with the five-strand construct. All patients underwent kinematic testing using the KneeKG System (EMOVI, CA) according to a strict testing protocol. The operative group underwent testing at six (T1) and twelve (T2) weeks postoperatively. Analysis of variance was used to compare six degrees of freedom kinematic data across groups and correlations were made between kinematic data and intra-operatively measured graft width. Post-operative kinematic data revealed no statistically significant differences between graft types. At 12 weeks significant differences were seen between the four-strand and con-

trol group in the flexion/extension cycle in the preloading phase and at terminal stance. Significant correlations were seen between graft width and rotational stability at Preloading (Pearson's $r=0.415$) and Maximum Internal Rotation (Femoral Width Pearson's $r=0.456$ and Tibial Width Pearson's $r=0.476$) at 12 weeks regardless of graft type.

This study demonstrated that to achieve anatomic knee kinematics in primary ACL reconstruction in the first 12 weeks postoperatively, a technique to optimise autograft width using a five-strand hamstring tendon autograft is useful. A relationship was found between graft width and more stable rotational kinematics of the knee during walking, regardless of graft type.

Introduction

The goal of anterior cruciate ligament (ACL) reconstructive surgery is to restore the stability of the knee to pre-injury (anatomical) function. Degenerative arthritis is a common long-term consequence of ACL reconstruction and has been linked to derangements in kinematics of the knee.¹ The width of the autograft used for reconstruction is relevant for the percentage restoration of the native anatomical footprint and biomechanical function of the ACL such that stability of the knee can be optimised postoperatively. A number of graft options exist for ACL reconstructive surgery. The current gold standard is the four-strand hamstring tendon autograft. Current evidence suggests that the use of a wider autograft construct may be beneficial for post-operative knee stability when unable to achieve 8mm in diameter using the gold standard four-strand repair.^{2,4}

Of particular relevance to the biomechanical behaviour of the graft is its capacity to restore the native anatomy and therefore biomechanical function of the two functional bundles of the ACL, in particular the posterolateral bundle that provides support when the knee is extended and internally rotated.^{2,3} Robinson *et al.* (2009) showed that wider autografts in single-bundle reconstruction better imitate the functional anatomy of the native ACL illustrating that an increase in graft diameter restored a larger percentage of both the anteromedial and posterolateral bundles and their native tensioning patterns.⁴ Furthermore wider grafts have been shown to produce lower meniscal and articular cartilage contact stress, suggesting that wider grafts may help to minimise the propagation of degenerative arthritis, perhaps by producing more

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anatomical knee kinematics.³

Hence, a novel approach to ACL reconstruction using a five-strand hamstring tendon autograft (three-strand Semitendinosus /two-strand Gracilis) has been proposed in an attempt to better restore the functional anatomy of the ACL at its footprints and optimise anatomic ACL reconstruction.^{5,6} Biomechanical comparisons have shown that the addition of a fifth strand does not increase the strength of the graft construct.⁷ However, recent studies have shown that clinically a five strand graft produced comparable results to a four strand graft >8 mm

in diameter, with no difference in re-rupture rates, suggesting the five strand technique is a useful way to increase graft diameter when faced with an undersized graft.^{8,9} The shortcomings of this approach include that that the effect of larger bone tunnels on healing is unknown and there must be sufficient length to form the five-strand graft.

Methods of objective functional assessment of the knee are imperative in assessing the success of ACL reconstructive surgery on the stability of the knee. The study of kinematics of the knee provides objective information on the 6-degree-of-freedom (6-DOF) movement of the knee and can provide a more global assessment of knee function post-operatively. The KneeKG system is a validated, reliable non-invasive tool that uses infra-red motion capture technology to provide quick, easy access to 3D knee kinematic data through the use of an exoskeleton attachment system proven to lessen skin motion artefact when compared to other methods. The system has an accuracy of -0.4° for ab/adduction and -2.3° for axial rotations over an arc of 65 degrees flexion.¹⁰⁻¹³ To date, there are no trials assessing kinematics of the knee post reconstructive surgery with a five-strand graft or comparing kinematic outcomes between the gold standard four- and newer five-strand hamstring tendon autografts in the literature.

Aim

The aim of this study was to determine whether the use of a wider five-strand hamstring tendon autograft in ACL Reconstructive surgery better replicated the kinematics of a normal non-injured knee than the gold standard four-strand graft.

Materials and Methods

Forty-four patients (27 operative and 17 normal control) were recruited for this study over a 12-month period according to a strict inclusion/exclusion protocol (Table 1).

Sample size

Assuming a true difference in mean rotational kinematics between graft types of 3 degrees of axial rotation and a pooled standard deviation of 3.5 degrees, we calculated we would require a minimum sample size of $n=7$ for each group (*i.e.* a total sample size of 21, assuming equal group sizes), to achieve a power of 80% and a level of significance of 5%, to declare that the five strand graft is superior to the four strand graft at 2 degrees margin of superiority.

Surgical cohort

Twenty-seven patients referred to a single consultant Orthopaedic Surgeon at our institution were recruited for this research. All patients included in this trial were diagnosed with ACL rupture by the orthopaedic surgeon leading the enquiry, which was confirmed during arthroscopic evaluation of the ACL at the time of operation. Patients suspected of having torn their ipsilateral MCL were not operated until the MCL injury had resolved clinically. Patients with suspected ipsilateral injuries to the medial and/or lateral menisci were considered for this research and details of arthroscopic treatment of any meniscal injury were recorded intraoperatively. All patients were managed by physiotherapy to ensure that inflammation had sufficiently subsided and an appropriate range of motion was achieved prior to surgery as determined by the consulting surgeon. All patients were rehabilitated according to a specific physiotherapy rehabilitation protocol. All patients were informed of the purpose of testing and consented according to a local ethics committee protocol.

Control cohort

Seventeen volunteers with no known current or past history of injury to knee structures were recruited for this study. The contralateral knee was not used as control given the potential influence of gait compensation from ACL deficiency on the kinematics of the contralateral knee.¹⁴ All sub-

jects were informed of the purpose of testing and consented according to a local ethics committee approved protocol.

Surgical procedure

ACL reconstructive surgery was performed by the same surgeon over a 12-month period. All procedures were performed under general anaesthesia with local anaesthetic infiltration. Prophylactic intravenous antibiotics were given and an above knee tourniquet was applied.

Semitendinosus and gracilis tendons were harvested via an anteromedial incision. Tendons were stripped of muscle, tubularized and whipstitched. The four-strand construct was formed and the cross-sectional width measured using a graft construct-measuring tool. If the construct measured less than 8 mm, a five-strand hamstring tendon autograft was prepared.

Preparation of the five-strand construct

Firstly, the semitendinosus tendon was sutured to the EndoButton (Smith & Nephew) loop. The opposite end of the semitendinosus was then brought through the EndoButton (Smith & Nephew) loop and folded back on itself to create an equally tensioned 3-strand construct (Figure 1). The two-strand gracilis construct was formed using the conventional method for a four-strand construct; the tendon was passed through the EndoButton loop and folded back on itself and equally tensioned.^{5,15} The width of the hamstring autograft and the corresponding bony tunnels were recorded. The final construct was measured at the tibial and femoral ends and the width recorded (Figure 1).

The ACL stump was visually identified on the lateral femoral condyle and used as a landmark for femoral tunnel placement. The femoral tunnel was always placed posteriorly to the lateral condylar (Resident's) ridge. The femoral hole was drilled through the anteromedial portal. A 4.5 mm cannulated EndoButton (Smith & Nephew) reamer was drilled all the way through the lateral femur

Table 1. Patients were included in this study according to a strict inclusion/exclusion protocol.

Inclusion criteria	Exclusion criteria
Surgical cohort	
Diagnosis of ACL Deficiency by Consultant Orthopedic Surgeon.	Any associated ipsilateral ligament injury requiring surgery.
Positive Lachman Test.	Previous ipsilateral knee ligament injuries.
Planned Endoscopic ACL Reconstructive Surgery with Hamstring Autograft.	Patient refusal of participation.
Control cohort	
No current or previous history of injury to knee structures.	Inability to consent.
No history of knee conditions greater than three months.	Withdrawal from study.
No current or chronic conditions of hip, foot or ankle, or previous injury to the lower limb.	Current injury or past surgery to contralateral knee.
	Concurrent surgical procedure known to have an effect on post-operative healing of the graft.
	Current or chronic conditions of hip, foot or ankle, or previous injury to the lower limb.

and then the pre-measured reamer was used to the appropriate tunnel depth. All bone debris was cleared.

The tibial tunnel was drilled using a standard intra-articular jig set at 55°. A guide wire was passed and the residual tibial ACL stump was utilised to gain anatomical positioning. The femoral and tibial tunnels were reamed to the width of the graft. The graft was then passed through the tunnels and tensioned by hand. Femoral fixation was achieved with an EndoButton (Smith & Nephew) and tibial fixation was achieved with an RCI interference screw sized to the tunnel and an extra small bone staple. Any abnormalities of the medial and lateral compartments were identified arthroscopically and recorded. Concurrent intra-articular pathology was treated as deemed appropriate and recorded. All patients were rehabilitated according to a physiotherapy protocol offered by the leading orthopaedic surgeon.

Data collection

Follow up

Kinematic testing for all patients was undertaken at six (T1) and twelve (T2) weeks postoperatively according to a strict protocol. These time points were strictly chosen to correspond kinematic testing points with critical graft healing time points in the postoperative period.¹⁶⁻¹⁹ Preoperative kinematic data were not used for longitudinal analysis to eliminate the potential bias carried by an adaptive gait pattern in ACL deficient knees.¹⁵

Testing protocol

All subjects were acquainted with the system, treadmill and femoral and tibial braces to be attached (Figure 2).

Femoral and tibial braces were attached to the subject according to manufacturer's instructions. Braces were tightened until the patient was comfortable and until the observer deemed the fixation to be strong enough such that it wouldn't slip during testing. The patient was asked to do a flexion-extension movement to acclimatise the patient to the device and report if any pain was present. The brace was adjusted as needed.

Treadmill habitualization

Subjects were invited to begin walking at 2 kmh⁻¹ (0.56 ms⁻¹) and the speed was gradually increased through a minimum 2 minute habitualization period to assure the subject was walking comfortably without the brace altering their gait and to allow for adjustments to marker sets to be undertaken if uncomfortable.

Calibration

Calibration was undertaken after the patient had comfortably walked for a minimum of 2 minutes. Calibration was completed for each subject according to manufacturer's instructions. This procedure involved:

- 1) Initialization of the Global Coordinate System to establish camera field of view and direction of walking.
- 2) Establishment of Ankle Joint Centre by digitizing most prominent points of the medial and lateral malleoli.
- 3) Establishment of Transepicondylar Axis by digitizing the most prominent points

- of medial and lateral femoral condyles.
- 4) Functional Calibration including: a) Establishment of Hip Joint Centre (Centre of Femoral Head) during a 5 second Hip Circumduction; b) Establishment of Knee Joint Centre during a 10 second continuous Flexion-Extension cycle; c) Establishing Extremities of Posterior Knee Joint Movement using the Postural Method.

Data acquisition

Patients were asked to begin walking and to advise the observer when comfortably walking. Data was acquired at 60 Hz for 45 seconds at a comfortable speed.

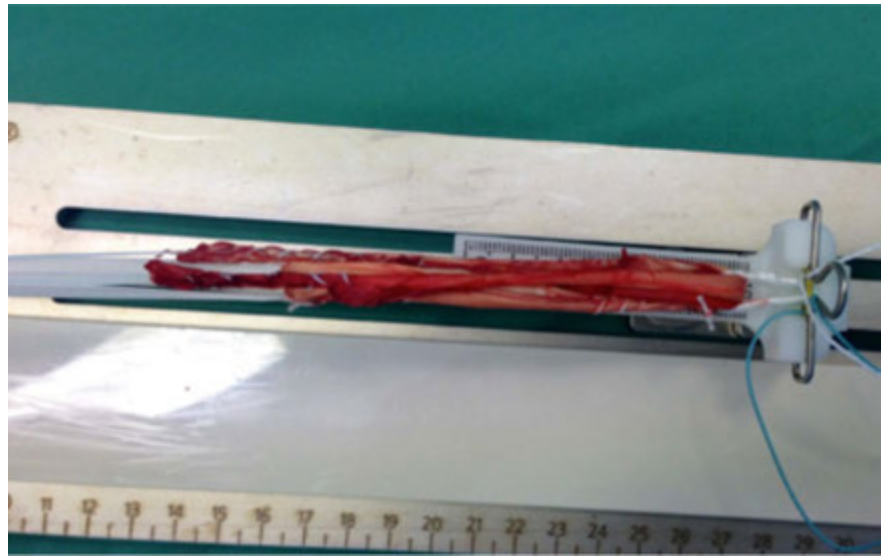


Figure 1. Final Five-Strand construct before insertion into femoral and tibial tunnels. Three-strand semitendinosus construct is formed by suturing the end of the tendon to the EndoButton loop. The opposite end of the semitendinosus is then brought through the EndoButton loop and folded back on itself to create an equally tensioned three-strand construct.



Figure 2. Lateral and anterior views of patient equipped with sacral belt, femoral and tibial braces, and subject walking on treadmill during data acquisition.

Data processing

Acquired data was extracted from the system for analysis. For each acquisition a minimum of 12 gait cycles were included. Gait cycles outside of 2.5 SD of the mean were excluded. These cycles were used to calculate a mean cycle for each acquisition, for the parameters flexion/extension, ad/abduction, internal/external rotation. The three acquisitions were then averaged to produce one mean gait cycle for analysis. Data points were expressed as a percentage (1-100%) of the mean gait cycle, with the start of the cycle (1%) defined as the first local minimum after swing phase (the largest increase in flexion). Ad/abduction and internal/external rotation data were similarly expressed as a percentage of the mean flexion/extension gait cycle.

Isolation of points for analysis

As we were limited by the inability to

determine the moment of heel strike (HS) and toe off (TO) by force plate measurement of ground reaction force (GRF), a key capability in determining relative rotations and translations with respect to the initiation of loading and unloading of the knee, a number of key points were isolated for analysis which represented local minimums and maximums in the gait cycle. These could be consistently identified for all subjects. The flexion/extension cycle was first used to identify the two local minimums and maximums that occurred in the gait cycle and the corresponding percentages for the other parameters were isolated (Table 2). Furthermore, the minimum and maximum values specific to the other parameters were isolated for analysis (Table 2, Figures 3 and 4). These points have been previously used in the literature^{14, 20-24}.

Data analysis and statistical method

Patient data was dichotomised into four-strand and five-strand groups.

All distributions were tested for normality using D'Agnostino-Pearson Omnibus Test for Normality and the statistical test chosen depending on this result.

Unpaired t-tests and Mann-Whitney Non-Parametric tests were performed to test for differences between the surgical groups for age, time to surgery and graft width, and between the surgical and control groups for demographic data.

One way analysis of variance with Tukey's post hoc tests and Kruskal-Wallis tests with pairwise comparisons were used to test for difference in kinematics between four- and five-strand groups, and the control group at 6 and 12 weeks postoperatively.

Pearson's and Spearman's correlation coefficients were used to quantify correla-

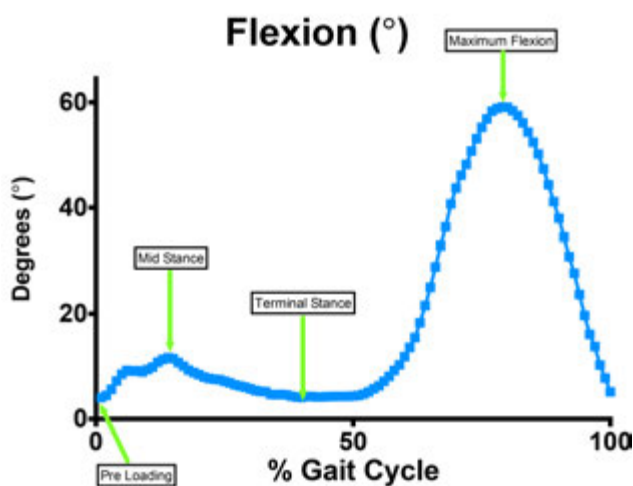


Figure 3. The flexion/extension cycle was used to identify local minimums and maximums in the gait cycle and the corresponding percentages for the other parameters were isolated.

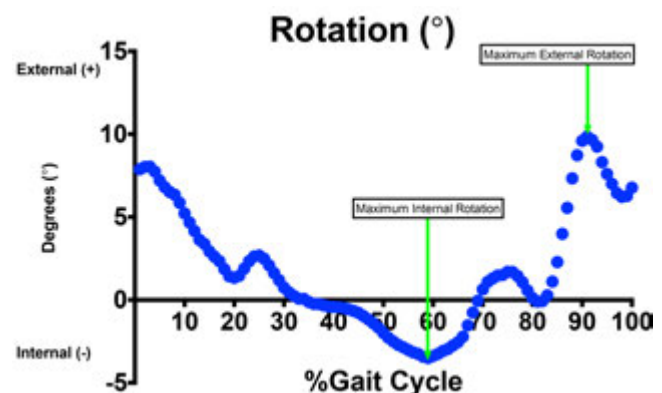


Figure 4. Minimum and maximum values specific to axial rotation were isolated for analysis.

Table 2. The flexion/extension cycle was first used to identify two local minimums and maximums that occurred in the gait cycle and the corresponding points in the axial and coronal planes were isolated. Minimum and maximum values in the axial and coronal plane were also isolated for analysis.

Point	Description	Previously used by
Flexion dependent		
Pre loading	Point corresponding to 1st local minimum after swing phase	(22)
Mid stance	Point corresponding to maximum value of stance phase between pre loading and terminal stance	(14, 20, 21, 23, 24)
Terminal stance	Point corresponding to local minimum between mid stance and maximum flexion	(14, 20, 21, 23, 24)
Maximum flexion	Local maximum of swing phase	(14, 20, 21, 23, 24)
Axial rotation specific		
Maximum internal rotation	Local minimum corresponding to maximum internal rotation	(14, 21, 23)
Maximum external rotation	Local minimum corresponding to maximum external rotation	(14, 21, 23)
Ad/abduction specific		
Maximum abduction	Maximum abduction for entire gait cycle	(14, 21, 23)
Maximum adduction	Maximum adduction for entire gait cycle	(14, 21, 23)

tion between kinematics at T1 and T2 and graft diameter. Correlations were performed between kinematic values and femoral and tibial widths for all graft constructs.

Results

Twenty-seven surgical patients took part in this study. 20 patients received a four-strand graft and 7 received a five-strand graft. There was no statistically significant difference between group in age or time to surgery. The four-strand group had proportionally more females (55%) than in the five-strand group (14.3%). There was a

statistically significant difference in graft widths between the two groups (Tibial Width $P<0.01$, Femoral Width $P<0.05$) (Table 3). The mean ages in the control and surgical groups were 26.9 ± 5.8 years and 29 ± 7.7 years respectively (Table 4).

Differences in postoperative kinematics

Flexion/extension in the gait cycle

Analysis revealed significant differences between groups at 6 and 12 weeks at preloading and terminal stance. At preloading, post hoc testing revealed significant differences between the four-strand and control group but no significant difference between graft types by 12 weeks. At termi-

nal stance there were no significant differences seen between graft types at 6 weeks but a difference was seen between the four-strand cohort and the control group at both 6 weeks ($P=0.001$) and 12 weeks ($P<0.05$) (Figure 5). A difference in maximum flexion was observed at 6 weeks between all groups but there was no demonstrable difference when graft types were compared individually.

Ad/abduction in the gait cycle

Differences were seen between groups at maximum abduction at 6 weeks ($P<0.05$) and a borderline significant difference at 12 weeks ($P=0.05$) (Figure 6). Post hoc analysis revealed no differences between graft types but a difference between the four-

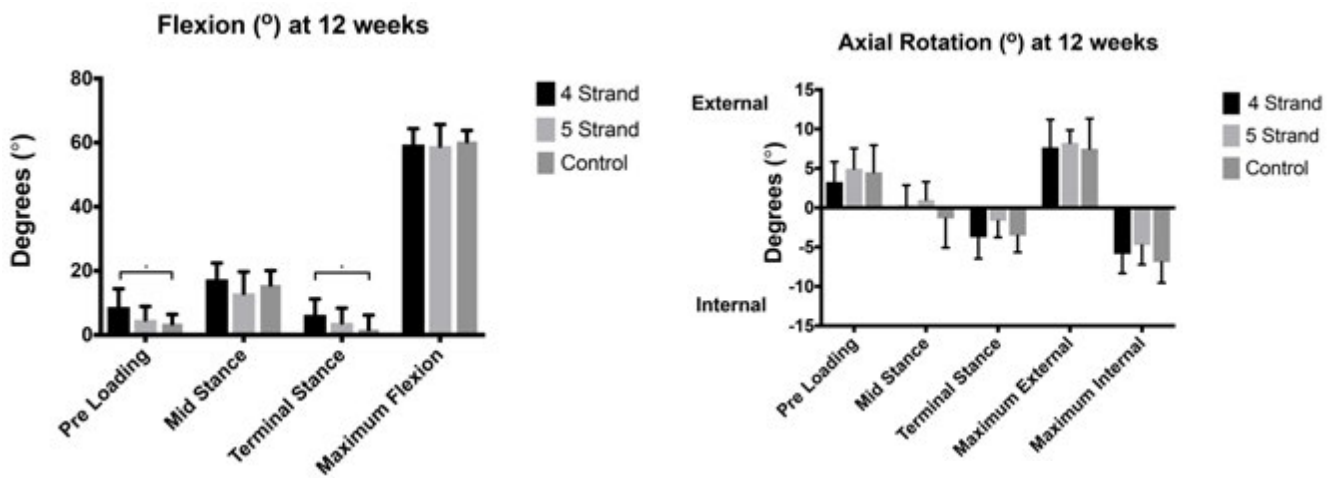


Figure 5. Comparison of mean flexion at key points in the gait cycle between surgical groups and control at 12 weeks postoperatively. A significant difference was seen in flexion between the Four-Strand group and control at preloading ($P<0.05$) and terminal stance ($P<0.05$). No differences were seen between graft types at any point in the gait cycle.

Figure 6. Comparison of mean external (+) / internal (-) rotation at key points in the gait cycle between surgical groups and control at 12 weeks postoperatively. No significant differences were seen between graft types or control at any point in the gait cycle.

Table 3. Demographics of the surgical cohort were not shown to be significantly different between the four-strand and five strand construct. The five-strand grafts were significantly wider than the four-strand group.

	Four-Strand (n=20)	Five-Strand (n=7)	Test between groups (P value)
Demographics			
Age (years)	30.0±8.4	25.1±4.1	0.13
Time to surgery (months)	16.0±27.8	5.7±3.9	0.44
Gender (F, M)	11 F, 9 M	1 F, 6 M	
Width of graft (mm)			
Femoral	8.0±0.6	8.4±0.2	0.04*
Tibial	8.0±0.6	8.6±0.4	0.003**
Concurrent injury			
Concurrent collateral injury	4 MCL 2 LCL	2 MCL 1 LCL	
Concurrent meniscal injury	5 Medial 7 Lateral 1 Both	1 Medial	
Partial meniscectomy	4 Lateral 2 Medial 1 Both	Nil	

strand and control group at maximum abduction at 6 weeks ($P<0.05$) and 12 weeks ($P<0.05$) (Figure 7).

Axial rotation in the gait cycle

At both time points there were no differences in axial rotation seen between groups at any point in the gait cycle. At 12 weeks postoperatively a trend to significance was seen between the four- and five-strand groups at terminal stance in favour of the five-strand graft (Figure 7).

Relationships between graft size and rotational stability

Significant correlations were only seen between graft width and rotational stability at pre loading (Pearson's $r=0.415$, $P<0.05$) and maximum internal rotation (femoral width: Pearson's $r=0.456$, $P<0.05$ and tibial width: Pearson's $r=0.476$, $P=0.01$) at 12 weeks postoperatively (Table 5). There were no correlations seen between any other kinematic parameters and graft width at 6 and 12 weeks.

and terminal stance in flexion initially suggest that patients reconstructed with the four-strand graft exhibited a less anatomical flexion/extension pattern at points in the gait cycle representing loading and unloading of the affected limb. However, when considering that kinematic data in the sagittal plane were comparable between graft types, it is evident that the five-strand graft is not superior in this respect.

Kinematic data in the coronal plane suggest that the use of the five-strand graft is beneficial for achieving anatomical kinematics at the extremities of abduction. However, previous studies have shown that there is much heterogeneity in abduction/adduction kinematic patterns in normal healthy volunteers.^{6,25} The variance in such patterns in the literature and a variance within our data bring into question the validity of our finding that suggested a benefit in the coronal plane.

No differences in rotational kinematics were found between all groups suggesting that at 12 weeks postoperatively ACL reconstruction using a method to assure that graft width is greater than 8 mm can produce rotational kinematics patterns evident in normal healthy knees. Interestingly a positive statistical correlation was seen between rotational stability and larger graft widths (irrespective of graft type) suggesting that techniques to achieve graft widths >8 mm are not only clinically comparable but are effective in achieving anatomic kinematic patterns.^{8,9}

These results are interesting when considered in contrast to a previous study undertaken at our institution, which illustrated that the five strand graft was inferior to the conventional four-strand graft in producing knee stability in the antero-posterior plane.²⁶ A key element of our study design was to correspond kinematic testing points

Discussion

This investigation illustrated that the use of a five-strand hamstring tendon autograft, when faced with a smaller four-strand graft width, produced postoperative knee kinematics comparable to both the four-strand reconstructed knees and a normal control knee. The differences between the four strand cohort and control at pre loading

Table 4. Demographics of the surgical cohort compared to the control group. Mean age was similar across groups. There were proportionally more females than males in the surgical cohort.

Demographics	Surgical cohort (n=27)	Control group (n=17)
Age (years)	29±7.7	26.9±5.8
Gender (F, M)	11 F, 14 M	2 F, 14 M

Table 5. Significant correlations were seen between graft width and rotational stability at preloading (Pearson's $r=0.415$, $P<0.05$) and maximum internal rotation (femoral width: Pearson's $r=0.456$, $P<0.05$ and tibial width: Pearson's $r=0.476$, $P=0.01$) at 12 weeks postoperatively. There were no correlations seen between any other kinematic parameters and graft width at 6 and 12 weeks.

	Pre loading	Mid stance	Terminal stance	Maximum external rotation	Maximum internal rotation
Femoral width					
<i>6 weeks</i>					
Correlation coefficient	-0.11	-0.03	-0.04	0.22	0.04
<i>12 weeks</i>					
Correlation coefficient	0.42*	0.25	0.35	0.36	0.46*
Tibial Width					
<i>6 weeks</i>					
Correlation coefficient	-0.20	0.01	0.08	0.15	0.06
<i>12 weeks</i>					
Correlation coefficient	0.37	0.20	0.38	0.32	0.48*

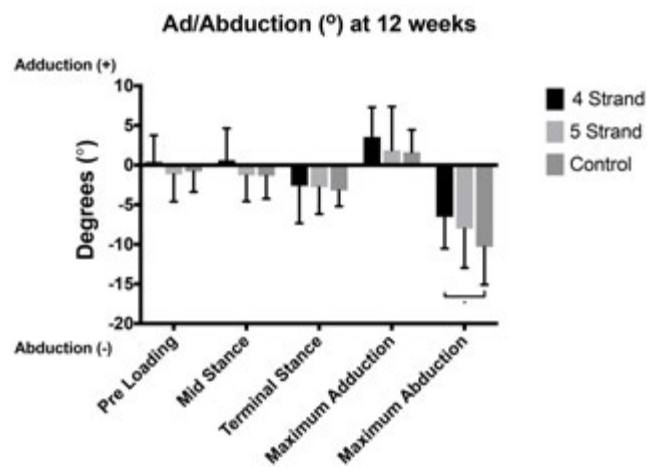


Figure 7. Comparison of mean adduction (+) / abduction (-) at key points in the gait cycle between surgical groups and control at 12 weeks postoperatively. A significant difference was seen in maximum abduction between the four-strand group and control ($P<0.05$). No differences were seen between graft types at any point in the gait cycle.

with critical graft healing time points in the postoperative period.¹⁶⁻¹⁹ We hypothesised that extra tendon material in the bone tunnel may have been disadvantageous to healing in the critical initial 12 weeks postoperatively. Furthermore, creating larger bone tunnels to accommodate the wider diameter of the graft may also have been disadvantageous to healing, suggesting a relationship exists between graft width, its size as a proportion of the surrounding tibial and femoral anatomy, tendon-bone healing and optimal antero-posterior stability of the knee. The findings of this study reveal another element of the complex relationship suggesting that increasing graft width optimises knee kinematics during walking and produce good clinical results as measured by knee scores but potentially at the expense of the antero-posterior stability of the knee.⁸

Limitations of this study include that follow up was designed to be short to closely study the differences between graft constructs during crucial parts of graft remodelling and incorporation of the new graft into the surrounding bone. Further follow up data is needed to establish a long-term relationship between graft construct and postoperative kinematics and is currently being sought. Secondly, ACL reconstructive surgery is a biomechanically complex procedure and key variables include anatomic positioning of tunnels, graft tensioning, variability in patient anatomy (particularly relationships between graft and native ACL footprint sizes), physiological characteristics affecting tendon-bone healing, and general surgical variability.^{17,27-29} Tunnel positioning is known to have an impact on tensioning properties and healing of the graft and although consistent surgical methods were used to assure anatomic positioning using the anteromedial portal, variability may have had an effect on results.³⁰⁻³² Lastly, the sample size of this trial was limited and repeated trials with larger samples in larger centres will be required to confirm the findings of this trial and enhance its generalizability.

Conclusions

This study demonstrated that to achieve anatomic knee kinematics in primary ACL reconstruction in the first 12 weeks postoperatively, a technique to optimise autograft width using a five-strand hamstring tendon autograft is useful. A relationship was found between graft width and more stable rotational kinematics of the knee during walking.

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