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Associations of knee angles, moments and function among subjects that are healthy and anterior cruciate ligament deficient (ACLD) during straight ahead and crossover cutting activities

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Abstract

The objective of this study was to compare knee angles and moments of healthy subjects ($n = 20$) and subjects that were anterior cruciate ligament deficient (ACLD) ($n = 16$) during stepping and crossover cutting activities. Subjects that were ACLD were separated into high ($n = 7$) and low ($n = 9$) functioning groups based on knee functional ratings. Knee angles and moments were estimated using three dimensional motion tracking and force plate data. The results suggest that knee angle and moment data were associated with level of functioning of ACLD subjects. Primarily knee frontal and transverse plane moments distinguished the stepping and crossover cut activities. Only some of the findings for the ACLD group were attributed to increasing knee stability.

Keywords: ACL; Anterior cruciate ligament; Biomechanics; Function; Cutting

1. Introduction

Subjects with anterior cruciate ligament deficiency (ACLD) report a disparate tolerance for physical activity [4,16,45,47]. For example, more subjects who are ACLD report moderate to severe limitations during turning and twisting activities (31–81%) compared with running (12–46%) or walking (0–31%) [4,16,46]. However, a small percentage of subjects (≈ 14%) [13,19,46] appear to tolerate all activities, including running and cutting during competition [19,21]. It is unclear if subjects who are currently classified as low functioning have the potential to achieve a high functional level through training or if subjects who function at higher levels possess other traits that enhance their knee stability. Clinicians, therefore, find it difficult to identify subjects who exhibit the potential to avoid surgery and are unsure of the appropriate rehabilitation that will return these patients to their premorbid functional level [6,13,21,22,37,46,68].

Successful motor control strategies that a subject with an ACL deficient knee might employ to maintain stability and prevent giving way episodes are a focus of debate [17,30,31,54,55]. Much of the previous research has been centered on the shear forces acting at the knee in the sagittal plane. Studies suggest that the hamstrings may act as an ACL surrogate during functional activities, helping to control anterior tibial translation [3,5,8,14,60]. Other studies suggest strong quadriceps contractions near 20° of knee flexion are avoided in order to minimize the associated anterior shear forces imposed by the quadriceps [2,7,61]. The combination of increased hamstring activity and quadriceps avoidance may help explain why some studies underscore the importance of observed decreases in the knee extensor moment at 20% of stance during walking [2,7,61]. Other investigators, however, have not confirmed these coping strategies, finding little or no change in the knee extension moment at 20% of stance during walking [10,18,26,54,66], running [2,7], and stairs gait

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[2,35]. These negative findings imply that there was no adaptation or that co-contraction of the hamstring was balanced by increased quadriceps force output resulting in a near equivalent net extensor moment [2,31,54].

One approach to identifying which adaptive knee angle and moment patterns benefit subjects that are ACLD, and which do not, is to study the differences among high and low functioning ACLD subjects [19,21,55]. One study suggests that ACLD subjects classified as non-copers demonstrate lower knee isokinetic moments than those classified as copers and healthy subjects [19]. Rudolph et al. [55] evaluated the sagittal plane knee angles and moments during walking and the ground reaction force during running in subjects that were ACLD and separated into copers and non-copers. Both the copers and non-copers demonstrated lower knee moments compared with the contralateral uninjured limb, suggesting copers do not utilize their ability to generate high knee extensor moments during a low demand straight ahead activity such as walking [55]. Lower peak knee flexion and vertical ground reaction force during running was typical of the non-copers; however, knee moments for running were not reported. Hence, whether high functioning subjects that are ACLD utilize their ability to generate higher knee moments during more challenging activities such as cutting and/or also adapt the knee moment pattern in other planes is uncertain. Given that ACLD subjects less frequently complain about straight ahead activities, the relevance of these findings is potentially less significant than comparisons during cutting activities [54].

Relative to straight ahead gait, cutting tasks are thought to generate substantially greater quadriceps demands and non-sagittal plane (transverse and frontal) moments at the knee [1,2,15,41,50,52,57,60]. During cutting, the deceleration that occurs prior to the change in direction is associated with strong quadriceps demand at knee angles $<40^\circ$ and is one factor that potentially places the ACLD knee at risk of giving way [15,25,50]. Other factors that potentially place the ACLD patient at risk are associated with the transverse and frontal plane knee moments generated during cutting activities, which may induce knee rotational instability [1,8,30,38,50].

The internal rotation associated with the crossover cut, may explain why the crossover cut is more problematic for subjects who are ACLD [1,14,30,60]. Tibone et al. [60] observed that subjects who were ACLD tolerated a sidestep cut, while over 40% refused to perform a crossover cut from fear of injury. During the crossover cut the subject places the swing leg over the stance leg to turn toward the new plane of progression, inducing internal tibial rotation [1]. Clinically, the pivot shift test is used as one of the definitive tests in diagnosing ACLD in that it is purported to determine the presence of anterolateral instability [23,48]. Measured in vitro, the pivot shift test is described as increased knee internal rotation (≈ 5–10°) and anterior translation (up to 1 cm) near 30° knee flexion [11,42,48]. Investigators comparing the knee kinematics and EMG during a crossover cut of healthy subjects and subjects who are ACLD observed no differences [14,60]. These studies failed to control the approach velocity, angle of cut and foot landing strategies potentially resulting in variable patterns and low statistical power [14,60]. In addition, previous authors were unable to capture knee internal rotation movements when evaluating cutting [12,53], a potential indicator of knee instability. Hence, any distinguishing characteristics of the three dimensional knee joint kinematic and moment patterns that might identify coping strategies in subjects that are ACLD during crossover cutting activities rely on clinical and anecdotal observations.

1.1. Purpose

The purpose of this study was to compare the sagittal and transverse plane knee joint angles and 3D knee moments among healthy, low functioning and high functioning subjects who were ACLD during both straight ahead and crossover cutting tasks. Two common straight ahead tasks (walk and step) and two equivalent crossover cutting tasks (walk+cut 45° and step+cut 45°) were selected to safely challenge the participants. The initial hypothesis was that healthy subjects and subjects who were ACLD would present with similar knee angle patterns across the activities. The high functioning subjects were expected to use higher knee extensor moments during early stance equal to healthy subjects indicating tolerance of high quadriceps demand, in contrast to the low functioning subjects who were expected to show lower knee extensor moments. The step and both cut activities were expected to accentuate differences among the groups because of the higher demands placed on the knee and subjective reports of poor tolerance of crossover cut activities by subjects who were ACLD. It was anticipated that the transverse plane moment might distinguish the high and low functioning subjects who were ACLD; however, the direction and magnitude of the adaptation were not certain prior to the experiment. The frontal plane moments were not expected to differ among subjects.

2. Methods

2.1. Subjects

A sample of convenience of 16 subjects, between 18 and 55 years old, with documented ACL rupture and 20 healthy subjects (ten females, ten males) with an average height (1.73 ± 0.12 m), weight (64.7 ± 12.0 kg) and age (28.3 ± 8.6 years) participated in the study. The injured

Table 1
Means and standard deviations of demographic and clinical variables of the ACLD groups

	Low functioning ($n=9$)	High functioning ($n=7$)	P-values
Age (y)	35.9±10.8	27.9±9.2	0.131
Height (m)	1.74±0.09	1.78±0.08	0.483
Mass (kg)	82.9±14.3	82.1±20.7	0.929
Sports hours (h)			
Current	75.2±82.0	194.7±226.1	0.225
Before injury	125.7±114.2	234.3±235.9	0.464
Occupation rating (%)	24.4±12.9	26.5±13.3	0.754
Strength			
Quadriceps ratio (inv/uninv or R/L) (%)	87.1±13.6	92.0±13.2	0.478
Hamstrings ratio (inv/uninv or R/L) (%)	102.8±17.1	110.4±21.9	0.302
Laxity: KT-1000 (mm)	5.9±3.7	7.5±3.0	0.373
Time from Injury (months)	63.6±69.3	52.1±46.1	0.699
Range	5–180	6–132	
Questionnaires			
Modified Noyes (%)	71.4±13.7	84.5±9.4	0.041*
Lysholm (%)	75.6±11.3	89.0±4.0	0.009*
Global question (%)	58.4±17.7	87.8±5.6	<0.001*

Bolded and * values indicates significantly different values ($P<0.05$) among groups based on a t-test assuming unequal variances.

subjects are described in Table 1. The healthy subjects were free of lower extremity pain for at least 6 months and had no previous history of knee injury. The ACLD subjects (nine males, eleven females) had documented complete ACL rupture by MRI or observation during arthroscopic surgery performed after participation in this study. Subjects were excluded if varus/valgus laxity tests were positive or subjects had known meniscus involvement that led to surgery. In addition, a difference in knee girth of greater than 2 cm along the joint line suggested joint swelling, and, hence, exclusion. Other exclusion criteria included painful active range of motion, leg length discrepancies and history of lower extremity pain in the last 6 months. Knee flexor and extensor torque was assessed using the average of three reciprocal knee flexion/extension movements on a Cybex II dynamometer at 60°/s. The peak isokinetic strength was expressed as a ratio of the involved/uninvolved x 100% for both flexion and extension. Joint laxity was side to side difference (laxity = involved − uninvolved) using the manual maximum force with KT-1000 arthrometer. Subject responses to questionnaires [39,62] used to characterize their health and function, along with other clinical measures are given in Table 1. All subjects who were ACLD were at least 5 months post injury, and, therefore, considered representative of chronic subjects.

Level of knee functioning was defined using a global question of knee function that read, 'If I had to give my knee a grade from 1 to 100, with 100 being the best, I would give my knee a _____________'. A global question of knee function has shown high correlations with popular knee questionnaires that were also included in this study (Table 1) [32,62]. Subjects who were ACLD and rated their function as higher than 80% and were involved in recreational sports and/or vigorous work were placed in the high functioning group ($n=7$). Subjects who were ACLD, rated their knee below 80% were placed in the low functioning group ($n=9$). The high functioning subjects participated in a variety of sports that are considered challenging to the knee (football (recreational) = 1, wrestling (Division 1 College) = 1, skiing = 1, volleyball = 2, running = 1, basketball = 1). In contrast, the low functioning subjects were either not participating in sports (4) or the sports were less challenging to the knee (biking = 3, running = 2).

2.2. Kinematics and force plate recordings

The infrared diode's (IREDs) of the Optotrak Motion Analysis System (Northern Digital, Inc., Waterloo, Ontario, model 3020) were tracked at a sampling rate of 60 Hz. Ground reaction forces were recorded at sampling rate of 300 Hz using a force plate (Kistler, Instrument Corp., Amherst, NY, model 9865B) mounted in the floor. Prior to processing the force (Fx, Fy and Fz) and position data (x, y, z), a residual analysis was performed on two healthy and two ACLD subjects to determine the optimal cut-off frequency (6 Hz for position data and 8 Hz for the force data) before smoothing the position and force data using a fourth order, low pass, Butterworth, zero phase lag filter.

2.3. Lower extremity modeling

A four-segment model of the lower extremity including the foot, leg, thigh and pelvis was used to estimate joint angles and moments in three dimensions. For the healthy subjects ten left sides and ten right sides were tested. For the ACLD subjects the group classified as high functioning included five left and two right sides and the group classified as low functioning included six left and three right sides. Rigid body representations of each segment were achieved by placing three IREDs on each segment similar to previous studies (Fig. 1) [27,29,30,65]. The IREDs used to represent the pelvis were placed on the right and left ASIS and a hollow aluminum rod extending from platform mounted on skin over the sacrum. The IREDs used to represent the femur include two IREDs mounted on a femoral tracking device and a marker placed 10 cm distal to the greater trochanter. The IREDs used to represent the tibia are placed over the anterior border of the tibia. The IREDs used to track the foot are placed on the lateral side of the shoe proximal to the 5th metatarsal head. All subjects were required to wear low top running style shoes.

Subsequently, estimated segment inertial properties [67] were combined with the filtered ground reaction force and position data to calculate net joint moments at the ankle and knee using the KINGAIT3 software package (Mishac, Inc., Waterloo, Ontario, 1995) [33], which

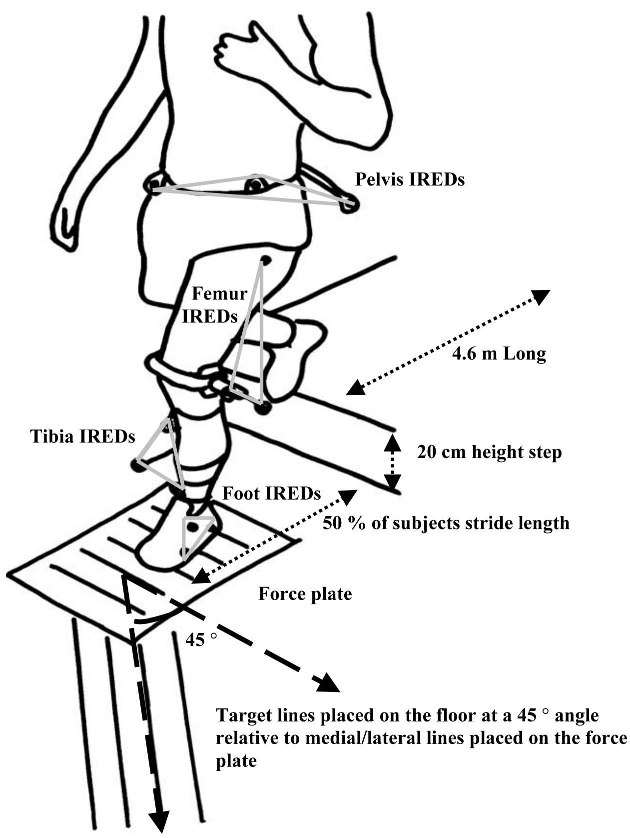

Fig. 1. The infrared emitting diodes for the four segment model of the lower extremity, arrangement of the step relative to the force plate and target lines used to help guide the subjects when performing the walk+cut and step+cut activities are illustrated.

utilizes the same approach as currently published methods [9,20,63]. Net joint moments were subsequently resolved into the local coordinates of the distal segment. The KINGAIT3 software package determines joint angles using current International Society of Biomechanics recommendations [64] and angle conventions proposed by Grood and Suntay [24]. Evaluation of the femoral and tibia tracking approach used in this study showed rms errors of $\pm 2^{\circ}$ in the transverse plane in a single subject over the first 85% of stance during walking and running [65]. A similar technique used to study three subjects observed rms errors around $\pm 2.6^{\circ}$ when tracking the femur and tibia during a squat [56]. A previous study of the reliability of knee joint angles and moments suggested good repeatability (intraclass correlation coefficient of >0.8 and standard error of the measurement of $\pm 2^{\circ}$) during walking and step+crossover cut activities used in the current study [29].

2.4. Procedures

Subjects completed four different activities, two straight ahead activities and two equivalent crossover cutting activities. The straight ahead activities included walking and stepping down off a 21 cm curb. The walk+cut and step+cut activities required subjects to turn 45° using a crossover cut movement (Fig. 2). The step platform was 4.6 m long allowing 4–5 strides prior to stepping down and was positioned so that the distance from the edge of the curb to the center of the force plate was 50% of the subject's stride length during over ground walking (Fig. 1). Colored tape placed around the force plate and custom software that displayed the cutting angle and foot placement was used to provide feedback to subject's ensuring a consistent change in direction near 45°. To document the change in direction performed by the subjects during the crossover cut activities, the cut angle (CA) was defined as the transverse plane angle of the pelvic segment in the global coordinate system at toe off.

Foot placement onto the force plate was required to meet two criteria. First, the heel was required to strike the force plate before the toe. Second, the subject was coached to keep the stance foot angled in line with the plane of progression. The angle of the foot relative to the global coordinate system in the transverse plane at foot flat (foot progression angle or FPA) was recorded to evaluate performance across subjects. The foot landing strategy was manipulated to decrease variability across subjects in the knee kinematics and moments, and subsequently, enhance power to detect group differences. The approach velocity (1.34 m/s) was controlled by having subjects keep pace with an overhead tracking system. Comparable CA and FPA among groups ensure that differences in the angles and moments are not due to a change in the challenge of the activity, but rather

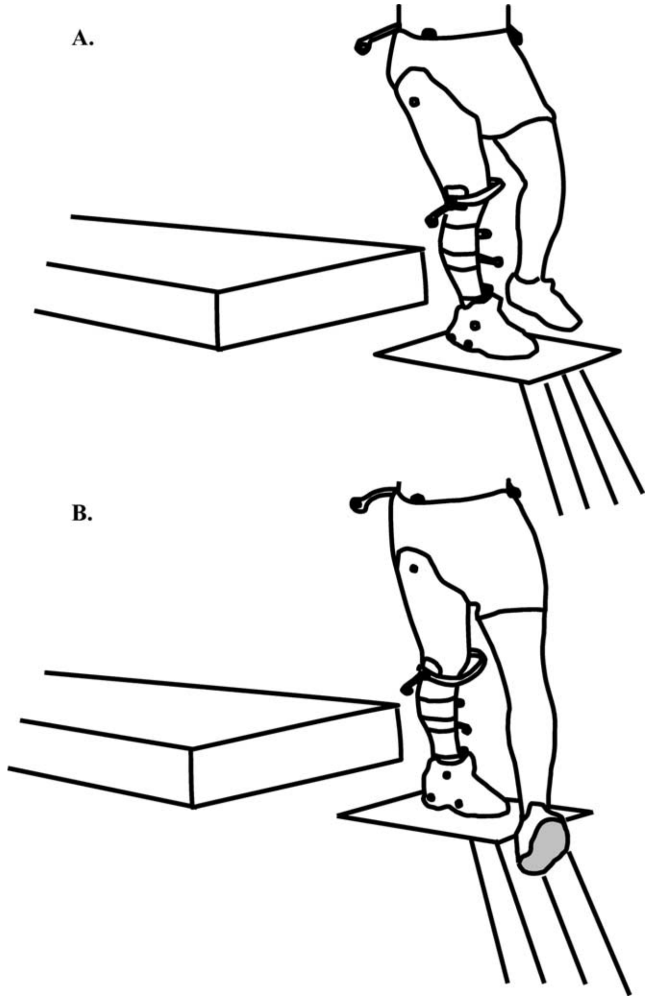

Fig. 2. The step + cut at approximately mid stance (A) and late stance (B) are illustrated.

are a compensation related to the injury and functional status. After at least ten warm-up trials, subjects completed five successful trials of each activity. The sequence of testing each activity was randomized.

2.5. Analysis

Knee angle and moment patterns for five trials were ensemble averaged at 2% intervals to gain a representative pattern for each subject across stance for each condition. At discrete points of stance, peak knee angles (sagittal and transverse) and moments (sagittal, transverse and frontal) were compared using a mixed two-way ANOVA model. One factor was group (fixed factor) with three levels including the high function (ACLD), low function (ACLD) and healthy subjects. The second factor was activity (random factor), with four levels, including walk, walk + cut, step and step + cut. In the presence of a main effect, a Tukey post hoc test was used to determine differences among groups. In the presence of an interaction, simple effects were tested using specific contrasts. Probability values less than 0.05 for each test were considered significant.

3. Results

3.1. Comparison of performance across activities

All of the variables used to define each task were similar among groups (Table 2). The average stride length normalized to height was $90.8 \pm 6.4\%$ for the healthy subjects and $88.3 \pm 6.8\%$ for subjects who were ACL deficient. Stance time was also similar across groups ($F_{2,33}$; $P < 0.675$), ranging in value from 0.653 ± 0.049 to 0.716 ± 0.055 s across all the activities (Table 2). The desired CA of 45° was, on average, within 3° of the target value (Table 2). A post hoc analysis of a single subject was performed to characterize the path of the center of mass of the pelvis in the global coordinate system (Fig. 3A) during the crossover cut activities (walk + cut and step + cut). Interestingly, the change in direction begins immediately at heel strike and progresses smoothly until toe off.

The average FPA suggested external rotation of the foot at foot flat around 10° (walk = $9.8 \pm 5.1°$ and step = $8.2 \pm 5.3°$) for the healthy subjects and for subjects who were ACLD (walk = $10.2 \pm 5.1°$ and step = $7.9 \pm 3.2°$) during the straight ahead activities. During the walk + cut and step + cut similar foot placements relative to the straight ahead activities were achieved (Table 2). The FPA throughout stance for a typical subject show that subjects were able to perform the activity as requested with the foot aligned close to the approach plane of progression until late stance (Fig. 3B).

3.2. Differences in sagittal plane knee angles and moments among groups

Peak knee flexion at 20% of stance depended both on the activity and subject group ($F_{2,6}$; $P < 0.001$). The ACLD groups used significantly less knee flexion during the step and step + cut activity by 2.6 to 6.6° compared with healthy subjects (Table 3). At 60% of stance ACLD subjects classified as low functioning used significantly ($F_{2,33}$; $P < 0.001$) greater knee flexion than both healthy subjects and ACLD subjects classified as high functioning across activities (Table 3). The differences in knee flexion were most distinct during the walk + cut and step activities, where the low functioning group used higher knee flexion angles by 3.2–5.3°. The pattern of knee flexion across stance of the step + cut activity shows the changes in knee angle utilized by the ACLD subjects compared with the healthy subjects (Fig. 4A).

The peak knee extensor moment used by subjects who were ACLD was significantly lower ($F_{2,6}$; $P < 0.001$) at

Table 2
Group means and standard deviations for measures of performance

	Group			
	Healthy	Low functioning	High functioning	*P-value
Walk+cut				
FPA	9.75±4.4°	12.2±5.5°	10.0±4.7°	0.312
CA	43.2±4.3°	43.1±3.7°	45.5±2.0°	0.446
Diff	33.4±5.3°	30.9±6.1°	35.5±5.9°	0.203
Stance time (s = seconds)	0.673 s	0.701 s	0.717 s	0.642
Step+cut				
FPA	8.3±5.3°	9.9±4.2°	7.1±4.7°	
CA	43.3±5.6°	42.2±3.4°	44.6±5.4°	
Diff	35.0±8.4°	32.3±6.1°	37.5±6.2°	
Stance time (s = seconds)	0.673 s	0.658 s	0.683 s	

FPA, foot progression angle; CA, cutting angle; Diff, difference between FPA and CA. *A two way ANOVA with factors as group (healthy, low and high functioning) and activity (walk+cut and step+cut). The P-values represent probability values for differences among groups.

20% of stance by 0.21–0.65 Nm/kg, compared with healthy subjects during the step and step+cut activities (Table 3; Fig. 5A). Expressed as a percentage of the peak knee extensor moment of healthy subjects, subjects who were ACLD used a peak knee extensor moment 18.5–39.3% lower. In addition, ACLD subjects classified as high functioning used a significantly ($F_{2,33}$; $P<0.001$) higher peak knee extensor moment than ACLD subjects classified as low functioning by 0.12–0.28 Nm/kg across activities. A post hoc analysis showed moderate Pearson Product correlations between the peak knee moment at 20% of stance and knee flexion during the step ($r=0.33$) and step+cut activities ($r=0.46$) of all the subjects considered together. At 60% of stance, healthy subjects and ACLD subjects classified as high functioning used similar peak knee flexor moments across activities, however, ACLD subjects classified as low functioning used a significantly lower ($F_{2,33}$; $P<0.001$) knee flexor moment across activities (Table 3).

3.3. *Differences of transverse plane knee angles and moments among groups*

The transverse plane knee angles across stance were not significantly different among groups (Table 3). The peak knee internal rotation angles were not significantly different at 20% of stance ($F_{2,33}$; $P<0.761$) or 70% of stance ($F_{2,33}$; $P<0.436$) or when comparing the peak throughout stance ($F_{2,33}$; $P<0.960$) across groups (Table 3). The pattern of transverse plane knee motion during the step+cut activity (Fig. 4B) or other activities did not differ among groups over the first 85% of stance. The transverse plane knee moments at 20% of stance showed that ACLD subjects who were high functioning used higher knee internal rotation moments across activities than healthy subjects and ACLD subjects who were low functioning ($F_{2,33}$; $P<0.003$). The higher knee internal rotation moments were accentuated during the step+cut activity (Fig. 5B). In late stance there was no difference in the transverse plane knee moments used among groups ($F_{2,33}$; $P<0.304$) (Table 3).

3.4. *Differences of frontal plane knee moments among groups*

The peak knee abductor moments used by subjects who were ACLD were significantly lower ($F_{2,6}$; $P<0.001$) at 20% of stance by 0.24–0.33 Nm/kg compared with healthy subjects during the step and step+cut activities (Table 3; Fig. 5C). Expressed as a percentage of the peak moment for healthy subjects, subjects who were ACLD used knee abductor moments 21.7–27.1% lower than healthy subjects. At 70% of stance the knee abductor moment was comparable among groups ($F_{2,33}$; $P<0.456$) (Table 3).

4. Discussion

The new findings of this study suggest that knee angles and moments of subjects that are ACLD are associated with their level of functioning. In addition, the most discriminating activities, as judged by the knee angles and moments, were the step and step+crossover cut and not the walk or walk+crossover cut activities, where relatively few differences were observed among groups. Also, the knee internal rotation angles, on average, were not different among groups; however, differences in moment data suggest subjects who were ACLD employ coping strategies that prevent internal rotation instability. The findings of this study are partially dependent on the definition of the patient groups and constraints imposed on performance during the stepping and crossover cutting activities.

Questionnaire scores that convey the degree to which subjects are coping with their injury suggest that

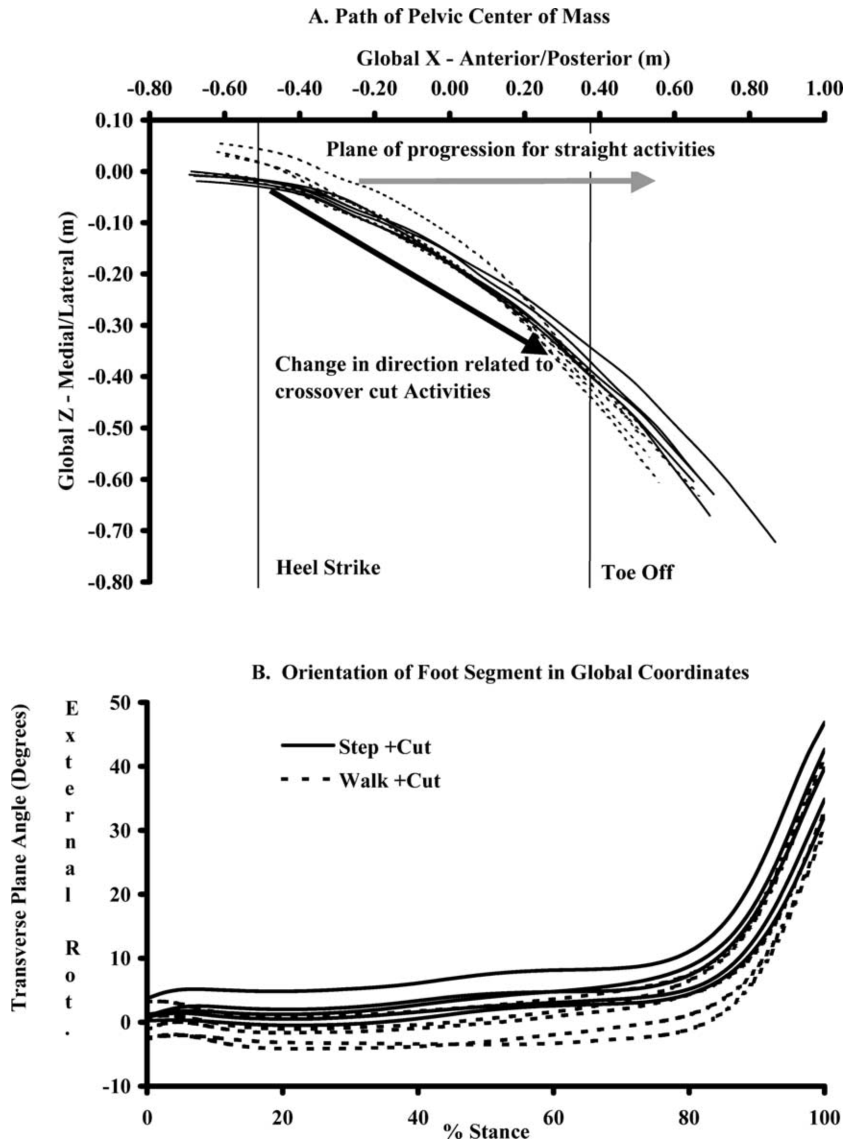

Fig. 3. (A) The path of the center of mass of the pelvis in the global coordinate system of individual trials of a single subject for the walk+cut and step+cut activities. (B) The orientation in the transverse plane of the global coordinate system of the foot segment over stance for individual trials of a single subject for the walk+cut and step+cut activities.

although the groups of ACLD subjects were small they were distinct relative to level of functioning (Table 1). Eastlack et al. [19], suggested the global rating of knee function is highly correlated with functional ability after an ACL rupture in addition to other scales. Though the questionnaire scores show distinct differences in function exist between the ACLD groups in this study, alternative definitions of functioning levels such as those proposed by Eastlack et al. may further distinguish group differences. Relative to clinical measures the groups showed similar impairments of anterior knee laxity and strength. Meniscus injury was not assessed, and, therefore, some differences in involvement of the meniscus across groups are possible, although the importance of this is uncertain since recent studies suggest menisectomy does not affect knee moment patterns during walking [43] and has a minimal effect on knee motion as measured during in vitro tests [59]. Although the type of sports in which the high functioning subjects were participating in differed from the low functioning subjects, the number of hours of sports participation per year was similar (Table 1). The results of this study are, therefore, limited by the definition of functioning level used, inclusion of subjects with meniscal injury and a variety of sports participation.

Previous studies evaluating differences in muscle function during more vigorous activities between healthy subjects and subjects who were ACLD were not conclusive [2,8,14,60]. Tibone et al. [60] suggested subjects who were ACLD avoided turning as sharply during a crossover cut compared with healthy subjects. Subsequently, Ciccotti et al. [14] noted no differences in

Table 3
Mean $\pm$1 S.D. of the peak knee angle and moment data from selected points of stance

Walk					Walk+cut			Sig.($P<0.05$)@
Knee moment (Nm/kg)	Stance (%)	Healthy	Low funct.	High funct.	Healthy	Low funct.	High funct.	
Extensor	20	0.64±0.21	0.55±0.26	0.67±0.25	0.56±0.16	0.50±0.25	0.50±0.22	
Flexor	60	−0.26±0.21	−0.15±0.21	−0.22±0.12	−0.33±0.14	−0.06±0.11	−0.24±0.20	
Abductor	20	0.66±0.16	0.65±0.19	0.54±0.11	0.39±0.15	0.41±0.19	0.31±0.12	
Abductor	80	0.35±0.10	0.32±0.13	0.39±0.17	0.56±0.11	0.56±0.19	0.59±0.20	
Internal rotator	15	0.04±0.03	0.02±0.02	0.02±0.03	0.06±0.03	0.05±0.02	0.07±0.04	
External rotator	80	−0.17±0.03	−0.16±0.04	−0.16±0.02	−0.28±0.05	−0.29±0.08	−0.29±0.05	
Knee angle (°)								
Flexion	20	18.9±3.7	21.4±7.0	18.9±3.0	21.4±4.6	21.4±5.1	19.9±7.3	
Flexion	60	4.3±3.4	6.0±6.7	7.3±3.2	8.3±4.5	11.5±1.3	6.2±3.5	
Internal rot.	20	4.2±2.4	3.5±4.2	3.2±3.0	3.5±2.3	3.9±3.6	4.0±3.7	
Internal rot.	70	4.8±2.5	4.6±2.3	2.4±2.9	8.3±2.5	7.3±2.2	5.7±2.6	
Step					Step+Cut			
Knee moment (Nm/Kg)	Stance (%)	Healthy	Low funct.	High funct.	Healthy	Low funct.	High funct.	
Extensor	20	1.71±0.42	1.04±0.46	1.32±0.38	1.66±0.42	1.01±0.54	1.23±0.31	Int. #1
Flexor	60	−0.18±0.18	−0.12±0.08	−0.14±0.15	−0.26±0.13	−0.08±0.24	−0.20±0.20	M.E. #1
Abductor	20	1.22±0.35	0.96±0.30	0.89±0.14	1.01±0.37	0.77±0.37	0.74±0.12	Int. #2
Abductor	80	0.32±0.11	0.32±0.19	0.30±0.19	0.54±0.14	0.57±0.21	0.57±0.23	n.s.
Internal rotator	15	0.03±0.07	0.02±0.03	0.07±0.07	0.08±0.06	0.06±0.04	0.13±0.07	M.E. #2
External rotator	80	−0.16±0.06	−0.14±0.04	−0.15±0.04	−0.28±0.06	−0.25±0.07	−0.28±0.07	n.s.
Knee angle (°)								
Flexion	20	33.2±6.0	30.6±7.5	29.2±4.6	35.8±5.1	29.2±5.7	30.4±6.8	Int. #2
Flexion	60	8.9±5.1	12.2±1.3	7.7±3.7	12.1±6.0	12.3±1.3	9.6±9.0	M.E. #1
Internal rot.	20	4.6±2.8	5.0±4.6	3.8±4.1	3.7±2.4	5.3±4.9	4.7±4.7	n.s.
Internal rot.	70	6.1±2.6	3.8±4.4	4.8±1.3	7.3±3.5	6.1±2.8	6.3±1.9	n.s.

@ Last column shows results of a two way mixed effects ANOVA with three levels of group (healthy, low and high funct.) and four levels of activity (walk, walk+cut, step and step+cut). The results of the Tukey Post Hoc test in the presence of a main effect are; main effect #1 (M.E. #1), low funct. group different than both healthy and high funct. group across activities. Main effect #2 (M.E. #2), high funct. group different than both the healthy and low funct. group across activities. Main effect #3 (M.E. #3), healthy group different than both low and high funct. groups across activities. The results of specific contrasts in the presence of an interaction between groups and activities of the two way mixed effects ANOVA include (significant differences are indicated by differences in shading for each activity): Int. # 1, differences amongst all three groups during the step and step+cut activities. Int. #2, difference between the healthy and low funct. groups and healthy and high funct. groups during the step and step+cut activity. (Funct., function; Rot., rotation; Sig., significance; n.s., not significant for main effect amongst groups or an interaction effect).

peak EMG normalized to percent MVC during a crossover cut when comparing healthy subjects and subjects who were ACLD. Ciccotti et al. [14], however, noted large variability in EMG patterns during a running crossover cut, suggesting poor statistical power. In this study the stride length, stance time, approach velocity, cutting angle and foot placement were comparable across groups, in part reflecting our attempt to control the activity and obtain reliable data (Table 2). We believe that the controls imposed make it more likely that any changes in knee angles and moments are related to differences in motor control strategies and not differences in global performance of the activity.

The change in direction associated with the crossover cut activity appears to start at heel strike (Fig. 3A). Previous studies of the anterior/posterior ground reaction force suggest a deceleration phase followed by an acceleration phase during a cut [57], which was supported by anecdotal observations [1] and EMG studies suggesting increased quadriceps demand during early stance [15,25,50,52]. Most authors suggest the deceleration is necessary to assist the trunk change direction toward the new plane of progression [1,15,25,50,52]. In order to characterize the crossover cut movement, a post hoc analysis of the center of mass of the pelvis (Fig. 3A) showed that the change of direction begins immediately at heel strike, when the lower extremity is decelerating the trunk. In addition, the knee extensor moment at 20% of stance of healthy subjects was comparable between the straight ahead and cutting activities ($F_{3,99}$; $P<0.670$) (Table 3). Hence, the view that cutting is associated with higher knee extensor moments, and, therefore, quadriceps demand, to decelerate the trunk was not supported. This may have occurred because subjects were able to anticipate the change in direction, which could be different during sports situations. Future studies might consider tracking the center of mass of the trunk in combination with lower extremity kinematics and moments similar to studies of walking [41] to determine how the lower limb modulates the smooth

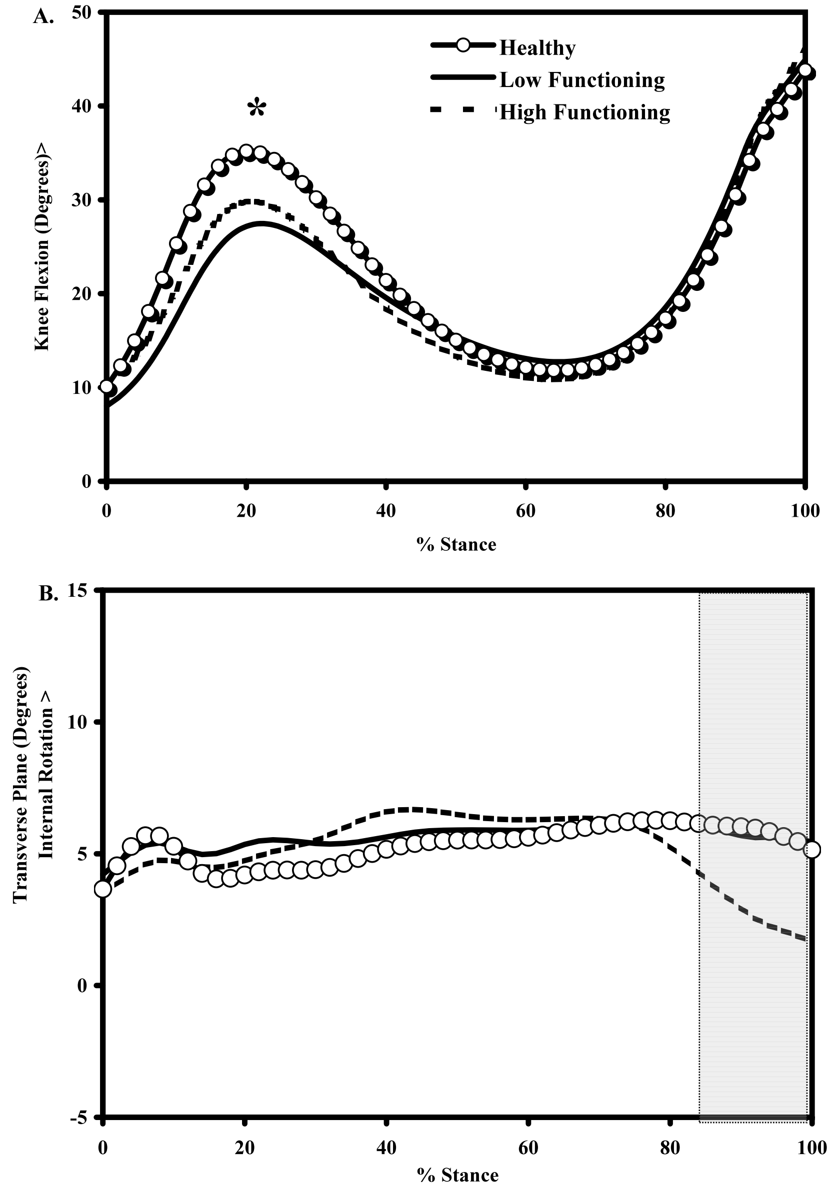

Fig. 4. (A) The average knee flexion across stance of the step+cut activity for all groups of subjects (* indicates peaks are significantly different). (B) The average knee internal rotation across stance of the step+cut activity for all groups of subjects (shaded area indicates the region the femoral tracking method is less accurate for transverse plane angles).

transition toward the new plane of progression during anticipated and unanticipated loads.

The constraints on foot placement led to the foot remaining in line with the approach plane of progression until late stance, after heel-off, when the foot rotated toward the new plane of progression (Table 2; Fig. 3B). By eliminating the toe-down foot landing strategy the knee moments were potentially biased toward higher values. With a toe-down strategy the period of foot flat is either diminished or absent, allowing the leg to rotate in the transverse plane around the ball of the foot. Therefore, the results of this study are specific to the foot placement strategy used.

This study suggests that the stepping, not the walking activities, challenged the ACLD subjects to use different knee moment patterns. Similar to some previous studies [18,26,54], healthy subjects and subjects who were ACLD showed no differences in knee flexion and knee extensor moment at 20% of stance during walking. Wexler et al. [61] in a cross sectional study observed a trend for subjects with a time from injury of up to 7 years to exhibit lower knee extensor moments. No similar trend existed in the subjects of this study whose mean time from injury was 4.5 years. The correlation between time from injury and the peak knee extensor moment during walking in this study was $r = -0.16$.

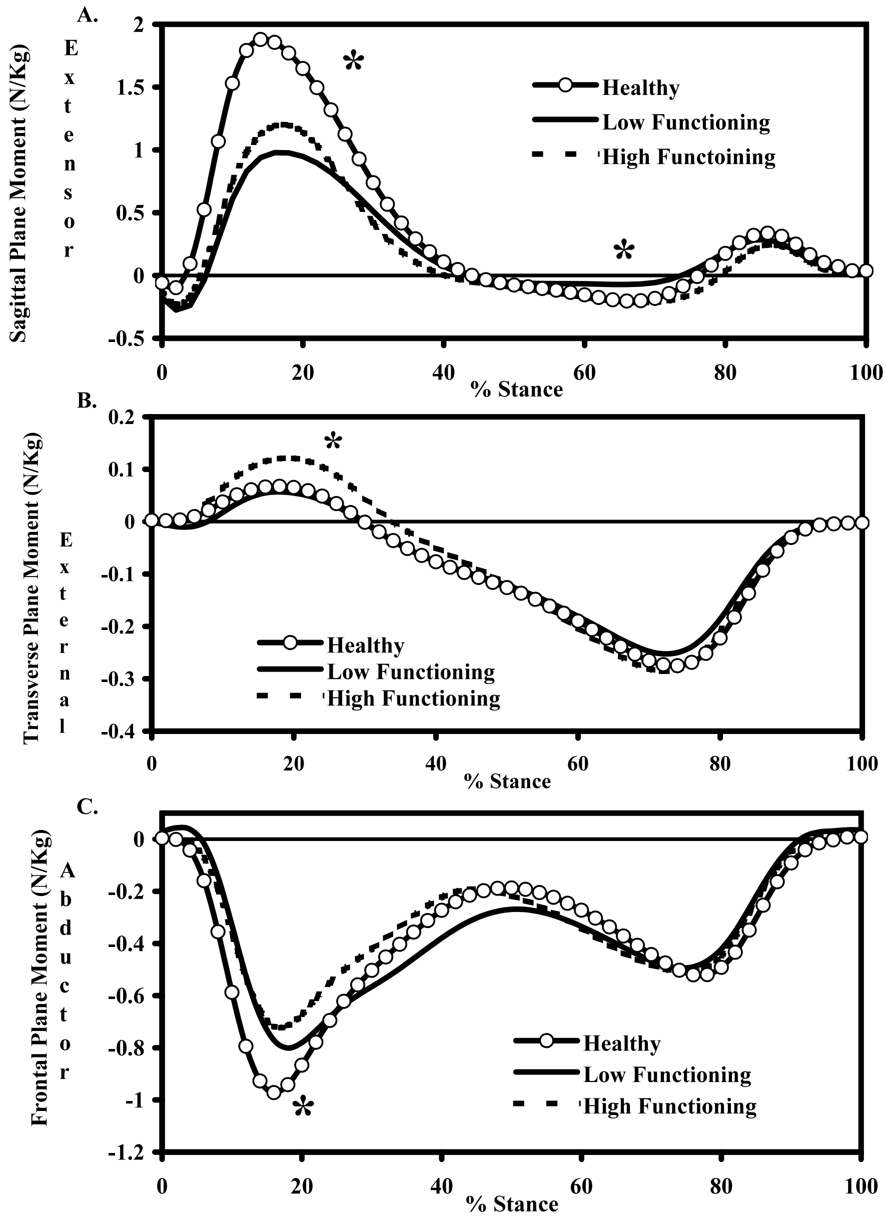

Fig. 5. Graphs A, B and C show the average knee moments across stance for all groups of subjects for the step+cut activity (* indicates peaks are significantly different).

Hence, the effect of time from injury on knee moment adaptations exhibited by ACLD subjects remains controversial.

The high functioning ACLD subjects were distinguished by a high knee extensor and internal rotator moments during early stance of the stepping activities, suggesting that specific knee moment patterns are associated with function. The stepping activities reproduced knee moments equal to running at 3.2 m/s [44], but lower than a running 90° crossover cut [50]. Compared with the low functioning group, subjects who are high functioning may utilize greater knee extensor moments because of the ability to more fully activate the quadriceps muscles [19], hamstring co-contraction [3,58] or by combining their loading patterns with transverse and frontal plane moments that tend to stabilize the knee [41,49]. At early stance (15%) of the step+cut activity, the lower extremity is internally rotating as the ankle planter flexes to bring the foot in full contact with the ground at foot flat ($\approx$10% of stance). The knee internal rotator moment suggests the external forces acting at the knee tended to move the knee toward external rotation; hence, a knee internal rotator moment was required to balance this moment. The ACLD subjects considered high functioning utilized higher knee internal rotator moments during early stance, suggesting a possible interaction of sagittal and transverse plane moments to assist in controlling knee motion.

The peak knee internal rotation angles that occurred across groups were similar, suggesting that subjects who were ACLD controlled knee rotation within the same range as healthy subjects. Previous studies of ACLD subjects using surface markers did not document transverse plane rotations due to difficulties overcoming skin artifact. Confidence in the current approach is supported by a previous study reporting reasonable accuracy ($\pm 2^\circ$) using this approach during walking and running in one subject [65]. The internal rotation magnitudes agree with previous studies noting 5 to 9° of transverse plane motion during walking [36,53], however, strict comparisons across studies are confounded by differences in establishing anatomic reference frames [51] and skin motion artifact [65]. A previous study also found no difference in three dimensional knee kinematics of the involved limb of subjects that were ACLD compared with control subjects during a step up activity [34]. Some low functioning subjects ($n = 2$) intermittently displayed abnormal kinematics associated with 'giving way' sensations during testing and were subsequently presented separately [27,30]. The lack of a significant difference in knee internal rotation suggests that, although intermittent increases in internal rotation may occur [30], during most motions subjects who are ACLD use compensatory strategies that limit knee internal rotation.

Alterations of the knee abductor moment observed during early stance are potentially associated with a lower overall load in the involved limb during the stepping activities [40] (Fig. 5C). Kowalk et al. noted significantly higher work values of the involved hip and ankle of subjects that underwent ACL reconstruction during stair ascent compared with healthy subjects, suggesting a lower load of the involved limb [35]. Both the knee abductor and extensor moment at 20% of stance are lower in the ACLD subjects during the stepping activities, also suggesting an overall decreased load at the knee. The lower knee abductor moment was not associated with function, and, hence, is potentially not a significant marker of a coping strategy.

4.1. Clinical significance

The main clinical interest is identifying which knee angles and moments might uniquely define subjects who are high functioning and ACLD and subsequently, discover if it is possible to train subjects to use similar patterns, theoretically leading to improved function with out surgery. Previous studies attempting to identify knee angle and moment patterns that may benefit subjects who are ACLD did not verify that performance was controlled [2] and failed to consider more vigorous activities that included high knee moments and crossover cutting activities [54,55]. This study suggests that subsets of subjects who are ACLD may achieve high levels of function by adopting specific knee angle and moment patterns during activities. However, the differences in some variables such as the peak knee angles during the step activity are small ($< 3^\circ$), and, therefore, may not be clinically significant.

The key findings that distinguished high functioning subjects from low functioning ACLD subjects included a higher knee extensor moment at 20% of stance and higher knee internal rotation moment at 15% of stance. Hence, the current view that higher knee extensor moments are associated with higher functional status is supported by this study. Unique to this study is the importance of modulation of the knee internal rotation moment, which is subtle (< 0.2 Nm/kg) during early stance, and is subsequently difficult to attribute to specific muscle actions without better measures of muscle force. Studies using EMG are helpful in confirming which muscles underlie the knee moments, yet, are unable to determine which muscle actions are responsible for the transverse plane moments [28]. In addition, it is unclear if subtle changes in muscle function, which were observed in the transverse plane knee moments, can be volitionally elicited, suggesting the need for further research related to cutting activities.

4.2. Conclusions

This study suggests that subjects who are ACLD reveal knee moment adaptations when asked to perform moderately vigorous activities that are not observed during less challenging activities. Some of the differences in knee moments are attributable to increasing knee stability, while others are possibly the result of global strategies to decrease the loading of the knee, and, hence, may occur during a variety of knee pathologies. The crossover cutting activities were distinguished from the straight ahead activities primarily by the transverse and frontal plane moments during early stance and the sagittal plane moment during late stance, therefore, these moments are potentially related to why subjects who are ACLD identify cutting as more difficult. Future studies should consider verifying the importance of the transverse plane moment with larger groups of subjects stratified into levels of function based on sports participation as well as functioning status.

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