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Influence of Anticipation on Movement Patterns in Subjects With ACL Deficiency Classified as Noncopers

Most subjects after an anterior cruciate ligament (ACL) injury experience intermittent episodes of giving way and difficulties during functional tasks that involve pivoting and turning.[2,14,28] Recent kinematic studies confirm that the instability associated with anterior cruciate ligament deficiency (ACLD) is asymmetrical, with greater movement of the lateral tibial plateau compared to the medial.[26,36,37] These abnormal kinematics,

STUDY DESIGN: Two-factor, mixed experimental design.

OBJECTIVES: To compare movement patterns of subjects who are anterior cruciate ligament (ACL) deficient and classified as noncopers to controls during early stance of anticipated and unanticipated straight and cutting tasks.

BACKGROUND: Altered neuromuscular control of subjects that are ACL deficient and noncoper theoretically influences movement patterns during unanticipated tasks.

METHODS AND MEASURES: The study included 16 subjects who are ACL deficient, classified as noncopers, and 20 healthy controls. Data were collected using an Optotrak Motion Analysis System and force plate integrated with Motion Monitor Software to generate knee joint angles, moments, and power. Each testing session included anticipated tasks, straight walking task (ST), and 45° side-step cutting tasks (SSC), followed by a set of unexpected straight walking (STU) and unexpected side-step cutting (SSCU) tasks in a random order. For all tasks speed was maintained at 2 m/s. Peak knee angle, moment, and power variables during early stance were compared using 2-way mixed-effects ANOVA models.

RESULTS: For both the straight and side-step tasks, the noncoper group did not show a dependence on whether the task was anticipated or unanticipated (group-by-condition interaction) for the knee angle (straight, $P = .067$; side-step cutting, $P = .103$), moment (straight, $P = .079$; side-step cutting, $P = .996$), and powers (straight, $P = .181$; side-step cutting, $P = .183$) during the loading response phase. However, during both straight and side-step cutting tasks, the subjects in the noncoper group used significantly lower knee flexion angles (straight, $P = .002$; side-step cutting, $P = .019$), knee moments (straight, $P = .005$; side-step cutting, $P < .001$), and knee powers (straight, $P = .013$; side-step cutting, $P < .001$).

CONCLUSIONS: This study suggests subjects that are ACL deficient and classified as noncopers use a common abnormal movement pattern of lower knee extensor loading even during unanticipated tasks.

KEY WORDS: anterior cruciate ligament, cutting task, knee instability, neuromuscular control

however, are distinct from giving-way episodes, which case studies suggest are quick, larger-amplitude movements.[20,22] Subjects with ACLD who function well, despite the potential for abnormal kinematics, are often referred to as "copers."[10,14] More commonly, subjects do not cope well with these abnormal kinematics and are termed "noncopers."[10,14] Clinically, screening criteria were developed to identify potential copers, who may learn neuromuscular control to limit abnormal kinematics.[5] This screening process correctly predicted that subjects would be able to return to sports without surgery 76% of the time, suggesting that this method is effective in distinguishing copers from noncopers.[17] The lack of adequate neuromuscular control is a common explanation for why most subjects with ACL injury fail to cope well after their injury.

The abnormal movement patterns that are unique to noncopers is the topic of several recent studies, all efforts to discriminate differences in neuromuscular control.[1,15,16,21,19,32-35] These studies employed tasks subjects perform routinely (walking and running)[1,32-34] or simulated a functional task (stepping and stepping and turning)[19,35] to define the abnormal movement patterns unique to noncopers. Noncopers are characterized by decreased knee flexion angles and knee extensor moments across tasks.[6,19,32-35]

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Because some studies using electromyography show alterations of hamstring/quadriceps activation and timing, combined with decreased knee flexion, this abnormal movement pattern has been identified as a joint-stiffening strategy.[6,32-35] These studies suggest a common abnormal movement pattern of the noncopers during anticipated tasks.

To extend the data from anticipated tasks, other studies employed moving force platforms during walking[16] and a standing balance task.[6] Studies of unanticipated tasks suggest that the abnormal movement patterns of the noncopers in response to force platform movement are in the intermediate reflex interval (60-129 milliseconds).[6,7] This suggests that noncopers are able to employ their abnormal movement patterns using feedback control when task demands are longer than this interval.[6,7] Although moving force platforms have validity for reproducing slip events, a criticism of this paradigm is that it lacks validity for simulating sports-related movements that do not involve slipping.[47]

Unanticipated tasks have validity for simulating sports-related movements while inducing loads in the lower extremity that may challenge subjects that have an ACLD.[3,4,18,25,30,31] Unanticipated walking cut tasks are studied by cueing subjects to choose a direction (straight or cut) after they reach a steady walking speed.[18,30,31] The minimum cue time (feed-forward planning time) necessary for a successful walking unanticipated cut task is longer than 200 milliseconds, typically near 300 milliseconds.[18,30,31] Alterations in lower limb loading associated with unanticipated cut tasks include a paradoxical trunk lean (away from the cutting direction) and reduced lateral placement of the stance foot.[18,30,31] This lower limb posture leads to adjustment in the knee valgus moment.[18] Further, unanticipated tasks have been associated with muscle cocontraction (agonist/antagonists) rather than selective activation of the agonist during running cut tasks.[3,4]

Deficits in neuromuscular control may interact with the motor control strategies utilized by subjects considered noncopers during unanticipated tasks. The ability to modulate muscle force is one key attribute of neuromuscular control, explaining the clinical emphasis on improving knee extensor strength.[42] Because knee extensor strength is influenced by muscle morphology and volitional activation,[42-45] both are hypothesized to influence abnormal movement patterns typical of noncopers. Therefore, functional tasks that influence the knee extensor load, such as unanticipated tasks, may challenge the neuromuscular control of subjects classified as noncopers. Because the intermediate reflex interval (60-129 milliseconds) is within the feed-forward planning time documented for unanticipated walking cut tasks (>200 milliseconds), altered neuromuscular control may contribute to abnormal movement patterns during unanticipated tasks. This leads to the hypothesis that subjects with ACLD may use similar abnormal movement patterns across tasks.

The purpose of this study was to compare movement patterns of subjects classified as noncopers and controls during early stance of anticipated and unanticipated straight and cutting tasks. Movement patterns were defined using the sagittal plane knee angle, moment, and power patterns from 0% to 50% of the stance phase of gait. Early stance was emphasized because of the role of the quadriceps in deceleration. It was hypothesized that the movement pattern utilized by the noncopers would not be influenced by anticipation regardless of the task performed (straight or side-step cutting).

METHODS

Subjects

A sample of convenience of 16 subjects with ACLD and considered noncopers and 20 control subjects participated in this study (**TABLE 1**). A power analysis using standard deviations and effect sizes from a previous study[19] suggested samples of 16 subjects per group were sufficient to achieve 80% power. All subjects signed informed consent approved by the Internal Review Boards of Ithaca College and the University of Rochester. The control subjects were between 19 and 45 years of age, were free of lower extremity pain for at least 6 months, and had no previous history of knee injury.

All the subjects classified with ACLD had greater than a 2-mm side-to-side difference on the KT-1000 test and arthroscopically confirmed tears of the ACL after participation in this study. Subjects were excluded if clinical 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, suggesting joint swelling, led to exclusion. Other exclusion criteria included painful knee active range of motion, a leg length discrepancy, and a history of lower extremity pain not related to their ACL injury in the last 6 months. Knee flexor and extensor torque was assessed with an isokinetic dynamometer (Lido Multijoint II; Loredon, Biomedical, Inc, Sacramento, CA), using a maximal isometric knee flexion/extension effort with the knee positioned at 60° of flexion. The peak isometric knee strength was expressed as a ratio of the involved/uninvolved × 100% for both flexion and extension.

Subjects were administered a screening examination if they had minimal joint effusions (less than 2-cm side-to-side difference in girth), equal range of motion (involved compared to uninvolved), and the ability to hop on their involved leg without pain. Subjects were included as a noncoper if they had 1 or more of the following: (1) more than 1 episode of partial or full giving way, (2) less than 60% on the Global Rating of Knee Function, (3) timed 6-m hop test less than 80% of the uninvolved side, and (4) Knee Outcome Survey-ADL Scale less than 80%.[13] Subject responses to questionnaires used to characterize their function, along with other clinical measures are given in **TABLE 1**. The functional status of the noncoper group is reflected in the Knee Outcome Survey (KOS) ADL and Sports Scales. These scales suggest that the noncopers had difficulty with both activities of daily living (mean ± SD KOS-ADL score, 79.7% ± 12.6%) and more strenuous sports-related tasks (mean ± SD KOS-Sports, 54.0% ± 24.1%). All subjects with ACLD were at least 3 months postinjury, therefore were considered to be in subacute or chronic condition.

Kinematics and Force Plate Recordings

TABLE 1 Demographic and Clinical Variables*

VARIABLE	NONCOPER	CONTROL
SAMPLE		
Age (y)	24.1 ± 9.1 (16-42)	23.4 ± 6.0 (19-45)
Height (m)	1.7 ± 0.1 (1.52-1.96)	1.7 ± 0.1 (1.57-1.83)
Mass (kg)	74.3 ± 16.4 (51.0-113.6)	70.9 ± 13.8 (52.3–106.8)
CLINICAL		
Injury time (mo)	8.7 ± 14.5 (3-59)	
Knee laxity, KT-1000 (mm)†	4.8 ± 1.84 (2-8)	0.6 ± 0.6 (0-2)‡
Isometric strength§		
Knee extension (%)	78.1 ± 14.3 (65.3-103.3)	99.1 ± 9.0 (78.4-116.0)‡
Knee flexion (%)	83.2 ± 28.4 (41.3-162.5)	96.3 ± 8.7 (76.2-113.9)
Hop index (%)°	83.2 ± 28.5 (52.3-118.8)	105.9 ± 8.4 (96.2-129.9)‡
Giving way (number since injury)	2.5 ± 1.9 (0-6)	
FUNCTIONAL RATINGS¶		
Global rating (overall) (%)	64.9 ± 18.4 (33-95)	
IKDC (%)#,[23]	60.6 ± 15.0 (30.0-85.1)	
Knee Outcome Survey (KOS)[25] ADL Scale (%)	79.7 ± 12.6 (56.3-100)	
Knee Outcome Survey (KOS)[25] Sports Scale (%)	54.0 ± 24.1 (20.0-100)	

Abbreviation: ADL, activities of daily living; IKDC, International Knee Documentation Committee.
** Values expressed as mean ± SD (range).*
† Side-to-side difference.
‡ Indicates significant (P<.05) difference between groups using an independent sample t test.
§ Involved/uninvolved × 100.
° Healthy subjects Hop Index is calculated as the nondominate/dominate side × 100.
¶ Higher scores indicate better function for all scales.
 # 2000 IKDC Subjective Knee Evaluation Form.

TABLE 2 Performance Variables*

VARIABLE	NONCOPER	CONTROL†
STRIDE LENGTH (m)	1.79 ± 0.15	1.82 ± 0.14
VELOCITY (m/s)		
ST task	1.9 ± 0.22	2.0 ± 0.17
SSC task	2.0 ± 0.25	2.0 ± 0.17
STU task	1.8 ± 0.32	1.8 ± 0.14
SSCU task	1.7 ± 0.26	1.7 ± 0.24
CUT ANGLE (°)		
SSC task	60.1 ± 6.3	61.5 ± 7.6
SSCU task	54.8 ± 6.0	52.7 ± 7.1

Abbreviations: ACLD, anterior cruciate ligament deficient; SSC, side-step cutting; SSCU, unanticipated side-step cutting task; ST, straight; STU, unanticipated straight.
** Values expressed as mean ± SD (range).*
† No significant differences (P<.05) were found between groups using an independent sample t test.

The infrared diodes (IREDs) of the Optotrak Motion Analysis System (model 3020; Northern Digital, Inc, Waterloo, Ontario) were tracked at a sampling rate of 100 Hz. Ground reaction forces were recorded at sampling rate of 1000 Hz using a force plate (model 9865B; Kistler Instrument Corp, Amherst, NY) mounted flush with the floor of a 15-m walkway. The force (Fx, Fy, and Fz) and position data (x, y, z) were filtered at a cut-off frequency of 50 and 7 Hz, respectively, using a fourth-order, low-pass Butterworth zero phase lag filter. A threshold of 10 N of vertical ground reaction force was used to determine heel strike and toe off.

Lower Extremity Modeling

A 4-segment model of the lower extremity including the foot, leg, thigh, and pelvis was used to calculate joint angles and moments in 3 dimensions. Rigid-body representations of each segment were achieved by placing 3 IREDs on each segment. The methods used to model the lower extremity are described in published studies[18,21] and are reviewed only briefly here. The IREDs used to represent the pelvis were placed on the right and left anterior superior iliac spine (ASIS) and a short hollow aluminum rod extending posteriorly from the sacrum. The femur was represented by 2 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 were placed over the anterior border of the tibia. The IREDs used to track the foot were placed on the lateral side of the shoe, proximal to the fifth metatarsal head. All subjects were required to wear low-top running-style shoes.

Subsequently, segment inertial properties were combined with the filtered ground reaction force and position data to calculate net joint moments and power at the knee, using Innovative Sports Training software (Innovative Sports Training, Inc, Chicago, IL), which utilizes the same approach as previously published methods.[16,43,45] Net joint moments were subsequently resolved into the local coordinates of the distal segment. This method of calculating the net joint moments determines the agonist contribution at a point in time.[46] The joint power is a scalar calculation that reflects the rate of energy generation (concentric action) or absorption (eccentric action) of the agonists.[46] The joint power is calculated by combining information from the joint angles and joint moments (joint power = joint moment × joint angular velocity).[46]

Procedures

Colored tape placed at 45° angles from the force plate was used to provide visual feedback to subjects, enabling reproducible cut angles near 45°. An infrared photorelay (Safehouse Infrared Photorelay; RadioShack, Fort Worth, TX) placed across the walkway triggered a visual display (**FIGURE 1**). For the unanticipated tasks subjects either performed a side-step cut in response to the visual display or continued straight ahead. The stance limb was always the involved limb for the injured subjects (**FIGURE 2**). During a practice session, the infrared light beam was placed 1 stride length from the center of the force plate. Subjects were allowed 3 to 5 practice trials and asked if they felt the activity was safe and within their abilities. If they answered yes, the distance was decreased by 15% of their stride length and the process was repeated until the subjects answered negatively. The last distance the subjects felt was safe and within their abilities was identified as the minimum cue distance. All the subjects' minimum safe cue distance, expressed as a percent of stride, was between 50% and 65% of a stride length from infrared beam to the center of the force plate and was similar between groups (**TABLE 2**). The practice session lasted approximately 30 minutes.

After the practice session, subjects attended a second session when they performed 2 anticipated tasks—walking straight (ST) and side-step cutting (SSC)—and 2 unanticipated tasks—walking straight (STU) and side-step cutting (SSCU). At least 5 trials of each task were recorded and used in the analysis for each subject. The ST and SSC tasks were performed first. Subsequently, the STU and SSCU tasks were performed in a random sequence to minimize the effect of a subject's tendency to guess whether the condition would be anticipated or unanticipated. Only trials in which subjects completed the task within the tape marks and at the monitored approach speed were kept for analysis.

Velocity during all tasks were monitored during the test sessions and measured after testing to determine whether the tasks resulted in similar overall demands. Subjects were given feedback of their target approach walking speed (2.0 m/s) using a timing system (Bower Timing Systems, Draper, UT). Subsequent analysis of the distance traversed by the center of mass of the pelvis from heel strike to toe off in the transverse plane (x, z plane) was divided by stance time to determine actual velocity of forward progression during each condition. The calculated velocity and cut angle for each condition were similar, suggesting the methods achieved a comparable cut angle and velocity (**TABLE 2**).

Analysis

Knee angle, moment, and power patterns for the 5 trials were ensemble averaged using linear interpolation at 1% intervals to gain a representative pattern for each subject across stance for each task. Because early stance is thought to challenge individuals with ACLD, peak angle, moment, and power variables were compared from 0% to 50% of stance. Further, early stance was broken down into 3 phases: initial contact (0% to 10% of stance), loading response (10% to 20% of stance), and midstance (20% to 50% of stance). Initial contact was included as a phase of gait extending from 0% to 10% of stance to approximate the point at which the knee moment switches from a flexor moment to an extensor moment and loading response.

Peak variables were evaluated using 2-way mixed-effects ANOVA models in SPSS 13.0. The straight and side-step cutting tasks were evaluated separately for the effect of anticipation. In each model, 1 factor was group (fixed factor) with 2 levels, including noncopers (ACLD) and controls. For the straight tasks, the second factor of anticipation (repeated factor) included 2 levels (ST and STU). For the side-step cutting tasks the second factor of anticipation (repeated factor) also included 2 levels (SSC and SSCU). Interaction effects were evaluated first, followed by main effects due to group (noncopers versus control). Interaction effects of group and condition were examined to determine if an unanticipated condition (STU/SSCU) required greater

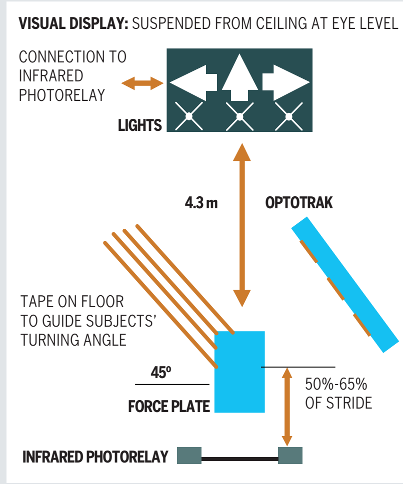

FIGURE 1. Diagram of the visual display used to cue subjects to cut or proceed straight.

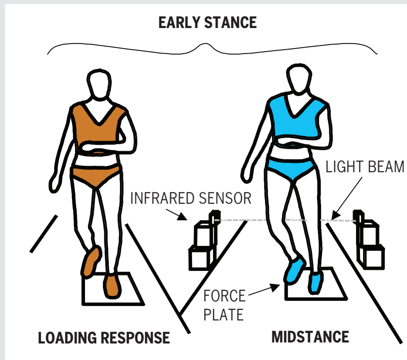

FIGURE 2. Subject at foot flat during the loading response and just before heel off, which is toward the end of midstance. The infrared photorelay used to trip the visual display is shown in background.

angle, moment, and power adaptations than an anticipated condition (ST/SSC) during either the straight or side-step cutting tasks. The 2-way ANOVA model was repeated for each dependent variable separately using a probability value of less than 0.05 to indicate significance.

RESULTS

Because there were no significant interaction effects (group × condition) during either the straight or side-step cutting tasks for any of the dependent variables, main effects are reported below (**TABLES 3, 4,** and **5**).

Straight Tasks

For the straight tasks, when averaged across both the anticipated and unanticipated conditions (**TABLE 3**), the subjects classified as noncopers used significantly lower knee flexion angles at initial contact (noncopers compared to controls, 5.9° ± 4.8° and 10.1° ± 4.0°, respectively; $P = .011$). The significantly lower knee flexion angles were sustained throughout the loading response (noncopers compared to controls, 22.9° ± 4.8° and 28.4° ± 4.9°, respectively; $P = .002$); however, they were similar to those of the controls at midstance ($P = .820$).

The means of the subjects classified as noncopers for the knee moment (**TABLE 4**) and power variables (**TABLE 5**) showed differences from the controls during loading response and midstance. When averaged across anticipated and unanticipated conditions, the subjects classified as noncopers during the loading response used significantly lower ($P < .005$) peak knee extensor moments (noncopers compared to controls, 0.68 ± 0.31 and 1.00 ± 0.34 Nm/Kg, respectively) and significantly higher ($P = .013$) peak negative power (noncopers compared to controls, –1.16 ± 0.87 and –1.92 ± 0.96 W/Kg, respectively) (**FIGURE 4**). Again, when averaged across anticipated and unanticipated conditions, the subjects classified as noncopers during midstance used significantly lower ($P = .01$) peak positive power (noncopers compared to controls, 0.74 ± 0.52 and 1.22 ± 0.57 W/Kg, respectively).

Side-Step Cutting Tasks

The knee flexion angles during the side-step cutting task were similar to the straight task; when averaged across both the anticipated and unanticipated conditions (**TABLE 3**), the subjects classified as noncopers used significantly lower knee flexion angles (noncopers compared to controls, 6.4° ± 5.2° and 11.4° ± 5.4°,

TABLE 3 Peak Knee Flexion Angle Measurements

Task/Analysis	Group	Initial Contact (0%-10%)	Loading Response (10%-20%)	Midstance (20%-50%)
STRAIGHT				
ST	Control	9.0 ± 4.6	27.1 ± 4.9	4.8 ± 5.1
	ACLD	5.1 ± 4.6	22.6 ± 4.2	4.4 ± 3.5
STU	Control	11.2 ± 4.7	29.6 ± 5.6	4.0 ± 5.6
	ACLD	6.7 ± 5.1	23.3 ± 5.5	3.7 ± 3.5
Analysis	Group	0.011*	0.002*	0.820
	Group × condition	0.277	0.067	0.874
SIDE-STEP CUTTING				
SSC	Control	10.9 ± 5.5	27.9 ± 5.8	5.1 ± 5.3
	ACLD	6.1 ± 4.9	24.3 ± 5.0	5.2 ± 5.3
SSCU	Control	11.8 ± 5.9	33.1 ± 8.2	6.0 ± 8.2
	ACLD	6.7 ± 4.6	26.8 ± 6.0	6.3 ± 6.0
Analysis	Group	0.007*	0.019*	0.931
	Group × condition	0.773	0.103	0.836

Abbreviations: ACLD, anterior cruciate ligament deficient; SSC, side-step cutting; SSCU, unanticipated side-step cutting task; ST, straight; STU, unanticipated straight.
** P<.05*

TABLE 4 Peak Knee Moments up to Midstance*

Task/Analysis	Group	Moments (Nm/kg): Initial Contact (0%-10%)	Loading Response (10%-20%)	Midstance (20%-50%)
STRAIGHT				
ST	Control	-0.65 ± 0.25	0.99 ± 0.33	-0.29 ± 0.16
	ACLD	–0.68 ± 0.26	0.62 ± 0.26	–0.28 ± 0.18
STU	Control	–0.63 ± 0.16	1.00 ± 0.38	–0.30 ± 0.17
	ACLD	–0.66 ± 0.26	0.75 ± 0.32	–0.28 ± 0.16
Analysis	Group	0.603	0.005†	0.857
	Group × task	0.543	0.079	0.663
SIDE-STEP				
SSC	Control	–0.51 ± 0.17	1.20 ± 0.44	–0.37 ± 0.18
	ACLD	–0.64 ± 0.27	0.70 ± 0.30	–0.32 ± 0.25
SSCU	Control	–0.45 ± 0.20	1.26 ± 0.39	–0.42 ± 0.29
	ACLD	–0.43 ± 0.27	0.76 ± 0.33	–0.47 ± 0.28
Analysis	Group	0.374	<0.001†	0.996
	Group × condition	0.117	0.996	0.258

Abbreviations: ACLD, anterior cruciate ligament deficient; SSC, side-step cutting; SSCU, unanticipated side-step cutting task; ST, straight; STU, unanticipated straight.
** Positive values, extensor; negative values, flexor.*
† P<.05

respectively) at initial contact (P = .007). The significantly (P = .019) lower knee flexion angles were sustained throughout the loading response (noncopers compared to controls, 25.5° ± 6.0° and 30.5° ± 6.4°, respectively); however, were similar to the controls by midstance (P = .931).

The means of the subjects classified as noncopers for the knee moment (**TABLE 4**) and power variables (**TABLE 5**) show differences from the controls during loading response and midstance. When averaged across anticipated and unanticipated conditions, the subjects classified as noncopers during loading response used significantly lower (P<.001) peak knee extensor moments (noncopers compared to controls, 0.73 ± 0.31 and 1.22 ± 0.34 Nm/Kg, respectively) and significantly higher (P<.001) peak negative power (noncopers compared to controls, –1.72 ± 1.37 and –3.36 ± 1.5 W/Kg, respectively) (**FIGURE 4**). Again, when averaged across anticipated and unanticipated conditions, the subjects classified as noncopers during midstance used significantly (P<.001) lower peak positive power (noncopers compared to controls, 0.55 ± 0.52 and 1.32 ± 0.57 W/Kg, respectively).

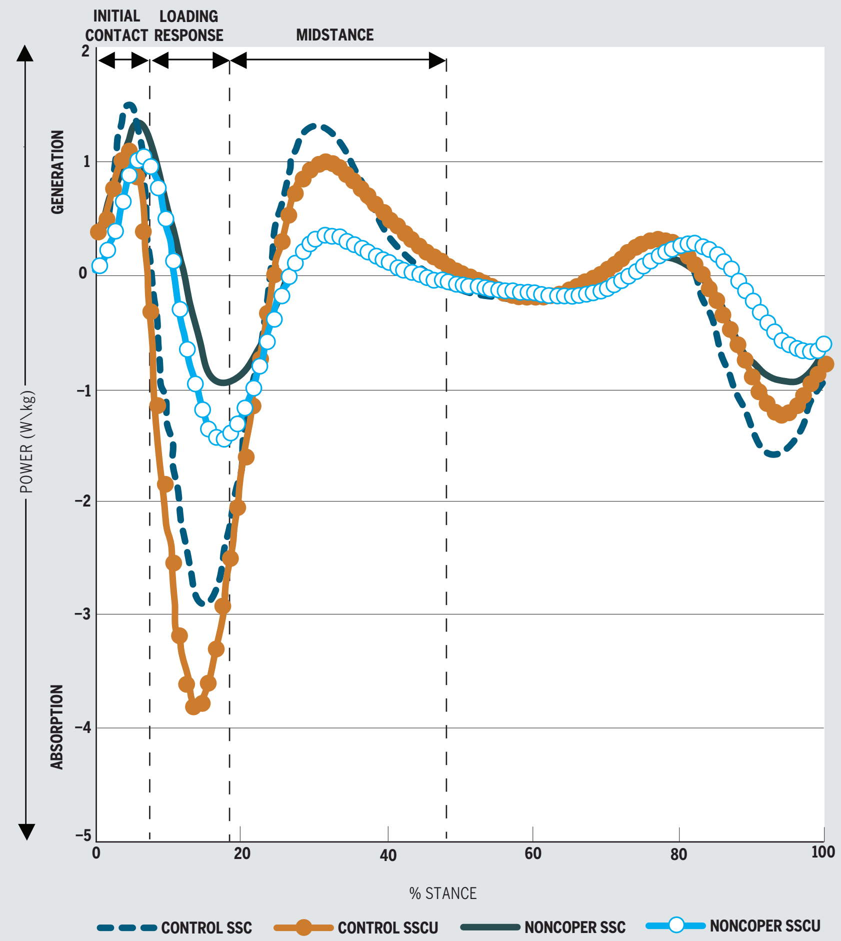

FIGURE 3. The knee joint sagittal plane power noncoper and control group during the side-step cutting tasks. Abbreviations: SSC, side-step cutting; SSCU, unanticipated side-step cutting task.

DISCUSSION

THE KEY FINDING OF THIS STUDY IS that subjects classified as noncopers show a limited ability to adjust their movement patterns to different task demands, as compared to controls. The noncoper subjects of this study demonstrated decreased knee angle and moment patterns similar to those previously reported by others.[21,19,32,33,35] New from this study is the observation that unanticipated tasks did not significantly influence the ability of the noncoper subjects to maintain a reduced knee angle, moment, or power pattern during either straight tasks or side-step cutting tasks. While this study evaluated straight tasks and side-step cutting tasks separately, the data suggest a trend for the noncoper subjects to maintain a decrease in joint load during each task and condition. For example, the subjects classified as noncopers maintained their knee power absorptions at less than 2.0 W/Kg, while the controls varied their knee power absorption up to 3.79 W/Kg (**FIGURE 4**). These findings support the main hypotheses that subjects classified as noncopers have a limited ability to modulate knee extensor loads independent of anticipation.

This is one of only a few studies[6,16] that examine the effect of anticipation on abnormal movement patterns in subjects with ACLD. In this study, the knee angles and moments show similar patterns of lower knee flexion angles and joint moments during loading response of both the anticipated and unanticipated tasks (**TABLE 3** and **4**). None of the dependent variables showed a significant dependence on group and condition, suggesting that unanticipated tasks did not exaggerate the response of the subjects with ACLD. Previous studies of the effects of anticipation on abnormal movement patterns are difficult to compare because they used moving force plates, did not include an anticipated task, and did not separate subjects with ACLD based on coping status.[6,16] Possibly relevant to this study is the timing of the electromyographic activity after initiation of forward plate movement.[6,7] In previous studies, the noncoper subjects activated their muscles within 60 to 129 milliseconds after initiation of plate movement.[7] This suggests that subjects classified as noncopers are able to implement an abnormal movement pattern within the planning time (time from visual cue to force plate contact), estimated at approximately 350 milliseconds, that occurred in the current study. Studies suggest that the causes of abnormal movement patterns in subjects classified as noncopers may be related to knee instability, deficits in knee strength, or deficits in neuromuscular control.

Lower knee flexion and knee extensor moments suggest a lower risk of anterior knee instability induced by the quadriceps muscle.[39] Biomechanical models predict that high patella tendon forces at knee flexion angles of less than 30° load the ACL.[38] However, muscle force is also affected by muscle length.[27] Consequently, lower knee flexion angles are associated with decreased capacity of the knee extensors to generate tension. Muscle modeling studies do not clearly indicate if the lower knee flexion angles of the noncoper group (3.6° to 6.3° lower) during the loading response, compared to controls, would be enough to influence patella tendon force.[27,39] In contrast, the knee extensor moments, which are lower in the noncoper group by 0.25 to 0.50 Nm/kg, suggest a net decreased agonist contribution of the quadriceps muscle.[39,46] The difference in knee joint power absorption is even more marked, with less knee extensor energy absorption of 0.62 to 1.86 W/kg (**TABLE 4** and **FIGURE 4**) in the noncoper group compared to controls. Decreased contribution of the knee extensors combined with increased hamstrings contribution, as noted in some studies,[32,35] may provide greater knee stability.[39] This has led some to describe this movement pattern as a joint stiffening strategy that results in higher joint compressive forces.[32,33] An alternative or complementary hypothesis to the abnormal movement pattern of the noncopers being solely associated with minimizing knee instability is that these subjects fail to learn to modulate knee extensor loads due to neuromuscular control deficits.

A key feature of the noncoper group of this study is the inability of these subjects to vary their knee joint energy absorption (eccentric action), followed by an energy generation (concentric action) during the loading response. Loading response and midstance are characterized by a knee extensor power absorption followed by a power generation (**FIGURE 3**). During the loading response of both the straight tasks (ST/STU) and side-step cutting tasks (SSC/SSCU), the noncoper subjects maintain a lower knee power absorption compared to the controls (**FIGURE 4**). The subjects classified as noncopers maintain a knee power absorption of less than 2 W/Kg across straight and side-step cutting tasks, in contrast to the controls, who exceeded 2.9 W/Kg during both the SSC and SSCU tasks (**FIGURE 4**). The abnormally low power absorptions of the noncoper group are followed by markedly decreased energy generation at midstance during both the straight and side-step cutting tasks (**TABLE 5** and **FIGURE 3**). These effects on the knee joint powers are attributable to the noncopers maintaining a common strategy of reduced knee joint power irrespective of anticipation. This failure to modulate the knee extensors during loading response and midstance suggests an inability to modulate knee extensor loads.

Studies identifying the contribution of quadriceps muscle atrophy and volitional activation to knee extension strength deficits in subjects classified as noncopers suggest their potential influence on abnormal movement patterns.[9,42-44] Consistent with findings by Eastlack et al,[14] the noncopers in this study demonstrated isometric strength deficits compared to controls. However, these strength deficits varied widely (**TABLE 1**). A recent study suggests that strength deficits may influence movement patterns, Patel et al[29] reporting a weak link (r = 0.56) between isometric knee extensor strength and knee extensor moments. Yet, studies of subjects with and without strength deficits suggest that strength deficits alone do not account for the decreased knee extensor kinetics (moments and powers) observed in this study.[19,25] Williams et al[45]

TABLE 5 PEAK KNEE POWER UP TO MIDSTANCE*

TASK/ANALYSIS	GROUP	POWER (W/kg) INITIAL CONTACT (0%-10%)	LOADING RESPONSE (10%-20%)	MIDSTANCE (20%-30%)
STRAIGHT				
ST	Control	2.07 ± 0.67	–1.99 ± 0.89	1.25 ± 0.64
	ACLD	1.60 ± 0.56	–1.08 ± 0.83	0.68 ± 0.54
STU	Control	2.15 ± 0.86	–1.86 ± 1.11	1.19 ± 0.70
	ACLD	1.75 ± 0.65	–1.24 ± 0.81	0.80 ± 0.29
Analysis	Group	0.065	0.013†	0.01†
	Group × task	0.578	0.181	0.261
SIDE-STEP				
SSC	Control	1.88 ± 0.64	–2.92 ± 1.67	1.40 ± 0.79
	ACLD	1.79 ± 0.76	–1.50 ± 0.99	0.57 ± 0.40
SSCU	Control	1.67 ± 0.87	–3.79 ± 1.89	1.24 ± 0.68
	ACLD	1.54 ± 0.71	–1.93 ± 1.18	0.53 ± 0.43
Analysis	Group	0.001	<0.001†	<0.001†
	Group × task	0.314	0.183	0.580

Abbreviations: ACLD, anterior cruciate ligament deficient; SSC, side-step cutting; SSCU, unanticipated side-step cutting task; ST, straight; STU, unanticipated straight.
** Positive values, generation; negative values, absorption.*
† $P<.05$

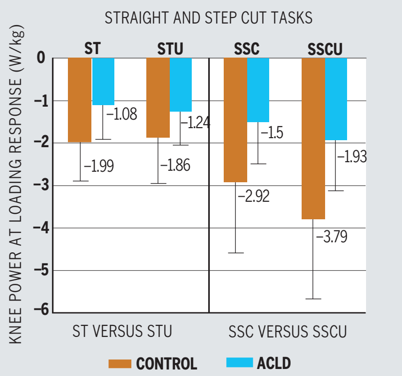

FIGURE 4. The mean (±1 SD) of the peak knee power absorption for the noncoper group and control group. Abbreviations: SSC, side-step cutting; SSCU, unanticipated side-step cutting task; ST, straight; STU, unanticipated straight.

showed that decreases in vasti muscle volume and volitional activation in subjects classified as noncopers explained 65% of knee extensor strength deficits. Because knee extensor strength alone does not explain abnormal movement patterns, neuromuscular control deficits are hypothesized to contribute. These studies together suggest a hypothesis that both weakness and neuromuscular control deficits contributed to the inability of the subjects in this study to modulate their knee extensor loads during anticipated and unanticipated tasks.

The influence of time from injury and specific clinical variables on movement patterns is not clear. All subjects in this study were free from joint swelling and range-of-motion deficits, and were able to hop in place without pain, ensuring that subjects were in the subacute phase of injury. Whether or not subjects may alter their movement patterns further after the subacute phase of injury is unclear. For example, some studies have suggested that abnormal movement patterns evolve over time,[41] while others have not.[21] The variability of the clinical variables listed in **TABLE 1** are a result of the classification scheme which emphasizes that failure to meet any one of the criteria based on self-report (eg, KOS-ADL Scale), hopping ability, or giving way results in classification as a noncoper. It is unclear how each clinical variable alone contributes to differences in movement patterns.

Clinical Significance

The abnormal movement patterns of subjects classified as noncopers are assumed to be less optimal than movement patterns adopted by subjects classified as copers. While the results of this study would be clearer had subjects classified as copers been included, studies suggest the movement patterns defined by joint angles and moments of copers are similar to controls.[32-35] While others suggest increased knee flexion angles and minimally decreased knee extensor moments,[1,40] all studies suggest that the knee extensor loads are less affected in copers compared to noncopers.[1,19,32,34,35,40] These results[1,19,32,34,35,40] place emphasis on training subjects to improve their ability to modulate knee extensor loads. Although some studies attempted to evaluate activation patterns of copers with training,[5] there is a lack of data on whether surgery or therapy is able to affect the movement patterns of subjects classified as noncopers. There is some evidence that movement patterns of subjects after ACL reconstruction remain distinct from controls.[11-13,16] However, it is unclear if these subjects would be considered noncopers and if noncopers would react differently to reconstruction.

The data from this study suggest that the ability of subjects classified as noncopers to vary their knee extensor load is limited. Therefore, improved ability of noncopers to modulate knee extensor load during a variety of tasks (anticipated and unanticipated cutting tasks) may indicate improved function. Theoretically, the abnormal movement patterns observed in this study are partially attributable to atrophy and neuromuscular control deficits of the knee extensors. Because of the focus on neuromuscular deficits, the development of techniques that may restore volitional control, such as perturbation training,[8] may be important in improving abnormal movement patterns.

CONCLUSIONS

THIS STUDY EXTENDS PREVIOUS STUDIES of abnormal movement patterns of subjects classified as noncopers after ACL injury by documenting a consistent abnormal movement pattern associated with anticipated and unanticipated tasks. The consistency of the subjects classified as noncopers across anticipated and unanticipated tasks leads to the hypothesis that these subjects are constrained to a single movement pattern independent of anticipation. Subsequent studies should target clinical methods that may alter abnormal movement patterns in subjects classified as noncopers.

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