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Giving Way Event During a Combined Stepping and Crossover Cutting Task in an Individual With Anterior Cruciate Ligament Deficiency

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Study Design: Case study.
Objective: To compare knee kinematics and moments of nongiving way trials to a giving way trial during a combined stepping and crossover cutting activity.
Background: The knee kinematics and moments associated with giving way episodes suggest motor control strategies that lead to instability and recovery of stability during movement.
Methods and Measures: A 27-year-old woman with anterior cruciate ligament deficiency reported giving way while performing a combined stepping and crossover cutting activity. A motion analysis system recorded motion of the pelvis, femur, tibia, and foot using 3 infrared emitting diodes placed on each segment at 60 Hz. Force plate recordings at 300 Hz were combined with limb inertial properties and position data to estimate net knee joint moments. The stance time, foot progression angle, and cutting angle were also included to evaluate performance between trials.
Results: Knee internal rotation during the giving way trial increased 3.2° at 54% of stance relative to the nongiving way trials. Knee flexion during the giving way trial increased to 33.1° at 66% of stance, and the knee moment switched from a nominal flexor moment to a knee extensor moment at 64% of stance. The knee abductor moment and external rotation moment during the giving way trial deviated in early stance.
Conclusions: The observed response to the giving way event suggests that increasing knee flexion may enhance knee stability for this subject. The transverse and frontal plane moments appear important in contributing to the giving way event. Further research that assists clinicians in understanding how interventions can impact control of movements in these planes is necessary.

Key Words: *anterior cruciate ligament deficiency, kinematics, knee kinetics*

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An isolated anterior cruciate ligament (ACL) rupture does not result in a predictable functional outcome.[6,7,17,19,22,23,43,51,68] In an early study, Noyes et al[51] reported variable return to function in subjects with ACL deficiency 5.5 years after the initial injury. Noyes et al suggested approximately one third of subjects with ACL deficiency report the ability to participate in high level sports, including twisting and turning, one third report moderate limitations during sports, and one third report the inability to participate in sports. Recently, Fitzgerald et al[23] provided evidence that a collection of information, including isometric knee extensor strength, response of a self-report scale, a global rating of knee function, and the number of giving way episodes, was useful for selecting subjects who may eventually learn motor control strategies that limit their knee instability and, therefore, may successfully avoid reconstructive surgery.

However, the necessary successful motor control strategies to prevent giving way episodes in subjects with ACL deficiency remain a focus of debate.[20,31,60] Studies suggest that the hamstrings may act as an ACL synergist during functional activities.[5,7,12,20,63,65,68] Others suggest strong quadriceps contractions near 20° of knee flexion are avoided because of anterior shear forces.[2,3,8,35,69] The combination of increased hamstring activity and quadriceps avoidance may explain why some studies reported a decreased knee extensor moment at 20% of stance during walking,[2,3,8,35,69] while other studies suggested little or no change in the knee extensor moment at 20% of stance during walking[13,21,31,34,59,60] and stepping[3,41] (the stance phase is from ipsilateral heel strike, 0%, to ipsilateral toe off, 100%). The disparity of results may arise from differences in motor control strategies among subjects with ACL deficiency[7,20,23,31,34,60,68,69] and the focus on a low-demand straight ahead activity, rather than on high-demand turning activities. For example, prospective studies of subjects with ACL deficiency who had more than 3 years of follow-up consistently report that jumping and turning maneuvers are at least mildly difficult in 56–86% of subjects.[6,19,51] In contrast, straight ahead activities, such as walking and using stairs, were rated mildly difficult in only 6–28% of subjects with ACL deficiency.[6,19,51]

In addition, specific types of cutting activities are potentially more challenging than others. Studies hypothesize that cutting tasks are unique in that subjects must decelerate to change direction of the trunk, then accelerate toward the new plane of progression.[1,18] Both crossover and sidestep cutting maneuvers require eccentric quadriceps activity in early stance.[18] Subjects with ACL deficiency show decreased eccentric knee extension peak torque during isokinetic testing,[61] suggesting possible adaptations during early stance. However, clinical measures of laxity and strength have been poorly associated with functional scores of subjects with ACL deficiency.[22] The type of cut may play a role, as indicated by Tibone et al[64] who observed that subjects with ACL deficiency tolerated a sidestep cut, but over 40% refused to perform a crossover cut because of fear of injury. Clinically, the laxity observed during a pivot shift test, which includes increased knee internal rotation and anterior tibial translation,[14,47,49,50] is thought to reproduce what might occur during a giving way episode.

The knee kinematics of a crossover cut appear consistent with the pivot shift test and in vitro tests that reflect substantial ACL load.[1] A crossover cut is a change in direction maneuver that involves placing the swing leg over the stance leg toward the new plane of progression, forcing the knee to internally rotate.[1] A crossover cut performed at a maximum running speed and a high cutting angle (90°) results in large transverse plane moments,[52] thus adding to the rotational stresses at the knee. In vitro studies confirm that internal rotation moments elevate ACL stresses[46] and strains.[4] While empirical and theoretical evidence show the crossover cut to be problematic for subjects with ACL deficiency, no studies have documented the knee biomechanics in subjects experiencing giving way sensations to confirm the possible association between the cutting maneuver and the pivot shift test.

Underlying this lack of evidence are the difficulties in measuring knee transverse plane angles, which precludes valid assessments of giving way because errors associated with femoral rotation exceed 100% of the motion.[15,25,55–57] However, a new femoral tracking method may significantly reduce the errors associated with transverse plane rotations (RMS errors ± 2°).[32,73] This method was used in a large study of subjects with ACL deficiency performing a stepping and crossover cutting activity.[31] During this larger study, 1 subject reported experiencing a giving way episode. The purpose of our case study is to compare the knee angles and moments of stance during a stepping and crossover cutting activity for the trials in which the subject did not experience giving way and the trial in which the subject did experience a giving way sensation. The knee angles and moments before the instability occurred suggest possible movements that contributed to the giving way event. Those knee angles and moments that occurred concurrent with or after the giving way suggest possible strategies that subjects might use to regain knee stability.

METHODS

Subject

The subject was a 27-year-old woman, 1.62 meters tall, weighing 72.7 kilograms, with a ruptured left ACL (Table). In addition to the clinical variables described in the Table, knee flexor and extensor torque were assessed using a Cybex II dynamometer (Lumex Inc, Ronkonkoma, NY) at 60°/s. After 5 submaximal, reciprocal knee extension and flexion movements, the subject was given a 1-minute rest and then performed 3 consecutive maximum efforts. The isokinetic strength tests revealed a knee extension limb symmetry index of 92% and a knee flexion limb symmetry index of 88.5% (limb symmetry index = involved/uninvolved × 100). Clinically, the subject had a positive Lachman and pivot shift test only on the left, suggesting left anterior and anterolateral instability.[26,49] Varus and valgus knee stress tests on the left and right were negative for instability at 0° and 30° of knee flexion. The subject consented to participate in the study in accordance with a protocol approved by the Institutional Review Board at the University of Iowa, Iowa City.

TABLE. Subject description.

Variable	Response
Chief complaint	Intermittent diffuse aching-type left knee pain (pain intensity* = 2/10)
Giving way	Frequent episodes of giving way (> 30 over the last 3 years)
Mechanism of injury	Planting and cutting during basketball in spring of 1996
Initial signs and symptoms associated with injury	Swelling for less than 24 hours; pain and decreased knee range of motion
Treatment history	Ice, elevation, knee extension brace for 1–2 weeks; failed to follow-up for additional treatment
Current sports activity level	Biking 3–6 h/wk, 16–20 wk/y; volleyball 2 h/wk, 16 wk/y
Modified Noyes questionnaire[70]	84%†
Lysholm scale[44]	80%†
Global question of knee function[70]‡	75%†

* Response to: "If I had to give my knee pain a grade from 0–10, with 10 being the worst, I would give my knee pain a ____."
† Higher scores indicate increased function.
‡ Response to: "If I had to give my knee a grade from 1–100, with 100 being the best, I would give my knee a ____."

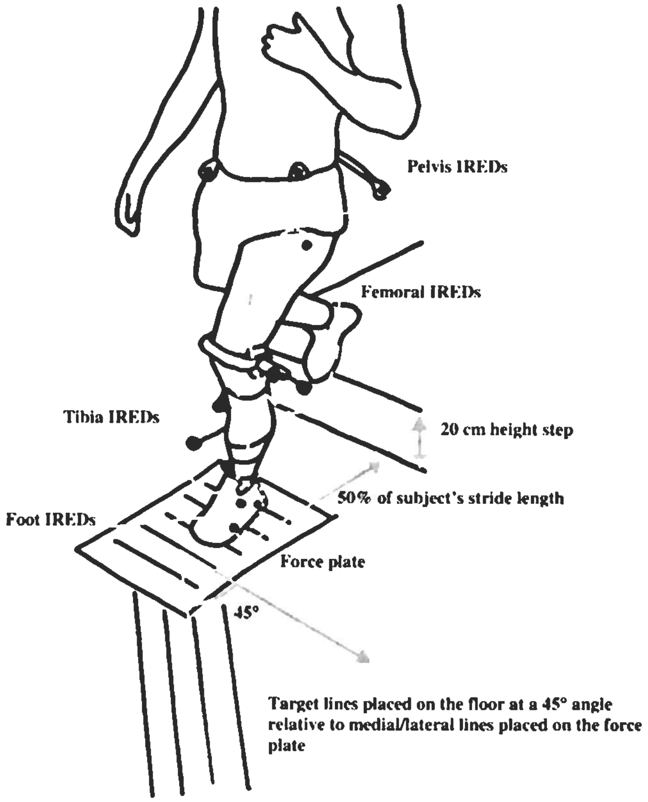

FIGURE 1. Three infrared emitting diodes (IREDs) were placed on the foot, leg, thigh, and pelvis to track each segment as the subject performed the crossover cut task. The 3 IREDs used to represent the foot were placed just posterior to the fifth metatarsal head, near the dorsum of the foot, and posteriorly toward the heel. All the IREDs used to track the tibia were placed along the anterior border of the tibia: 1 distal, 1 proximal, and 1 extending 10 centimeters anteriorly on an aluminum rod. The IREDs used to track the femur included 2 IREDs placed on a device that clamped onto the femoral condyles and a marker placed approximately 5 centimeters distal to the greater trochanter. The markers used to track the pelvis include a marker placed on a wand that was secured to the posterior sacrum and a marker placed adjacent to the left and right anterior superior iliac spines. The figure also shows how the step was placed relative to the force plate and the target lines used to monitor whether subjects successfully completed the 45° crossover cutting activity.

Instrumentation

A 4-segment model of the lower extremity (Figure 1), including the foot, leg, thigh, and pelvis, was used to estimate joint displacement and moments in 3 dimensions consistent with previous studies.[31–33,39,73] Unique to this study was a new approach to tracking the thigh segment[31,32] that was recently shown to produce knee angles (± 2°) similar to bone mounted markers in a single subject.[73] The new approach uses 2 infrared emitting diodes (IREDs) placed on a femoral tracking device and 1 IRED placed 10 centimeters distal to the greater trochanter (Figure 1).

The IREDs were tracked at a sampling rate of 60 Hz using an Optotrack 3020 Motion Analysis System (Northern Digital, Inc, Waterloo, Ontario, Canada). Based on a residual analysis,[71] the position data were filtered at 6 Hz with a fourth order Butterworth zero phase lag digital filter prior to calculating joint angles and moments. Each activity required subjects to land on a Kistler Model 9865 B force plate (Instrument Corp, Amherst, NY) mounted in the floor. The ground reaction force data were sampled at 300 Hz and subsequently low pass filtered using a fourth order Butterworth zero phase lag filter with an 8 Hz cutoff frequency. This cutoff frequency also was established using a residual analysis technique.

After filtering, the ground reaction force data were combined with anthropometric and position data to calculate an inverse dynamic solution to estimate net internal joint moments at the ankle, knee, and hip.[12,71] The convention of reporting internal joint moments in the reference frame of the distal segment was adopted to reflect the muscle contributions in response to an external load.[71] Inertial properties and segment mass were estimated using a previously published protocol.[74] The 1995 Kingait3 Version 1.6 software package (Mishac Kinetics, Waterloo, Ontario, Canada)[37] was used to filter and process joint angles[28,72] and net joint moments.[12,71] All kinetic and kinematic patterns were normalized to percent stance duration where 0% was heel strike and 100% was toe off.

Procedures

The testing procedure required the subject to complete 4 different activities: (1) walking, (2) stepping down off a 20-centimeter high curb, (3) walking and cutting at a 45° angle, and (4) stepping down and cutting at a 45° angle.[31,33] All tasks were performed at the same walking speed of 1.34 m/s, controlled by requiring the subject to keep pace with an overhead tracking system. The walking platform was 5.0 meters long, 0.9 meters wide, and 0.21 meters above the floor, which allowed for 3 to 4 approach strides before stepping down. Only the 4th activity, stepping and cutting, is reported in this paper. The distance of the step from the center of the force plate was 50% of the subject's stride length. The cutting angle was controlled by requiring the subject to land on the force plate and place her crossover foot on a target at a 45° angle with the force plate (Figure 1). The target consisted of colored tape placed at a 45° angle from the plane of progression, which provided feedback of foot placement.

Foot placement onto the force plate was required to meet 2 criteria: (1) the heel was required to strike the force plate before the toe and (2) the subject was coached to keep the stance foot angled in line with the plane of progression. The foot-landing strategy was manipulated to decrease variability across subjects in the knee kinematics and moments, and hence enhance power to detect group differences in the larger study.[31] The subject was given at least 10 practice trials and was required to successfully perform at least 5 trials before starting the data collection. During the initial 4 trials of the stepping and cutting activity, the subject did not experience a sensation of giving way. When the subject completed the fifth stepping and cutting maneuver trial, she stated she had felt her knee give way during the trial. Subsequently, this trial was designated as "the giving way trial."

The performance of the crossover cutting task was evaluated by measuring the foot progression angle and cutting angle. The foot progression angle was the angle formed by the anterior/posterior axis of the foot relative to the global anterior/posterior axis (x-axis) taken immediately following foot flat in the transverse plane (x-z plane). The cutting angle was the angle formed by the medial/lateral axis (z-axis) of the pelvis with the global medial/lateral axis (z-axis) at toe off in the transverse plane (x-z plane).

RESULTS

The stance phase of the giving way trial was shorter (0.58 s) compared to the average of the nongiving way trials (0.64 ± 0.01 s). However, the foot progression angle (16°) and cutting angle (47.4°) of the giving way trial were comparable to the average foot progression angle (12.8 ± 1.9°) and cutting angle (44.2 ± 2.9°) of the nongiving way trials.

The transverse plane angles of the knee during the giving way trial varied from 16–22% and from 42–80% of stance duration when compared to the nongiving way trials (Figure 2A). For the nongiving way trials, knee internal rotation peaked at 50–80% of stance at 9.4 ± 0.6°. During the giving way trial, knee internal rotation peaked at 54% of stance at 12.6°, a difference of 3.2° (> 2 standard deviations) relative to the peak knee internal rotation of the nongiving way trials.

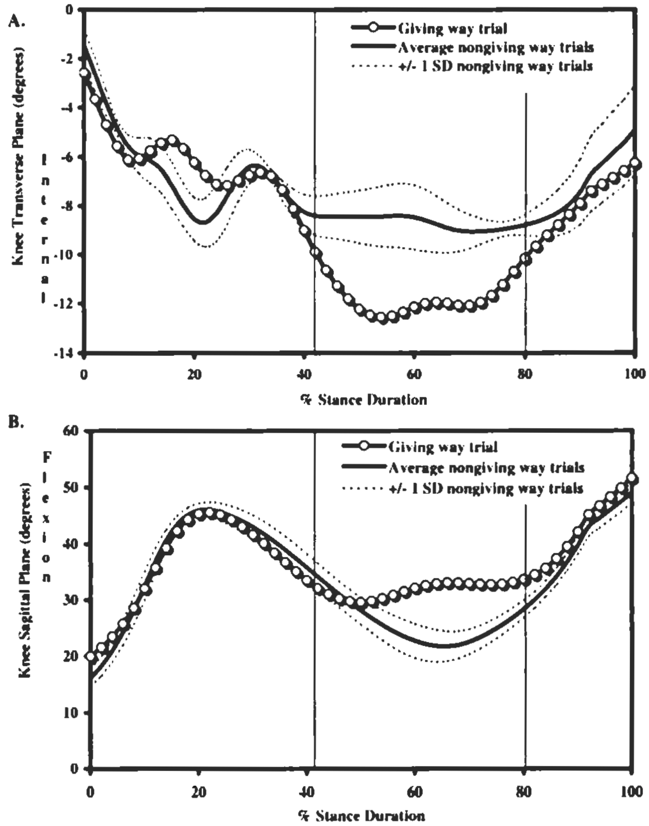

FIGURE 2. (A) The transverse plane tibiofemoral angles for the giving way and nongiving way trials across stance. The giving way trial displayed increased tibiofemoral internal rotation from 42–80% of stance duration, demarcated by the vertical lines. (B) The sagittal plane tibiofemoral angles for the giving way and nongiving way trials across stance. The vertical lines match when knee internal rotation was increased during the giving way trial (42–80% of stance duration). Notice that the increase in knee flexion occurs approximately 6–8% of stance duration after the knee begins to rapidly internally rotate.

During the giving way trial, knee flexion increased to 33.1° at 66% of stance duration compared to 21.6 ± 2.2° for the nongiving way trials (Figure 2B). During the nongiving way trials, there was a nominal knee flexor moment of −0.04 ± 0.08 N-m/kg at 65% of stance duration compared to a knee extensor moment of 0.38 N-m/kg during the giving way trial (Figure 3A).

The knee abductor moment during the giving way trial at 20% of stance duration was decreased 25% relative to the nongiving way trials (Figure 3B). The nongiving way trials peaked at 1.27 ± 0.08 N-m/kg at 20% of stance duration compared to 0.96 N-m/kg during the giving way trial. The nongiving way trials reached a minimum abductor moment of 0.24 ± 0.05 N-m/kg at 60% of stance duration compared to 0.39 N-m/kg (a 40% increase) during the giving way trial (Figure 3B).

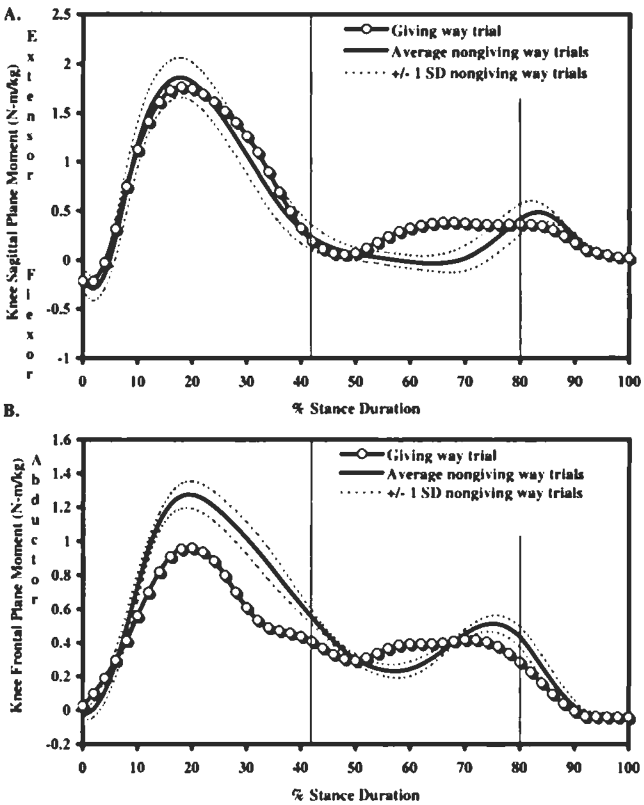

FIGURE 3. (A) The knee sagittal plane moments for the giving way and nongiving way trials across stance. The vertical lines mark the frames that match when knee internal rotation was increased during the giving way trial (42–80% of stance duration). (B) The knee frontal plane moments for the giving way and nongiving way trials across stance. The vertical lines mark the frames that match when knee internal rotation was increased during the giving way trial (42–80% of stance duration).

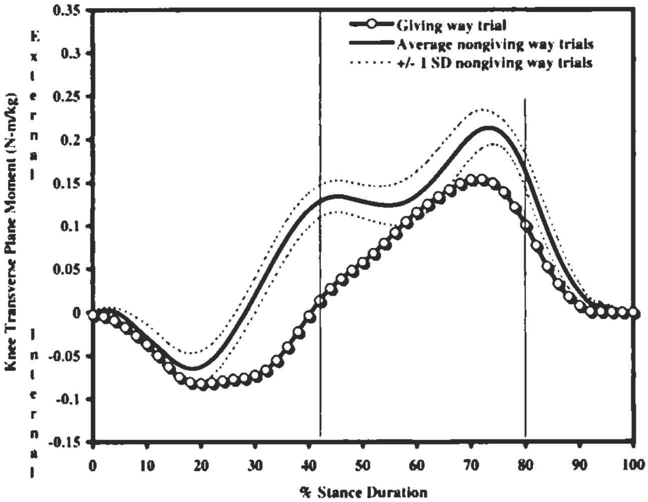

FIGURE 4. The knee transverse plane moments for the giving way and nongiving way trials across stance. The vertical lines mark the frames that match when knee internal rotation was increased during the giving way trial (42–80% of stance duration).

The transverse plane knee moment pattern suggested an initial internal rotator moment peaking at 20% of stance duration followed by a peak external rotator moment at 74% of stance duration (Figure 4). The point at which the knee moment switched from an internal to an external moment was 42% of stance duration for the giving way trial compared to 26% for the nongiving way trials. At 45% of stance duration during the nongiving way trials, the knee external rotator moment reached a peak of around 0.14 ± 0.02 N-m/kg.

DISCUSSION

To our knowledge, the data presented in this paper is unique, representing the first biomechanical analysis of a giving way episode. While it is possible to identify the giving way episode, as evidenced by the increased internal rotation of the knee, it is more difficult to identify the precise time the event was initiated. The first evidence of knee dysfunction is seen as early as 10–30% of stance duration in the abductor moment and the transverse plane angles and moments. However, it is not until about 42% of stance duration that there is clear evidence of a giving way episode via the increased internal rotation angle (Figure 2A). The increased knee internal rotator moment and decreased knee abductor moment preceded the increased knee internal rotation angle, suggesting this combined loading pattern may have contributed to the giving way event. The sagittal plane angles and moments lag transverse plane movement into greater internal rotation by about 6–8%, suggesting this is a response to the giving way event and not a cause of the event.

The kinematics of the giving way event are partially consistent with the instability observed during a pivot shift test.[14,47,49,50] The increased knee internal rotation of 3.2° was 2 standard deviations greater than the other 4 trials and distinguished the giving way event, similar to in vitro simulations of the pivot shift test.[14,47,49,50] The increased knee internal rotation began at 42% of stance duration when the knee flexion angle was 32°. This corresponds to the point at which internal rotation peaks in some studies during a pivot shift maneuver.[47,49]

Knee internal rotation increased after 42% of stance duration and then reached a plateau at 12.6° at 54% of stance duration (Figure 2A), which corresponded to a period of 70.0 ms (70.0 ms = 0.12 × 583 ms). Pope et al[53] suggested a voluntary response to an external perturbation took approximately 180–215 milliseconds, which is significantly longer than the quick internal rotation that occurred during the giving way trial. This suggests that a reflex response was necessary to control giving way. For example, the sagittal plane angles (Figure 2B) and moments (Figure 3A) of the giving way trial deviated from the nongiving way trials at approximately 50% of stance duration, 8% after the rapid increase in internal rotation began and before the peak internal rotation was reached at 54% of stance duration.

The knee sagittal plane moment at 66% of stance duration of the giving way trial was an extensor moment, not a flexor moment as observed during the nongiving way trials (Figure 3A). The net joint moments reported in this paper are internal moments, which reflect the minimum agonist contribution necessary to maintain equilibrium at a joint.[71] At 66% of stance duration during the nongiving way trials, the agonist is the knee flexors, which theoretically control knee transverse plane movements. However, during the nongiving way trials, the subject did not take advantage of this typical knee flexor moment pattern to control her knee instability. Rather, to regain control, she adopted a flexed knee posture and knee extensor moment, which required a net contribution of the knee extensors.

This is a surprising finding since 2-dimensional modeling studies of the knee extensor mechanism suggest larger anterior shear forces on the tibia at knee angles less than 60°,[16,30,31,36,40,58,62,66,67] which would potentially aggravate the instability. A limitation of net joint moments is that they do not account for antagonist muscle contributions during periods of co-contraction.[71] Therefore, the amount of co-contraction of the hamstrings is unknown during midstance of this stepping and cutting task, particularly during the giving way trial. Studies using electromyography are necessary to clarify the muscle activation patterns associated with this activity. Some authors have interpreted increased knee flexion, which occurred in this subject, as placing the hamstrings at a mechanical advantage to control translation[7,20,36] and, by inference, tibial rotation.[11] However, there is a trade-off; as the hamstring contribution increases, the knee extensor contribution must also increase to achieve the same knee extensor moment.[2,16,40] The consequence of this type of strategy is increased joint reaction forces and energy cost.[2,71]

Alternatively, recent studies of ACL strain suggest a different rationale for why subjects with ACL deficiency might adopt a flexed knee posture to regain control of knee rotation. In vivo studies[9,24] of ACL strain during stepping and squatting suggest that the role of the ACL is diminished at knee flexion angles of greater than 25°, with control of knee rotation attributed to other soft tissues.[4,9,24,46] If the same pattern applies to stepping and cutting activities, adopting a flexed knee posture may move the knee to a position where knee stability is not dependent on the ACL and compensatory hamstring co-contraction is unnecessary.

The peak knee abduction moment of the giving way trial decreased 30% relative to the nongiving way trials near 20% of stance duration (Figure 3B). Associated with the decreased knee abduction moment was a prolonged knee internal rotator moment (Figure 4). During the nongiving way trials, the external rotator moment that occurred near 40% of stance duration may have acted to prevent a giving way event. The peak knee internal rotation angle of the giving way trial coincided with the peak knee external rotator moment of the giving way trial, suggesting the external rotation moment acted to control knee motion. Both passive (noncontractile) mechanisms [10,29,38,42] and active mechanisms (muscle actions)[7,11,68] may have contributed to this external rotator moment.

Understandably, previous studies of straight ahead activities have focused on knee loads during weight acceptance as potential causes of a giving way event;[2,18,48,60] however, our data suggest that a crossover cutting activity challenged this subject with ACL deficiency. The stepping and cutting activity used in our study was significantly less demanding than a maximum running speed 90° crossover cut;[52] however, the number of trials may have contributed to fatigue. Nyland et al[52] reported alterations in the knee moments associated with fatigue and subsequently hypothesized that fatigue was a potential contributing factor to knee injury.[52] It is possible that the number of trials prior to the giving way may have induced fatigue and, therefore, predisposed this subject to knee instability.

Clinical Relevance

Clinically, training programs have proposed various approaches to improve the function of patients who opt to not have reconstructive surgery;[23,27,43,45,75] however, the success of these programs remains controversial.[20] The giving way event experienced by the subject suggests training programs that incorporate control of 3-dimensional loading patterns may have a greater chance for success than programs that primarily focus on sagittal plane control. Activities that may challenge the subject to control frontal and transverse plane loads include perturbation training,[23] figure-of-eight maneuvers,[45] and sidestep shuffle maneuvers.[43] Also, increasing knee flexion in the subject was associated with regaining control of knee instability. This observation lends support to the recommendation that increasing knee flexion during exercise may help subjects to control knee motion.[7,20]

Because this is a case study, no attempt was made to represent the subject's response as typical.[54] In fact, the number of giving way episodes experienced by the subject is extreme (> 30),[23] suggesting that the patient's response to her ACL injury may be unique. However, case studies are useful for exploratory research,[54] and our study may form the basis for hypotheses related to the knee kinematics and moments associated with giving way events.

CONCLUSION

The period of stance during which this subject experienced a giving way event was unique and suggests that previous models of giving way potentially neglect an important phase of loading that occurs during a crossover cutting activity. The subject of our case study adopted a flexed knee posture and knee extensor moment in response to the giving way event. Clinically, this suggests that moving to a knee flexed posture and a knee extension moment may help subjects to control knee motion during a crossover cutting maneuver. The frontal and transverse plane moments are potentially important for causing such giving way events to occur, and, therefore, prevention of giving way events may require control of motion in the transverse and frontal planes. These observations were made on a single subject, and future research is necessary to confirm the association of these patterns with giving way.

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Invited Commentary

In their case study,[7] Dr Houck and Dr Yack have provided a thorough kinetic analysis of a single subject with ACL deficiency during a combined step down-crossover cut task. During the last of 5 step down-crossover cuts, the subject displayed a giving way episode similar to that which she had experienced more than 30 times over the 3 years following ACL injury.

My first concern is whether we really know enough about this individual to effectively interpret the detailed biomechanical data that was reported. What do we know about the true functional status of this subject? Although she participates in biking about 35% of the year and plays volleyball about 31% of the year, biking minimally stresses the ACL, and volleyball-related stresses vary considerably depending upon the competitive level. Because it is unlikely that either of these activities stress the knee in the same manner as basketball, I am led to believe that she has modified her recreational activities to minimize her disability level.

Her report of a minimal pain level suggests that her disability level is also minimal; however, we do not know the context of the pain level assessment question. I assume the rating represented her knee pain level prior to biomechanical data collection. Would the subject have responded differently if the question had been more specific to the more than 30 giving way episodes she has experienced? The composite scores reported on the modified Noyes, Lysholm, and Global rating scales each combine function and symptoms data, making it difficult to relate the detailed biomechanical test results to specific functional events. Was consideration given to performing a correlational analysis of isolated functional activity scores and specific biomechanical parameters?

We know that the subject had bilateral isokinetic knee extensor and flexor torque symmetry of 92% and 88.5% respectively, but we do not know what the actual torque values were. Sequelae from the initial ACL injury, the lack of a structured, supervised rehabilitation program, and modifications in recreational activity and competitive level over the 3-year post-injury period may all have contributed to bilateral lower extremity strength, power, and endurance deficits, thus making bilateral comparisons of limited value. Others have reported that the quadriceps femoris muscle group provides a vital ground reaction force attenuating service during the impact of early stance phase and may[1] or may not[11] be inhibited following ACL injury. While isolated isokinetic tests are certainly of value, tasks such as the single leg hop-for-distance would have provided both a functionally relevant clinical assessment of composite lower extremity sagittal plane movement and insight into the possibility of associated dysfunction at other stance phase knee joint extensors (hip extensors, ankle plantar flexors).

With positive Lachman and pivot shift tests, I am assured of ACL deficiency; however, I am unsure about the extent of other tissue impairments. Was there any evidence of associated meniscal or patellofemoral dysfunction? Without this information, which could have been provided by additional clinical examination tests, magnetic resonance imaging, or arthroscopic confirmation, I cannot be assured that isolated ACL deficiency and its sequelae were the sole contributing factors. Based on the clinical examination information provided and the subject's history of more than 30 episodes of giving way over the 3-year post-injury period despite modifying her recreational activities, I suspect that the condition of the subject's left knee has increased her disability level. As the authors suggest, she is not a "coper."[6] Also, in my opinion, she is slow to acquire a "quadriceps femoris avoidance" gait pattern,[1,3,4] possibly because she avoids situations that might elicit a pivot shift response, such as the step down-crossover cut task.

The combination of stepping down from an 8.25-inch step and performing a crossover task is not common to athletics but does simulate many activities common to daily living. The authors are to be commended for using an improved femoral tracking method without the error of excessive thigh soft tissue movement. The giving way episode occurred during the last trial of the last of 4 tasks performed by the subject. All tasks were performed at 1.34 m/s (a slow walking pace). At the instant of giving way, the subject had performed at least 60 trials. Fatigue may have been a factor, but we cannot be sure. Additional information provided by a more detailed clinical examination, electromyographic signal analysis, physiological testing, or perceived exertion scale data would have better delineated the potential influence of neuromuscular fatigue on this subject.

Detailed analysis of stance phase kinetics revealed some distinct differences between the last step down-crossover cut task trial and the mean values for the other 4 trials. The foot progression angle of 16° for the giving way trial versus a $12.8 \pm 1.9°$ angle for the other trials was considered comparable; however I suspect the subject may have assumed a more externally rotated leg position in an attempt to better facilitate quadriceps femoris activation at stance phase initiation during this trial. This is supported by the switch from a nominal knee flexor moment of −0.04 ± 0.08 N-m/kg to a knee extensor moment of 0.38 N-m/kg. Birac reported that a true "quadriceps femoris avoidance" gait pattern might take approximately 6 years to develop.[4] During the giving way trial, both knee flexion (33.1°) and knee internal rotation (12.6°) magnitudes were substantially increased compared to the initial 4 trials (21.6° knee flexion and 9.4° knee internal rotation), suggesting that the quadriceps femoris was inhibited or was otherwise ineffective in controlling deceleration in association with ACL deficiency. Others have also reported increased knee flexion during stance phase among subjects with ACL deficiency.[2,9]

Transverse plane knee moment patterns were similar between the giving way trial and the initial 4 trials; however, the transition points occurred considerably later during the giving way trial (42% of stance phase) compared to the initial 4 trials (26% of stance phase). The prolonged internal rotation of the leg during the giving way trial suggests that a pivot shift has occurred and controlled dynamic stability was inhibited. At 45% of stance phase during the initial 4 trials, knee external rotator moments peaked (0.14 N-m/kg), while for the giving way trial this value was approximately 0.03 N-m/kg (approximately 79% reduced). This knee external rotator moment appears to be vital to controlling knee internal rotation. What contractile and noncontractile tissues primarily contributed to this important internal moment? Although the knee abductor moment for both the giving way trial and the initial 4 trials occurred at identical instances (20% of stance phase), the magnitude of this value was reduced by 25% for the giving way trial (0.96 N-m/kg vs 1.27 N-m/kg). Additionally, the minimal knee abductor moment value at approximately 60% of stance phase was increased by approximately 38% during the giving way trial (0.39 N-m/kg vs 0.24 N-m/kg). Again, what contractile and noncontractile tissues primarily contributed to this important internal moment?

Andriacchi[1] and Berchuck et al[3] have reported how an increased external knee adduction or varus moment resulted in a shortened stride length and increased external rotation ("toeing out") of the foot during stance phase. By toeing out, the ground reaction force vector moves closer to the knee joint center, thereby reducing the lever arm of the external ground reaction force. Did this subject display genu varus? A subject with tibial varus would be predisposed to having an increased internal knee abduction net joint moment to balance the external knee adduction or varus net joint moment. Any intact soft tissues that could prevent lateral joint opening would contribute to this balancing moment. Appropriately timed muscle activation has been shown to increase knee joint stiffness and unload soft tissues, thus protecting them from external loads. When appropriate muscle generated forces are inadequate or poorly timed, the knee is totally dependent upon noncontractile soft tissues for stability. Because the lateral soft tissues and the ACL are the primary soft tissue restraints to lateral joint line opening, a genu varus alignment in conjunction with ACL deficiency could greatly increase the functional limitations for this subject.

The authors stated that the first evidence of giving way may have occurred between 10 and 30% of stance phase with reduced knee abduction and knee internal rotation moments; however, clear evidence did not occur until 42% of stance phase when excessive knee internal rotation range of motion was observed during the giving way trial. The increased knee internal rotation moment and decreased knee abductor moment that preceded the increased knee internal rotation angle possibly suggested that this combined loading pattern may have contributed to the giving way event. The authors acknowledge difficulty in identifying the exact instance of giving way. This may illustrate the usefulness of video-based motion analysis systems or augmenting a nonvideo-based system with a single high-speed video camera. With a video record, the investigator could review the event frame-by-frame, with or without subject assistance, and possibly gain additional insight to help guide kinetic data analysis.

Because the sagittal plane moments and angles displayed changes approximately 6–8% after transverse plane changes, the authors surmised that sudden knee internal rotation served as the giving way catalyst, primarily between 42 and 54% of stance phase, (a period of 70 ms) and beginning at approximately 30° knee flexion (an angle similar to that used for the clinical pivot shift test). The authors suggested that the only dynamic means of attempting to control the giving way event would be a neuromuscular reflex response but acknowledged that any response would be too slow to compensate for the suddenness of the giving way episode. The presence of appropriately timed neuromuscular activations (eg, from the hamstrings) could potentially increase the dynamic stability of the joint.[5,8] Electromyographic assessment would have been useful in identifying the activation timing, sequence, and amplitude of the lower extremity muscles that contribute to dynamic knee joint stability. Electromyographic assessment also would have provided insight as to the possible contributions of neuromuscular agonist-antagonist coactivation to synergistically facilitate dynamic knee joint control. These data, in combination with the kinetic data and a more detailed clinical examination, would have increased the clinical relevance of these findings and provided greater insight for therapeutic exercise program planning for subjects with ACL deficiency.

Although the 1.34 m/s test velocity was certainly relevant for most activities of daily living, it is the equivalent of a 27.3 second 40-yard dash! Even the 2–2.5 m/s velocity employed in our study[10] was only the equivalent of a 14.6–18.3 second 40-yard dash. Relatively slow test velocities are often used in biomechanical studies to ensure subject safety during testing. How do you think this subject, who displayed evidence of giving way during this well-controlled task progression, would perform in a competitive volleyball match? If this subject became your patient, based on your clinical examination and biomechanical data, what would your recommendations be if she desired to return to competitive basketball? I enjoyed having the opportunity to comment on this interesting paper and invite the authors to address the questions raised in my commentary.

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Author Response

We thank Dr Nyland for his review and appreciate having the chance to respond. Of the numerous intriguing issues raised by Dr Nyland, we will attempt to address some of the more interesting and controversial ones. As stated in our article, we caution the reader that ours is a case study and, therefore, the response of the subject may not represent a typical response to giving way.

First, Dr Nyland questions the functioning level of the subject and the status of the meniscus. It is correct to assume that the subject demonstrated minimal functional limitations, as reflected in her self-report scores. We think she achieved this by adjusting her activity level to accommodate the knee instability. This is supported by her response to the question, "Why have you limited your activities?" She stated, "I have decreased my activity level in order to decrease wear and tear on my knee." Using the criteria defined in a recent study,[11] the subject would qualify for operative treatment, yet she found a way, at least temporarily, to manage her knee instability and avoid surgery.

We agree that the status of the meniscus is uncertain, however, we question how this would change the interpretation of the data. The importance of the meniscus in dissipating joint contact pressure and preventing the development of osteoarthritis are supported by recent studies;[23] however, the association of meniscal injury with knee instability is less clear.[1,17,18,19,22,23] Some cadaver studies examining the combined effect of a cut ACL and medial and lateral meniscus removal found minimal change in tibiofemoral kinematics with application of a 100 N anterior load, with no axial load, at knee angles of less than 30°.[17,18] Compressive loads combined with anterior shear loads[22] produced an anterior tibial shift after both cutting the ACL and removing the meniscus, which did not occur when only the ACL was cut. However, there was no increase in anterior/posterior knee laxity when the ACL was cut and menisci were removed. Using a robotic manipulator, Allen et al[1] found only a subtle effect on knee kinematics (2–4 mm anterior translation) when comparing in vitro ACL cut knees to ACL cut knees with the medial meniscus removed. These and other[23] studies suggest that even with complete removal of the menisci, which is avoided in patients with ACL deficiency, the role of menisci in restraining joint motion is subtle. Therefore, although we agree that the integrity of the menisci is important to function and management of this patient, research suggests that the influence of the menisci on the joint rotations observed in this subject is not a prominent factor.

As pointed out in the commentary, gross changes in foot position might affect the knee moment data; however, we believe that the foot position and cutting angle did not significantly influence the giving way trial. During the giving way trial, the subject increased the "towing in" position of her foot by approximately 3° (12.8 ± 1.9° versus 16°). Because the cutting angle was 47.4°, the lower limb transverse rotation during the giving way trial was 31.4° (47.4°–16.0° = 31.4°) compared to 31.4° for the nongiving way trials (44.2°–12.8° = 31.4°). Thus, comparable changes in lower extremity transverse plane angles were required during all trials, with the giving way trial accomplished at a rate of 0.06 seconds faster (0.64 s − 0.58 s = 0.06 s). We, therefore, do not believe that the minimal differences in foot position or the small decrease in stance duration significantly affected the kinematic or kinetic data.

In the commentary, the quadriceps avoidance pattern seems to be identified as a coping strategy that will inevitably emerge if enough time is allowed. We question the prevalence and the importance of a quadriceps avoidance walking pattern as a coping strategy in subjects with ACL deficiency. While some studies[4,24] observed a reversal of the sagittal plane knee extensor moment at 20% of stance duration of walking in subjects with an ACL-deficient knee, other studies suggest this pattern is not typical of subjects with ACL deficiency.[3,9,14,20] In addition, the use of walking as a paradigm to study coping strategies of subjects with ACL deficiency is dubious because most subjects with ACL deficiency only have difficulties with more strenuous activities, such as running or twisting and turning tasks.[7] Therefore, the quadriceps avoidance strategy is not universally accepted and is based on walking research that has questionable validity for most subjects with ACL deficiency. We, as well as Dr Nyland and other investigators, are attempting to develop more appropriate paradigms to look at coping strategies.

In the commentary, an attempt was made to relate the increased knee flexion documented in the giving way trial to the increased knee flexion seen in walking in patients with ACL deficiency.[3,20] In our paper, we identified this as potentially important because, with higher knee flexion angles (> 25°), the strain in the anteriomedial bundle of the ACL declines to levels of less than 50% of those observed at 20° of knee flexion during stair stepping and squatting.[5,12] Thus, moving to a higher knee angle (> 25°) may place the joint in a position where active and passive joint restraints interact to stabilize the knee compensating for the ACL deficiency, which is achievable independent of adaptive hamstring muscle contraction.[5,12] The papers cited in the commentary, however, are not comparable in that they report knee angles of less than 20° during walking, thus staying within the range where peak ACL strain has been documented.[3,20]

The commentary and article raise the possibility that hamstring contraction may explain how this subject restrained knee internal rotation after 54% stance duration. While this is consistent with contemporary thinking, it should be pointed out that the changes in the knee moments do not appear to support this theory. The change of the nominal knee flexor moment to a knee extensor moment is a clear indication of a change in muscle recruitment independent of electromyography (EMG) activation recordings. The nongiving way patterns demonstrated a nominal knee flexor moment that suggests the gastrocnemius and/or hamstring muscles act as the agonist. Recent studies of nonimpaired subjects provide evidence that both the hamstrings and gastrocnemius contribute to this flexor moment.[14,15] If a hamstring contraction is the dominant activation necessary to regain control after the giving way event starts, why didn't the subject accentuate the knee flexor moment pattern during the giving way trial? Although we cannot confirm the force generated in the hamstring muscles in response to the giving way, the knee moments do not favor hamstring contraction as an explanation for the subject's ability to restrain knee internal rotation.

The presence of genu varus is raised as a factor that may predispose this subject to instability and influence the interpretation of the knee frontal plane moment. During the standing calibration trial, the subject demonstrated a genu valgus knee angle of 4.8°, which is within ± 1.0 standard deviation of nonimpaired subjects,[2] suggesting the knee frontal plane angle was not unusual. The primary agonist muscles generating the knee abductor moment are the gluteus maximus and tensor fascia latae acting through the iliotibial band. However, it should be noted that joint modeling studies suggest a significant amount of compressive force is also necessary for equilibrium, possibly generated through muscle co-contraction to prevent lateral joint opening and, subsequently, strain in the lateral ligaments.[21] During early stance of the giving way trial, the knee abductor moment is lower than during the nongiving way trials, suggesting less of a tendency for lateral joint opening (and hence strain on the lateral ligaments) and greater lateral joint reaction forces.[21] Increased lateral compressive joint contact forces are a hypothesized mechanism underlying the pivot shift test;[13,16,19] therefore, the lower knee abductor moment that occurred during the giving way trial may have contributed to joint instability. This is also supported by the higher knee abduction moment that is associated with the plateau in the knee internal rotation angle after 54% of stance duration when the subject controlled knee internal rotation. However, this is speculative and difficult to confirm because the medial and lateral joint reaction forces were not modeled for this subject.

Ideally, we would explain the various muscle, ligament, and joint contact forces responsible for the transverse plane moment, as requested in the commentary; however, we do not believe the kinetic analysis (or EMG analysis) allows that detailed an interpretation. A simple interpretation would suggest the knee internal rotator moment is a result of the pes anserine, medial gastrocnemius, popliteus, and medial hamstring contributions in early stance duration, and the external rotator moment during late stance duration is a result of the contribution of the biceps femoris. However, the transverse plane moments are small and are also generated by joint contact and ligament forces,[6] raising doubt as to which mechanism is dominating the transverse plane moment. Using EMG to identify these relationships, as suggested in the commentary and the article, also has limitations. While EMG patterns have value, the interpretation of EMG amplitudes is not straightforward because of the 3-dimensional complexity and subtleties of the motion, and the potential involvement of over 12 muscles that cross the tibiofemoral joint. A recent EMG study compared muscle activation during a step and crossover cut and during a straight step in nonimpaired subjects.[15] The results showed higher medial hamstring activation from 30 to 70% of stance duration for the crossover cut compared to the straight step,[15] yet the knee internal rotator moment is increased in early stance (< 30% of stance duration) during the cutting activity. Is another muscle not recorded from (ie, popliteus or pes anserine muscles) potentially responsible for the knee internal rotator moment? Or, are changes at the hip changing the hamstring muscle mechanics and undercutting our ability to compare data? Or, does the relatively small knee internal rotator moment result in subtle changes in the overall functioning of the muscle, which are not detected with surface EMG? The usefulness of EMG amplitude as a method for gaining a better understanding of the mechanism is considered by us to be tempered by its limitations. What is needed is a better measure of muscle force to truly differentiate which muscles are responsible for controlling knee moments. Although some have used EMG amplitude to estimate muscle forces, the accuracy of this approach during dynamic tasks is complex and controversial.[8]

We agree with the commentary that using video recordings of the subject's performance might have assisted in obtaining some impression of trunk position and the opposite lower extremity. However, studies of visual gait analysis suggest poor reliability (Kappa values ranged from 0.11 to 0.51), so we also recognize that using video data analysis may lead to erroneous conclusions.[10] We understand that this proposal and others in the commentary arose from a desire to draw additional clinical data from the subject, which is a goal we share. Although we sought to address many of the questions posed by Dr Nyland, we felt frustrated by the current state of our understanding and, hence, the ability to apply this data directly to rehabilitation strategies. To our knowledge, this is the first time that such a complete analysis has been used to document a giving way episode, and we hope that it provides some insights, as well as challenges, to our current understanding, underscoring the need for more research and new methodologies. We thank the *Journal* for providing this forum and Dr Nyland for a stimulating discussion.

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