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Self-Reported Giving-Way Episode During a Stepping-Down Task: Case Report of a Subject With an ACL-Deficient Knee

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Study Design: Case report.
Objective: To describe the knee kinematics and moments of a giving-way trial of a subject with an anterior-cruciate-ligament– (ACL) deficient knee relative to his non–giving-way trials and to healthy subjects during a step-down task.
Background: Episodes of giving way are believed to damage joint structures, therefore treatments aim to prevent giving-way episodes, yet few studies document giving-way events.
Methods: The giving-way trial experienced by a 32-year-old male subject with ACL deficiency during a step-down task was compared to his non–giving-way trials (n = 5) and data from healthy subjects (n = 20). Position data collected at 60 Hz were combined with anthropometric data and ground reaction force data collected at 300 Hz to estimate knee displacement and 3-dimensional angles and net joint moments.
Results: The knee joint displacement was higher during the giving-way trial: from 4% to 32% of stance, reaching 9.0 mm at 18% of stance as compared to 1.6 ± 0.7 mm for the non–giving-way trials. After 4% of stance, the knee flexion angle of the giving-way trial was 6.6° higher than the non–giving-way trials and was associated with a higher knee extension moment. The knee frontal plane moment was near neutral during early stance of the giving-way trial in contrast to the non-giving way and healthy subjects which demonstrated a knee abduction moment.
Conclusions: The response of this subject to the giving-way event suggests that higher knee flexion angles may enhance knee stability and, in reaction to the giving-way event, that knee extension moment may increase.

Key Words: *anterior cruciate ligament, biomechanics, kinematics, knee instability*

Current practice trends suggest that some patients with an anterior-cruciate-ligament- (ACL) deficient knee may control their knee instability by using motor control strategies without surgical reconstruction.[13,14,18–20,39,57] But, abnormal kinematics that are not controlled by muscle action may lead to joint damage[33,34] and partially explain the greater decline in functional ability observed in some studies of subjects who do not undergo surgical reconstruction.[50,64] Recent studies suggest that subjects who are ACL deficient may experience an anterior tibial shift[33,34] and greater internal tibial rotation[16] during walking, suggesting that ACL deficiency is associated with abnormal knee kinematics. However, during giving-way events, the knee kinematics are potentially more distinct.[27] A previous case report[27] of a subject with an ACL-deficient knee suggested that a rapid 3° to 4° internal rotation of the tibia was associated with a giving-way event during a crossover cut task. Further observations linking abnormal knee kinematics and giving-way sensations experienced by subjects who are ACL deficient are desirable to extend current theories describing the development of joint damage. Yet, studies of the nature of giving-way events during functional movement are limited by the difficulties of obtaining valid kinematic data[11,40,43–45] and the risk posed by inducing actual giving-way events in injured subjects.

Identifying the knee loads that provoke a giving-way event and the

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subsequent response to maintain control of knee motion may further enhance our ability to develop rehabilitation strategies to prevent giving-way episodes in addition to strategies that may assist subjects in regaining control after experiencing giving way. Inducing giving-way events poses a threat to patients and is therefore rarely practical during experiments involving weight-bearing movements. Serendipitously, while participating in a cross-sectional study comparing knee angles and moments of ACL-deficient and healthy subjects performing a landing-and-turning task,[26] a subject experienced a giving-way sensation while stepping down from a 21-cm curb. This subject's data provided a unique look at the knee-loading pattern prior to the giving way and response after the giving-way event occurred. The purpose of this case report is to describe the knee kinematics and moments of the giving-way trial of this subject compared to his non–giving-way trials and the normal trials of healthy subjects during a stepping-down task. Similar to other studies,[1,2,4,52] we hypothesized a positive association between indications of higher quadriceps load (ie, knee extension moment) and signs of knee instability.

TABLE 1. Description of subject that experienced giving way.

Variable	Response
Chief complaint	Intermittent throbbing and aching left-knee pain (pain intensity,* 1/10)
Giving way	3 episodes since injury
Mechanism of injury	Playing basketball 5.5 wk prior to testing
Initial signs/symptoms associated with injury	Swelling, pain, and decreased knee range of motion
Treatment history	Ice, elevation, knee extension brace 1 to 2 wk, reconstructive surgery planned
Current sports activity level	None
Modified Noyes questionnaire[58]	50%†
Lysholm scale[36]	64%†
Global question of knee function[58‡]	50%†

* Pain intensity was measured by response to the following question: "If I had to give my knee pain a grade from 0 to 10, with 10 being the worst, I would give my knee pain a . . ."
† Higher scores indicate better function.
‡ Global question of knee function was determined by response to the following question: "If I had to give my knee a grade from 1 to 100, with 100 being the best, I would give my knee a . . ."

METHODS

Subjects

The subject was a male, 32 years old, 1.82 m tall, weighing 88.6 kg, who had a ruptured left ACL. In addition to the clinical variables[36,58] described in Table 1, knee flexor and extensor isometric torques were assessed using a Cybex II dynamometer (Cybex International, Inc., Medway, MA). After 3 repetitions performed at submaximal efforts, the subject was given a 1-minute rest and then performed 3 repetitions at maximum efforts with approximately 20 seconds between each trial. The isometric strength tests revealed a knee extension limb symmetry index (LSI) (torque of involved leg/torque of uninvolved leg × 100) of 75% and a knee flexion LSI of 88.5%. Clinically, the subject had a positive Lachman and pivot shift test on the left side only, suggesting left anterior and anterolateral instability. Varus and valgus knee stress tests on the left and right side were negative for instability at 0° and 30° of knee flexion. The KT-1000 manual maximum side-to-side difference was 7 mm greater on the left side, suggesting significant anterior laxity. The subject consented to participate in accordance with an approved protocol. The data of this subject were compared to that of a group of healthy subjects (n = 20, 10 female, 10 male) with an average (±SD) age of 28.3 ± 8.6 years, mass of 64.7 ± 12.0 kg, and height of 1.73 ± 0.12 m, which constituted the control group of the larger study.

Instrumentation

A 4-segment model of the lower extremity, including the foot, leg, thigh, and pelvis, was used to estimate joint displacement and moments in 3 dimensions, which was consistent with previous studies.[26–29] Three infrared emitting diodes (IREDs) were placed on each segment consistent with locations illustrated in 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). Each activity required subjects to land onto a Kistler model 9865B force plate (Kistler Instrument Corp., Amherst, NY) mounted in the floor and ground reaction forces were sampled at 300 Hz. Both position and ground reaction forces were filtered with zero-phase-lag fourth-order Butterworth filters prior to calculating joint angles and moments. The ground reaction forces were filtered at a cutoff frequency (8 Hz) similar to that of the kinematic data (6 Hz) to remove inconsistencies between smoothed kinematic data and ground reaction force data.[55]

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.[8,59] The convention of reporting intrinsic joint moments in the reference frame of the distal segment was adopted to reflect the combined contribution of passive tissues and agonist muscles to an external load. Inertial properties and segment mass were estimated using a previously published proto-

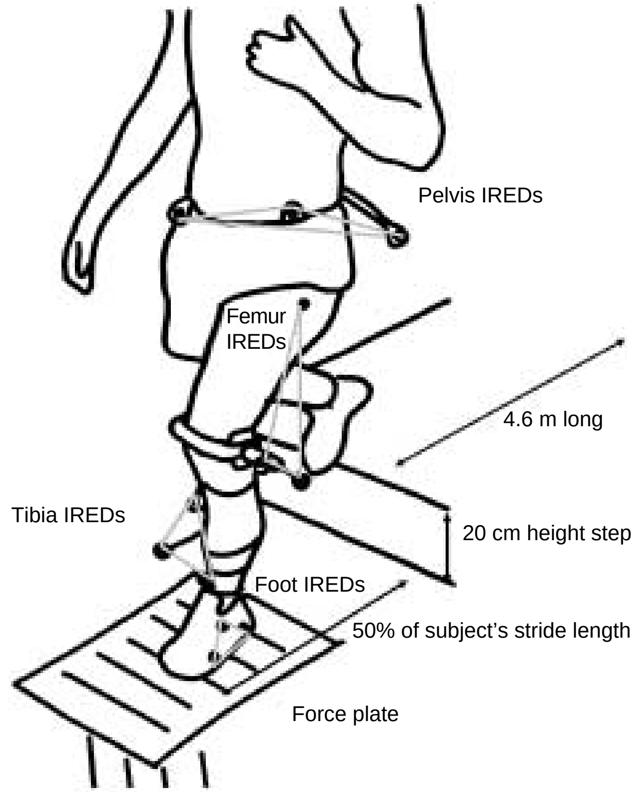

FIGURE 1. The placement of the infrared emitting diodes (IREDs) used to track lower extremity motion and placement of the step relative to the force plate. Each triangle represents the IREDs used to track each segment of the 4-segment model.

col.[63] KinGait3 Version 1.6 software (Mishac Kinetics, Waterloo, Ontario)[30] was used to filter and process joint angles[22,60] and net joint moments,[8,59] consistent with published studies. Joint angles were based on the system proposed by Grood and Suntay[22] and subsequently recommended by the International Society of Biomechanics.[60] The knee joint center was estimated as the midpoint between the medial and lateral condyles of the femur consistent with studies locating the knee joint axis.[10,25,31] Joint displacement was measured as the distance from the knee joint center estimated from the tibia reference frame to the same point estimated from the femoral reference frame. All kinematic and kinetic patterns were normalized to percent stance duration, where 0% was heel strike and toe-off was considered 100%, using a 10-N threshold from vertical ground reaction force data.

Procedures

The testing procedure required all subjects to complete 4 different activities including walking, stepping down off a 21-cm-high curb, walking and cutting at a 45° angle, and stepping down and cutting at a 45° angle.[26,27] All tasks were performed at the same walking speed of 1.34 m/s and controlled by requiring the subject to keep pace with an overhead tracking system. The platform traversed before stepping down allowed for 3 to 4 approach strides before stepping down. The distance of the step from the center of the force plate was 50% of the subject's stride length and the foot-landing strategy was manipulated so that the subjects landed heel first at initial contact. Only the third activity, stepping down, which followed the walking and walking-and-turning activities for this subject, were reported in this paper.

All subjects were given at least 10 practice trials to familiarize them with the tasks. During the first 2 trials of the stepping activity, this subject did not experience a sensation of giving way. For the third trial, the subject completed the stepping task successfully, similar to the other trials, yet it was obvious to the researchers observing the trial that the subject experienced knee instability during the movement. The subject confirmed this by volunteering that he felt his knee give way during the trial. Subsequently, this trial was interpreted as representing a mild to moderate episode of knee instability or a giving-way event. After resting for a few moments the subject repeated the stepping task 3 more times for a total of 5 non–giving-way trials.

Data Analysis

The 5 non–giving-way trials were averaged at 2% intervals across the first 86% of stance to estimate the normal variability in performance expected during early to mid stance of the stepping activities. The stance time for the giving-way trial was 700 ms compared to 670 ± 25 ms for the non–giving-way trials and 673 ± 52 ms for the healthy subjects. Assuming that the 5 non–giving-way trials approximated a normal distribution, a 2-sided z score suggests that values during the giving-way trial which vary more than 1.96 standard deviations (SD) are significantly different.[41] Hence, peak values of the knee displacements, angles, and moments during the giving-way trial were compared to the average ±1.96 SD of the non–giving-way trials and the trials of the healthy subjects. Further, to assess the peak within-session variability of the joint displacement data across the stance phase, the peak variability of the joint displacements of 10 healthy subjects from 0% to 86% stance was assessed at 2% intervals (Table 2). The peak difference was calculated for each interval of stance as the absolute value of the observed value minus the average value for each subject's 5 trials. The largest variability across stance occurred for subject 3 at 3.6 mm (Table 2). This value was used as an additional benchmark to suggest when the knee displacement data of the giving-way trial exceeded maximum within-session variability (Figure 2).

TABLE 2. Within-session variability of the peak knee joint displacement (mm) of healthy male subjects (n = 10) across 0% to 86% of stance for 5 trials.

Subject	Peak Difference (Mean ± SD)	Peak Difference (Maximum Value)
1	1.4 ± 0.8	3.1
2	0.7 ± 0.4	1.9
3	1.9 ± 0.7	3.6
4	0.7 ± 0.4	1.4
5	1.4 ± 0.7	3.4
6	1.3 ± 0.7	2.6
7	1.6 ± .04	2.4
8	1.2 ± 0.5	2.0
9	0.7 ± 0.3	1.5
10	1.3 ± 0.8	1.3

RESULTS

The most distinct sign of knee instability during the giving-way trial occurred in knee joint displacement (Figure 2). The knee joint displacement from 4% to 18% of stance (84 ms) increased rapidly reaching a peak of 9.0 mm at 18% of stance, as compared to 1.6 ± 0.7 mm at 22% of stance during the non–giving-way trials (Figure 2). In addition, the knee joint displacement of the giving-way trial exceeded ±3.6 mm of the average of the non–giving-way trials from 6% to 28% of stance (Figure 2). Further analysis showed that the differences in joint displacement primarily arose from a rapid increase in anterior translation peaking at 8.3 mm at 18% of stance compared to 2.6 ± 1.3 mm for the non–giving-way trials. Peak superior-inferior and medial-lateral translations were less than 3.4 mm for all trials of this subject.

In apparent response to the giving-way sensation, knee flexion angle was higher during the giving-way trial (Figure 3A). A maximum knee flexion angle of 41° was measured during early stance as compared to 34.4° ± 3.9° during the non–giving-way trials, which was similar to that of healthy subjects (34.6° ± 4.6°) (Table 2). During late stance (60% of the stance phase) the non–giving-way trials suggest that this subject used higher knee flexion angles (25.7° ± 2.2°) than those of healthy subjects (9.0° ± 5.0°) and accentuated his knee flexion further during the giving-way trial (Figure 3A). Other knee joint angles were comparable between the giving-way and non–giving-way trials suggesting no rotational instability (Table 3).

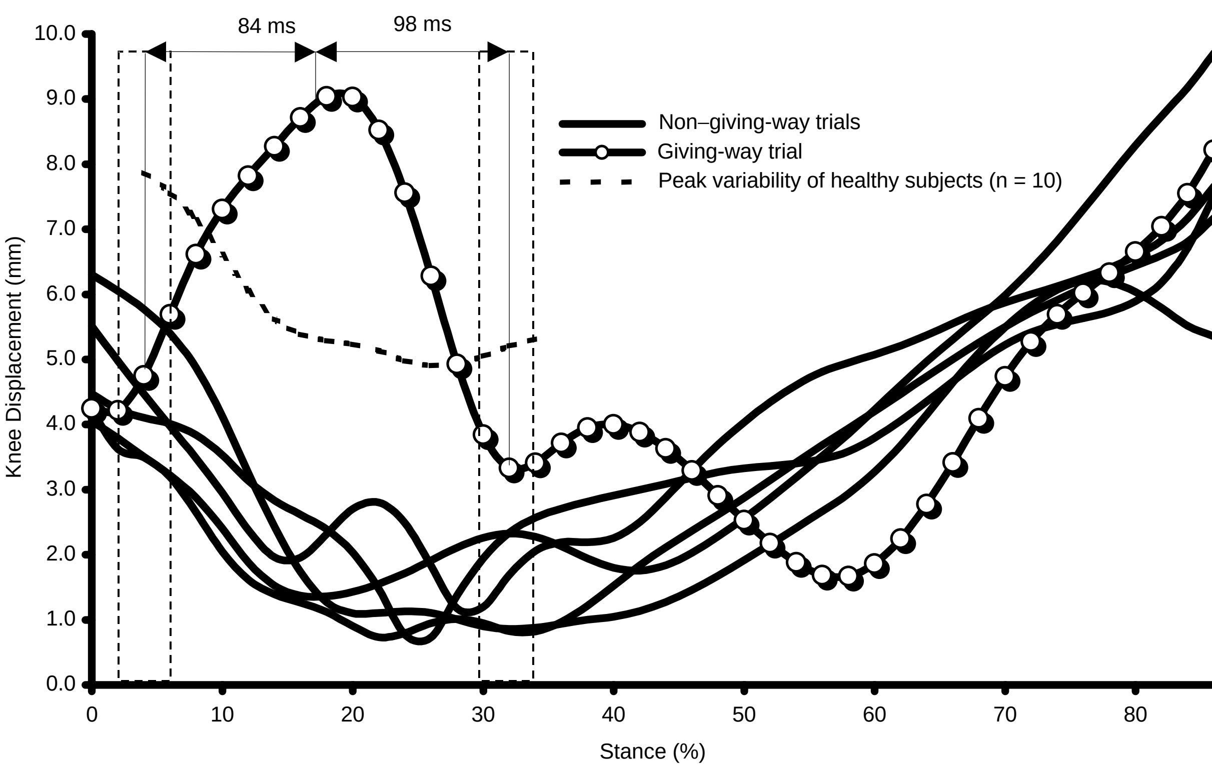

FIGURE 2. Tibia displacement relative to the femur over 86% of stance for the giving-way and non–giving-way trials. The area between the vertical dashed lines (2% to 6% and 30% to 34% of stance) indicates the period during stance when the giving-way trial deviates from the non–giving-way trials. During the period from 4% to 18% of stance the peak displacement increases rapidly. During the period from 18% to 32% of stance the displacement decreases rapidly, reaching similar values to the non–giving-way trials after 32% of stance. The dotted line represents the average of the non–giving-way trials ±3.6 mm, the maximum observed within-session variability of healthy subjects. Vertical dashed-line areas mark the period when the knee displacement suggest that the giving-way event began and when the knee displacement returned to similar values as the non–giving-way trials.

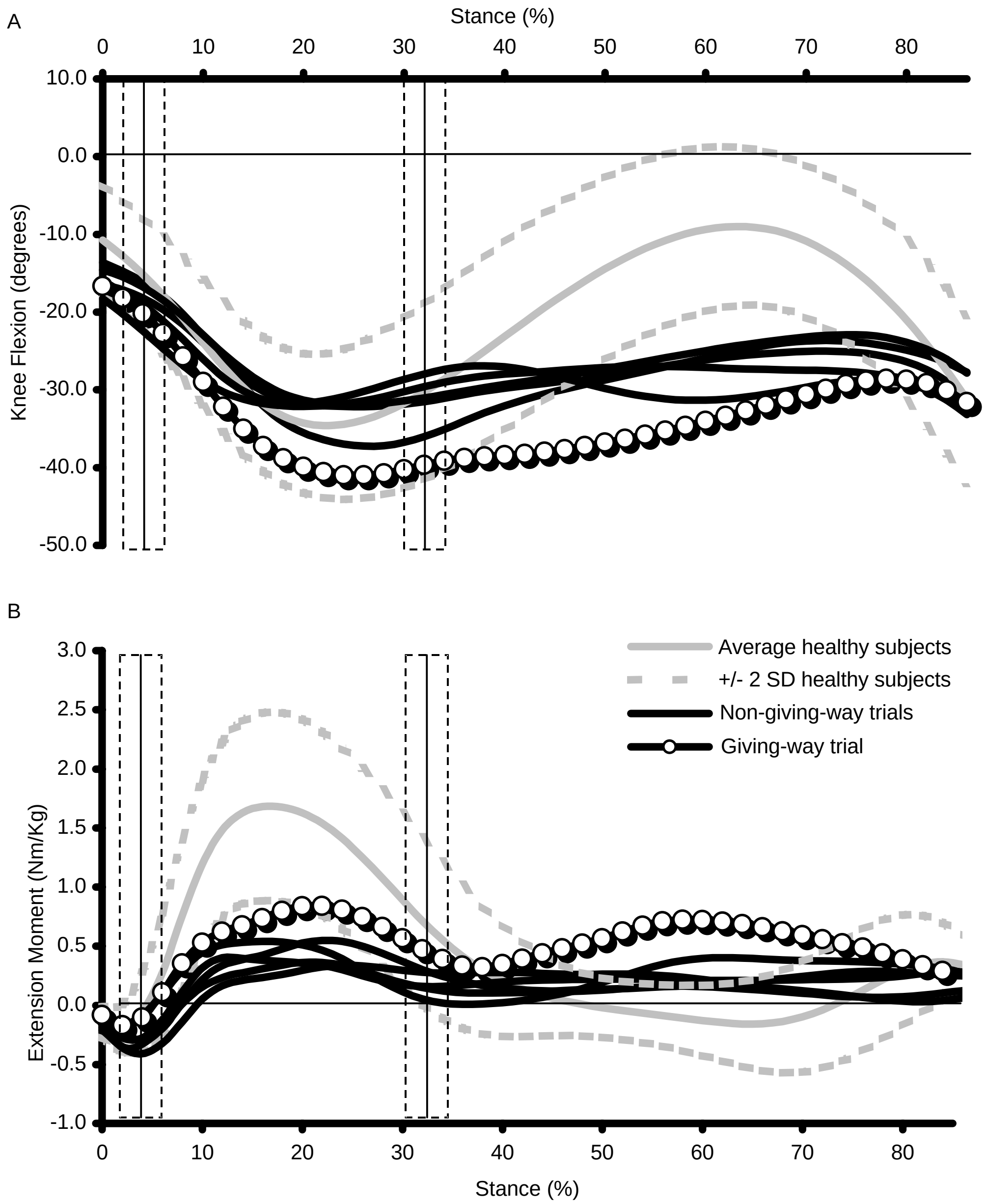

FIGURE 3. Knee flexion angle (A) and intrinsic knee extension moment (B) from 0% to 86% of stance for the healthy subjects, non–giving-way, and giving-way trials. The area between the vertical dashed lines (4% to 32%) indicates the period during stance when giving way took place (defined as a period of excessive tibial displacement).

The knee joint moments suggest this subject used a different knee moment pattern before and after signs of knee instability indicated by the knee displacement pattern. During early stance (<6% stance) the knee adduction moment of the giving-way trial is greater than that of both the non–giving-way trials (1.4 SD) and healthy subjects (4.5 SD) (Figure 4). Interestingly, the frontal plane moment of the giving-way trial remained close to 0 until mid stance (40% to 50% of stance) in contrast to the non–giving-way trials and healthy subjects, which both demonstrated a knee abduction moment. This trend is reversed in late stance (≈60% of stance) when the knee abduction moment of the giving-way trial exceeds both the value of the non–giving-way trials and the value of the healthy subjects by 2 SD.

In contrast to the knee frontal plane moment, the knee extension moment appears to vary in response to the giving-way event marked by the knee displacement. From 4% to 6% of stance, the knee sagittal plane moment is switching from a knee flexion to a knee extension moment. The non–giving-way trials show a lower peak knee extension moment near 20% of stance relative to the pattern of the healthy subjects. In contrast to trials of the healthy subjects, which show a knee flexion moment during late stance, the non–giving-way trials of this subject show a knee extension moment (Figure 3B). The sagittal

TABLE 3. Values for range of motion and moment variables near selected points of stance (% stance).

	Stance (%)	Non–Giving-Way Trial (Mean ± SD)	Giving-Way Trial	Healthy Subjects (Mean ± SD [Range])
Knee Angles (Degrees)				
Transverse plane*	10	5.0 ± 0.8	5.9	4.6 ± 2.8 (0.2–10.0)
	60	0.3 ± 0.6	−0.3	6.1 ± 2.6 (0.0–9.1)
Frontal plane†	0	−4.7 ± 0.5	−4.7	1.4 ± 2.4 (−5.0–7.0)
	45	0.5 ± 0.7	0.3	1.8 ± 2.9 (−2.2–5.8)
Sagittal Plane‡	20	−34.4 ± 3.9	−41.0	−34.6 ± 5.0 (−27.8–−43.4)
	60	−25.7 ± 2.2	−28.6	−8.9 ± 5.0 (0.0–22.0)
Knee Moments (Nm/Kg)				
Transverse plane*	30	0.04 ± 0.04	−0.04	0.04 ± 0.06 (−0.17–0.12)
	80	0.10 ± 0.03	0.05	0.15 ± 0.06 (0.06–0.34)
Frontal plane†	4	−0.17 ± 0.08	−0.28	−0.01 ± 0.06 (−0.14–0.09)
	20	0.30 ± 0.15	0.04	1.2 ± 0.34 (0.40–1.86)
	60	0.19 ± 0.09	0.38	0.18 ± 0.07 (0.00–0.30)
Sagittal plane‡	4	−0.28 ± 0.09	−0.17	−0.19 ± 0.10 (−0.08–−0.38)
	20	0.16 ± 0.15	0.47	1.7 ± 0.40 (0.91–2.55)
	70	0.27 ± 0.20	0.72	−0.16 ± 0.18 (−0.70–0.08)

* + external rotation.
† + abduction.
‡ + extension.

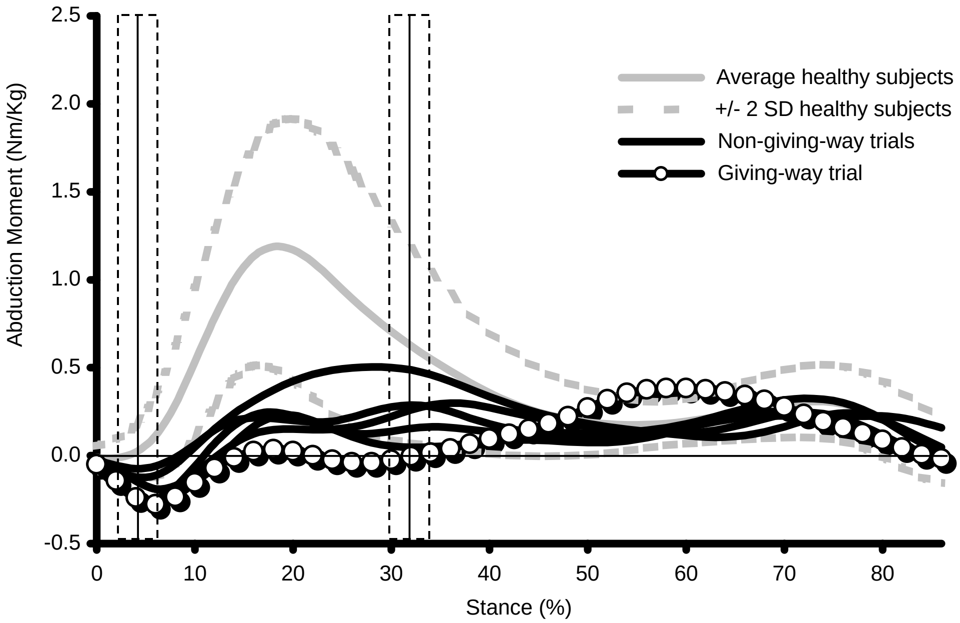

FIGURE 4. Intrinsic knee abduction moment from 0% to 86% of stance for the healthy subjects, non–giving-way trials and giving-way trial. The area between the vertical dashed lines (4% to 32% of stance) indicates the period during stance when giving way took place (defined as a period of excessive tibial displacement).

plane knee moment pattern of the giving-way trial begins to deviate from the non–giving-way trials at approximately 12% of stance. A peak difference of 2.1 SD higher than the non–giving-way trials is noted at 24% of stance (Figure 3B). In late stance, the giving-way trial shows an accentuated knee extension moment (higher than the non–giving-way trials), rather than the knee flexion moment utilized by the healthy subjects (Figure 3B).

DISCUSSION

The findings of this case report provide some suggestions about the joint moments that may contribute to a giving-way episode during early stance and the possible motor control strategies that may act to control the giving-way event in this subject. This subject demonstrated knee angle and moment patterns distinct from healthy subjects during a non–

giving-way step-down maneuver. This fact suggests that the giving-way event that occurred during the step-down maneuver took place despite this subject's attempt to control his knee instability. Signs of anterior tibial translation instability associated with the giving-way event occurred between 4% to 32% of stance in contrast to a recent case report which observed signs of transverse plane rotational instability during mid to late stance (after 50% of stance) during a cutting activity.[27] Immediately after initial contact with the ground, the subject with an ACL-deficient knee used an unusual knee adduction moment that was accentuated during the giving-way trial. After 4% of stance, the peak knee extension moments were higher during the giving-way trial, suggesting a larger contribution of the knee extensors. Interestingly, the higher knee extension moment of the giving-way trial appears to be associated with the recovery of knee stability and not the loss of stability as was suggested by the knee displacement pattern.

While the absolute magnitude of the joint translation values cannot be established,[11,35,44,45] the joint displacement during the giving-way trial exceeds the expected within-session variability of the healthy subjects and the non–giving-way trials of this same subject from 4% to 32% of stance. Confidence in the joint displacement pattern of this subject arises from the low within-session peak differences among trials of healthy subjects ($<\pm 3.6$ mm) across stance (Table 2), suggesting that the knee displacement data of the giving-way trial is not explained by repeatability errors. Other studies have also reported good within-session reliability for knee angle and moment data.[27,32] Errors due to skin artifact are usually systematic and consistent between trials[11,35,43–45] and therefore do not seem a likely explanation for the abnormal knee joint displacements observed during the giving-way trial. The similarity of the knee displacement pattern of the 2 trials before and 3 trials after the giving-way event suggest that the tracking system did not merely shift during the giving-way trial. Indeed, the pattern of the knee joint displacement data of the giving-way trial appears to uniquely mark the mild giving-way event and suggests that the subject experienced knee translational instability during early stance (4% to 32%).

Although the exact time the giving-way event began is uncertain, the joint displacements suggest that the giving-way event occurred too quickly to allow for voluntary responses to maintain equilibrium. Postural responses to a floor perturbation in standing suggest the time to EMG activation is approximately 100 ms[15] and slightly longer for a mechanical effect (ie, joint torque or angle change) due to electromechanical delay.[12] However, stretch superimposed on ankle torque produces an EMG response in approximately 50 ms.[54] Judging by the interval from the apparent start of the giving-way event (2% to 6% of stance) to the initial changes in the knee flexion angle and knee extension moment ($\approx$12% of stance), a mechanical response to the giving-way event corresponds to a period of 42 to 70 ms. This short time frame suggests that an initial reflex response was necessary to maintain knee stability in response to the giving-way sensation and agrees with the previous case report which suggests an equally short time to an initial mechanical response.[27]

The changes in the sagittal plane knee angles and moments during the giving-way trial are consistent with in vivo observations of ACL strain,[6] but not with current models that suggest an association of higher anterior tibial forces with knee instability. In vivo observations of ACL strain show that at higher knee flexion angles ($>25°$), the role of the ACL diminishes and therefore other soft tissues stabilize the knee.[5,21] The non–giving-way trials suggest that this subject had already significantly reduced his knee extension moment, apparently limiting the quadriceps demand in an attempt to control knee instability. When this strategy failed, the subject increased the knee flexion angle 6.6° during early stance of the giving-way trial and maintained an abnormally high knee flexion angle ($>25°$) throughout mid stance, which is similar to a previous case report of a giving-way event.[27] This greater knee flexion angle is associated with a larger knee extension moment, suggesting increased load of the quadriceps muscle.

This subject's response to his giving-way episode differs from current theories that associate high quadriceps loads with knee instability. When the joint is not near end range, the net joint moment indicates the minimal agonist contribution to maintain joint equilibrium.[59] The larger knee extension moment during the giving-way trial, therefore, suggests a larger contribution of the quadriceps muscles to the knee moment. At knee angles less than 45° to 60° the pull of the patella tendon is anterior, hence, a larger quadriceps contribution is thought to aggravate anterior knee instability at angles less than 45°.[24,56] However, the data of this subject suggest that the quadriceps contribution to the knee moment increases after the giving-way is initiated (2% to 6%), which is possibly a reaction to, and not the cause of, the giving-way event. A consequence of the larger knee extension moment is a higher joint compressive load, which some hypothesize may limit anterior instability and may have enhanced this subject's response to the giving-way event.[62,61]

The response to the altered afferent feedback produced by the high knee displacement during the giving-way trial may explain the higher knee angle and knee extension moment. The giving-way event is potentially similar to experiments that tested subject responses to surprise landings.[17] Duncan and McDonagh[17] tested subject responses to a drop landing through a false floor, constituting a surprise landing. During surprise landings, postimpact electromyographic responses occurred 50 ms after impact in response to changes in joint angles.[17] The joint displacement, if viewed as a surprise change in afferent input, may have triggered a change in knee angle and knee extension moment during early stance of the giving-way trial. Viewed in this context, the improved knee stability is potentially a consequence of a motor control response to maintain equilibrium rather than a specific response to regain knee stability.

While other researchers discuss the role of the hamstrings in maintaining knee stability,[3,4,7,38,53] the role of the hamstrings for this subject is uncertain. A recent EMG study confirms cocontraction of the hamstrings and quadriceps during early stance of this stepping activity,[28] therefore, the precise contribution of the hamstrings during the giving-way trial was difficult to determine for this subject. The first signs of knee instability occur when the knee moment is transitioning from a knee flexion to a knee extension moment, suggesting that this subject failed to control the switch from a knee flexor as the agonist to the knee extensor. Therefore, it is possible that the giving-way event involved failure of the hamstring muscles to modulate the quadriceps, as this muscle was becoming the agonist. Preventing further episodes of giving way in this subject may depend on his ability to learn to control the quadriceps load without sacrificing performance during functional activities.

The frontal plane moments are unique for the giving-way trial before and after 4% of stance. This subject used a knee adduction moment markedly lower for all trials relative to healthy subjects (Figure 4), suggesting that the strategy used by this subject required less of a contribution from lateral stabilizers acting through the iliotibial band. A previous case report of a giving-way episode also noted a tendency for the knee frontal plane moment to move toward an adduction moment preceding a giving-way event.[27] Markolf et al[37] noted that in vitro tests indicated that combined anterior and varus/valgus loads increased the force in the ACL and therefore suggested that combined loading states occurring during activities place subjects at higher risk of injuring their ACL. The unusual frontal plane moment, relative to the healthy subjects, suggests that this subject adopted a unique abduction/adduction and muscle/ligament control strategy to maintain stability, relying more on the knee adductors as the agonist during early stance than would healthy subjects. During the giving-way trial, this strategy was altered further as evidenced by the near 0 abduction/adduction moment throughout early stance, suggesting that there was no dominant agonist muscle acting in the frontal plane. These data support current theories that a reduced knee abduction moment may predispose ACL-deficient subjects to instability[27] and place healthy subjects at risk of ACL injury[5] by decreasing the stiffness of the lateral stabilizers and thereby allowing for greater rotation.[51] However, new studies are needed to verify the influence of the frontal plane moment on knee stability.

The limitations of this case report are also important to consider. Because this subject did not fall down or suffer any signs of joint damage (ie, joint swelling or pain) after his giving-way episode, the severity of this subject's giving way was assumed to have been mild. More severe giving-way episodes may result from different tasks.[27] For example this task required subjects to land heel first, which may have elicited different muscle recruitment patterns than a toe-first landing strategy would have.[23] In addition, knee kinematic and moment data are sensitive to the filtering and modeling approaches used.[55] The 8-Hz cutoff frequency used to smooth the ground reaction force in this study was low and may have resulted in attenuated moment estimates at initial contact with the ground.[55] Finally, giving-way episodes may not be associated with a single mechanism and, therefore, the data from this subject may not generalize to other subjects who have ACL-deficient knees[29,46–49] or other tasks.[1,26] Although it is difficult to generalize the results of case report, case reports are useful for exploratory research, especially for unique observations, which in this case enables us to test current hypotheses related to muscle control during a mild giving-way event.

CONCLUSIONS

This case report suggests that this subject demonstrated an unusual frontal plane moment during early stance of a step-down maneuver, which may have contributed to the mild giving-way episode. The knee displacement data appear to mark the giving-way event at 4% to 6% of the stance phase, indicating that the point at which the motor control pattern changes from the knee flexors as the agonist to the knee extensors may be important therapeutically to control. Surprisingly, the response to the giving-way event included increased knee flexion, which is associated with a higher knee extension moment and by inference quadriceps load. Current theories suggest that higher quadriceps loads may aggravate knee instability. However, the data from this case report suggest that this subject regained control in the presence of a higher quadriceps load. Alternatively, moving to a higher knee angle, where the strain in the ACL is reportedly lower, may have led to this subject regaining knee stability.

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INVITED COMMENTARY

While many researchers have been studying the biomechanics of the ACL and the differences between healthy individuals and those with ACL-deficient knees, this study captured an event that provides added insight into the conditions that destabilize the knee and cause giving-way episodes. The giving-way event captured in this case report was described as a mild to moderate episode that took place during a step-down test. The fact that the subject was able to recover and complete the trial also provides the opportunity to examine the adaptive response to the event.

The onset of the giving-way episode was marked by 2 conditions in early stance: an increased adduction moment and large displacement of the knee. The abnormal adduction moment appears to precede the abnormal displacement, suggesting that the adduction moment at the beginning of stance was the initial cause of the giving-way episode. It should be noted that the authors report the moments generated by internal structure, muscle, and passive soft tissue forces rather than the moments that act on the limb due to external forces. An adduction moment as defined in this study would be required to balance external forces that tend to thrust the tibia in a valgus direction. The increased adduction moment at the beginning of stance could indicate the onset of valgus knee opening as recently described.[1,2] This type of valgus opening or buckling has been observed in video footage of ACL injuries.[4] In valgus buckling, there is a rapid valgus opening of the knee during weight acceptance, followed rapidly by the collapse of the leg. Previous cadaver studies have also shown that under a valgus load, the ACL becomes tense before the medial collateral ligament (MCL), while under a varus load the lateral collateral ligament (LCL) becomes tense first.[5] The MCL cannot shield the ACL from the load that occurs during a valgus thrust of the knee, so it is possible that injuries may occur in this manner.

This valgus buckling mechanism for the noncontact ACL injury is consistent with magnetic resonance images of many injured patients that show a bone bruise on the lateral femoral condyle.[6] A valgus opening concentrates the compressive force through the lateral compartment, causing a bone bruise, while opening the medial compartment. The subsequent collapse in flexion is likely caused by inhibition of the knee extensors in response to pain. The subject in this case report was able to recover before complete collapse into flexion. It should be noted that the 8-Hz cutoff frequency used to smooth the ground reaction force data could have reduced the actual initial peak of the adduction moment at initial contact. Similarly, the 6-Hz cutoff for the kinematic measurements could have masked an initial rapid valgus thrust at initial contact.

It is also interesting to consider the response to the giving-way episode. Recall that the subject was able to recover and complete the trial. Thus, there was clearly an adaptive response. The response to the onset of the giving way appeared to include increased knee flexion and extension moments through the rest of stance and lower frontal plane moments through early stance. The subject in this study had an acute ACL tear, having only had 5.5 weeks to adapt his gait since the injury. Yet the subject had experienced 3 similar giving-way events in the past, and he may have developed his ability to sense valgus instability and respond to it in a way that permitted him to successfully complete the step-down task even when the giving-way event occurred. Without the ACL present to bear some of the load, the motion of the knee under valgus loading may change to a degree perceptible to the subject, even if it is not large enough to be distinguished clinically as valgus instability.

The larger knee extensor moment began at approximately 12% of stance, approximately 50 ms after the onset of abnormal motion. The authors explanation that the extra activation of the knee extensors was due to a stretch-reflex response is reasonable. The stretch reflex is highly sensitive to the stretch rate,[3] the increased flexion velocity from 4% to 12% of stance is likely to have triggered the increased extensor response. Of course, once the knee was flexed to a larger angle from 12% of stance onward, a larger extensor force was required to maintain the increased knee flexion position.

The one interpretation of the giving-way episode that remained unclear was related to the increased knee displacement during early stance. The initial confusion started with the definition of knee displacement in the Instrumentation section, where it was difficult to determine the reference frame for the motion. The description in the Results section and labels on graphs report knee displacement rather than tibial or femoral displacement. It was not until the Discussion section that the abnormal displacement was described as anterior tibial displacement. If the displacement described is in fact anterior displacement of the tibia with respect to the femur, it is difficult to identify a combination of loads that could cause anterior tibial displacement during stepping down. The authors explain that the anterior pull of the extensor mechanism could cause the tibia to displace anteriorly because the knee was at approximately 22° of flexion during this phase of the giving-way episode. However, this anterior quadriceps pull on the tibia is dependent on the tibia being in a neutral position, because only in that neutral position is the tibial insertion of the patellar ligament posterior to its patellar origin. If the tibia moves forward, the anterior pull of the quadriceps on the tibia will be reduced, even at angles of flexion less than 45°. The increased quadriceps activity suggested by the larger knee extension moment could actually substitute for the ACL by preventing the tibia from moving further forward. A large anterior tibial displacement could convert the extensor mechanism to a synergist of the ACL, even near extension. Thus, one must look for other forces that would drive the tibia forward during stance phase. Typically, during a step-down task, the entire mass of the body except for the stance foot and shank are moving forward. With the foot and shank restrained by contact with the floor, the inertia of the body keeps it moving forward, which should result in anterior translation of the femur with respect to the tibia. Therefore, it is difficult to identify a configuration of the limb that would cause such a large anterior tibial translation during the stance phase of a step down task. It would be interesting for the authors to provide further discussion of the increased anterior displacement during the giving-way episode.

In summary, this case report provides very interesting and important new information that can improve our understanding of the function of the ACL and the adaptations that a patient with an ACL-deficient knee may develop during a giving-way episode. It is especially useful to stimulate discussion and the formation of new ideas. As such, it should be expected that case reports like these provoke new questions that we hope will motivate further research in this area.

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AUTHORS' RESPONSE

The authors appreciate this chance to respond to the thought provoking and insightful commentary provided by Dr. Andriacchi and Mr. Chaudhari in an effort to more fully understand the subject's response reported in this case report. Their commentary focuses on mechanisms related to frontal and sagittal plane control of knee motion. The observations related to frontal plane control are based on injury mechanisms obtained from video footage, in vitro studies, and modeling. The sagittal plane issues are based on current understanding of the quadriceps mechanism and possible deviations from this mechanism in individuals with ACL-deficient knees. Finally, the commentary challenges us to more fully explain the initial contact mechanics of the step-down task.

The importance of frontal plane moments in controlling knee stability is reinforced in the commentary and by the continuing work of these reviewers. We have acknowledged in this manuscript, as well as in previous publications, the association between decreased internal knee abduction moments or the reversal of frontal plane moment to an internal knee adduction moment (as in the current case report) and anterolateral instability (analogous to the pivot shift test).[5] We, however, do not believe that the results for this subject necessarily support the concept of valgus thrust, nor do they single out lateral joint loading as the primary cause of lost stability as implied in the commentary.

Recognizing the importance of the frontal plane moment and the possible association of medial/lateral tibiofemoral joint contact forces with knee instability, we modified, as part of a separate project, the joint contact force model developed by Schipplein and Andriacchi[8] to account for an ACL-deficient knee and applied this model to the data of this subject.[3] During early stance, this subject experienced a significant decrease in medial joint contact forces. However, no medial joint space opening was predicted from the model. This analysis suggested there was an atypical reduction in the contribution of the passive and active lateral joint stabilizers and a shift in the balance of joint contact toward the lateral tibial plateau coincident with the onset of increased knee displacement (4% to 6% of stance). After the knee displacement indicated the beginning of knee instability (after 7% of stance of the giving-way trial), the lateral joint contact force increased and remained high relative to the non–giving-way trials from 10% to 30% of stance. The change in the lateral joint contact was partially a result of the knee frontal plane moment remaining near 0 until 30% of stance (Figure 4). The higher lateral joint contact occurred when the knee displacement indicated that instability was decreasing and not increasing. This result suggested that lateral joint contact forces alone did not correlate with the instability observed in this subject. In the knee angle data, there was no evidence of an abnormal thrust, even when the data were reanalyzed with less smoothing. (Increasing the cutoff frequency for the kinematic data to 15 Hz, as compared to 6 Hz, resulted in angle differences of less than 2°.) Therefore, we agree that an internal knee adduction moment is potentially problematic for subjects that have an ACL-deficient knee, however, an abnormal frontal plane moment alone may not be enough to cause instability unless extremely large or coupled with other shear forces or rotational loads.

As discerned by the reviewers, the knee displacement data suggest that the knee instability experienced by this subject was anterior instability. Described in the Methods section of our paper, we first calculated the knee displacements as the absolute distance of the tibia relative to the femur. We also calculated the component of the translations along the anterior/posterior axis, using the approach described by Grood and Suntay,[2] as reported in the Results section, to identify the instability as primarily anterior tibial movement relative to the femur. The difference in anterior tibial translation between the giving-way and non–giving-way trials at 18% of stance is 5.7 mm. As noted in the paper, measurement error due to skin movement (artifact) typically obscures translation data. However, in some subjects the data may be valid.[6,7] Due to possible problems with skin artifact, we emphasized the patterns of knee displacement as a marker of knee instability, rather than focusing on the magnitudes of tibial translation, and we encourage readers to do the same.

We agree with the commentary that the increased knee extension moment after 12% of stance is a response to knee instability and not the cause of the giving-way event. The idea that the anterior tibial translation associated with the instability experienced by this subject may convert the pull of the patella tendon from an ACL antagonist to an ACL synergist is an additional explanation of why the subject responded to the instability by increasing the knee flexion angle and internal knee extension moment. We calculated the average length of the patella tendon at 51 ± 9 mm from magnetic resonance images of healthy subjects (n = 8; age range, 18–40 y). Given the average length of the patella tendon of 51 ± 9 mm, a 5.7-mm anterior shift in translation would change the angle of pull by 6.4° (6.4° = sin-1 [5.7/51]). Herzog et al[4] suggest the angle of pull of the patella tendon at 30° of knee flexion is approximately 10° to 15°. We agree that the increased anterior translation may have reduced the effect of the anterior pull of the patella tendon, yet our uncertainty in the absolute magnitude of the anterior translation values precludes us from knowing whether the patella tendon was actually converted to an ACL synergist.

Consistent with the commentary we acknowledge that the exact cause of the giving way during early stance is uncertain, however, we speculate that the muscle balance between the hamstrings and quadriceps failed to provide appropriate stabilization immediately following initial contact, at which point we suggest that the anterior pull of the patella combined with the ground reaction forces and internal knee adduction moment led to the giving way. Immediately following initial contact, the tibia is rapidly decelerating ($\approx 1260°/s^2$) until 6% of stance in preporation for foot flat near 15% of stance. Winter[9] described the internal knee flexion moment from initial contact to 6% of stance as a "byproduct of the hamstrings that are involved in a strong hip extensor moment."[9] We also propose that the hamstrings were acting to decelerate the anterior rotation of the tibia at initial contact during this step-down task. However, during the giving-way trial at this point of stance the internal knee flexion moment is decreased and the knee displacement increases coincident with when the knee extensors are becoming the agonist. At this point of stance, the knee displacements of the giving-way trials were similar to those of healthy subjects, suggesting that the knee was at neutral or in a stabilized position when the angle of pull of the patella tendon resulted in anterior displacement,[4] which may usually be partially restrained by the intact ACL.[1] What we propose is that the decreased role of the lateral stabilizers (passive and active), judged from the frontal plane moment, combined with a failure of the knee flexors to attenuate the onset of the knee extensors as the agonist, led to the knee instability at 4% to 6% of stance. Subsequently this was controlled by increased knee flexion angle and knee extensor moments later in stance.

In summary, we found the cause of the giving way more difficult to determine than the response with our present data. Early stance is complicated by significant muscle cocontraction and quickly changing knee moments. As indicated in the commentary and the paper, our choice to filter the ground reaction force at 8 Hz affected the magnitude of the knee moment data at initial contact. However, the patterns of the moments remain the same, and therefore the interpretation does not change. In our view, the key ideas that arise from these data for further testing are (1) that knee instability may not necessarily occur when shear forces are highest, but, rather, during periods of transition that require balance of muscle control, and (2) that combined loading states involving shear and internal knee adduction moments may lead to knee instability. We thank Dr. Andriacchi and Mr. Chaudhari for a stimulating discussion and hope this spurs further ideas related to the cause of knee instability during dynamic tasks.

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