The Journal of Bone & Joint Surgery

JB&JS

July 6
2011
Vol. 93-A No. 13
ISSN: 0021-9355
JBJS.ORG

EXCELLENCE THROUGH PEER REVIEW

Founded by the American Orthopaedic Association in 1903
The Official Scientific Publication of the AAOS

93-A pages 1185—1280

THE JOURNAL OF BONE AND JOINT SURGERY · VOLUME 93-A · NUMBER 13 · JULY 6, 2011 · JBJS.ORG

Laboratory Evaluation of the Pivot-Shift Phenomenon with Use of Kinetic Analysis

A Preliminary Study

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Background: Currently, a suitable and reliable noninvasive method to evaluate rotational stability in vivo in anterior cruciate ligament-deficient knees, particularly during sports movements, does not exist. We speculated that if there is a rotational instability, the patient would avoid reaching a high pivoting moment during pivoting activities as a defense mechanism, and that the ground reaction moment, as registered by dynamometric platforms, would be reduced. On the basis of this hypothesis, we developed a study using kinetic analysis to evaluate rotational stability under dynamic loading.

Methods: Thirty recreationally active athletes, including fifteen healthy subjects and fifteen with an anterior cruciate ligament-deficient knee, were recruited for this study. Patients performed jumping with pivoting with internal tibial rotation and external tibial rotation on the dynamometric platform with both the healthy and the injured limb. The quantitative results were graphically plotted, and the following parameters were evaluated: loading moment, pivoting moment, torque amplitude, loading slope, pivoting slope, percentage of pivoting with load, loading impulse, pivoting impulse, and maximum body rotation angle.

Results: There were no significant differences between the dominant and nondominant knees in the control group during the jumping with pivoting and external tibial rotation test with regard to the pivoting moment ($p = 0.805$), pivoting slope ($p = 0.716$), pivoting impulse 2 ($p = 0.858$), and pivoting impulse 3 ($p = 0.873$). In patients with a chronic tear of the anterior cruciate ligament, there was a significant decrease of the pivoting moment ($p = 0.02$), pivoting slope ($p = 0.005$), pivoting impulse 2 ($p = 0.006$), and pivoting impulse 3 ($p = 0.035$) during the jumping with pivoting and external tibial rotation test in the anterior cruciate ligament-deficient knee compared with the healthy, contralateral knee.

Conclusion: Kinetic analysis with use of a dynamic platform can objectively detect alterations of rotational stability in anterior cruciate ligament-deficient knees, which may allow this to be a useful research tool for evaluating treatment strategies in patients with anterior cruciate ligament injuries.

Level of Evidence: Diagnostic Level IV. See Instructions to Authors for a complete description of levels of evidence.

The KT-1000 arthrometer (MEDmetric, San Diego, California) is the benchmark for measuring for knee stability in vivo and for reporting outcomes of anterior cruciate ligament (ACL) reconstructions[1]. However, as only anterior tibial translation is measured, use of the KT-1000 arthrometer is therefore not appropriate for the evaluation of outcomes after ACL reconstruction. In fact, a poor correlation between subjective International Knee Documentation Committee (IKDC) scores and anteroposterior knee laxity, as measured by the KT-1000 arthrometer, has been reported[2]. On the contrary, a positive pivot-shift test is closely related to patient-reported instability with pivoting or cutting activities, poor subjective and objective outcome scores, and failure to return to the preinjury level of sport[2-4]. Moreover, patients with

Disclosure: None of the authors received payments or services, either directly or indirectly (i.e., via his or her institution), from a third party in support of any aspect of this work. None of the authors, or their institution(s), have had any financial relationship, in the thirty-six months prior to submission of this work, with any entity in the biomedical arena that could be perceived to influence or have the potential to influence what is written in this work. Also, no author has had any other relationships, or has engaged in any other activities, that could be perceived to influence or have the potential to influence what is written in this work. The complete **Disclosures of Potential Conflicts of Interest** submitted by the authors of this work are available with the online version of this article at jbjs.org.

a positive result on the pivot-shift test are more prone to osteoarthritis[5]. While accurate assessment of the pivot-shift test is clinically important, the pivot-shift test, which evaluates rotational stability, is a subjective measurement with low sensitivity and low interobserver reliability as well as high variability, depending on the tester's experience and ability[6]. Moreover, the rotational load applied to the knee during the pivot-shift test is much lower than the load applied to the knee during sports activities. Therefore, a negative result on the pivot-shift test does not necessarily imply a normal rotational stability. There is a need for an objective method to evaluate in vivo rotational stability during dynamic functional activities.

It is well known that patients with chronic tears of the ACL modify their running, attempting to run in a straight line to avoid pivoting, because the knee will give way if they pivot. On the basis of this observation, we hypothesized that, if there is a rotational instability in the knee, the patient will avoid reaching high moments, generated by the foot stepping on a dynamometric platform, during pivoting activities, and the pivoting ground-reaction moment would also be reduced. On the basis of this hypothesis, we developed a study using kinetic analysis to assess rotational stability of the knee in vivo during dynamic functional activities.

To our knowledge, no study of rotational stability with use of kinetic analysis has been published. The purpose of our study was to determine the utility of kinetic analysis to detect functional deficits in ACL-deficient knees and to determine parameters of knee function that are affected by an ACL deficiency.

Materials and Methods

Subjects

Thirty recreationally active athletes who participated in sports that included jumping, cutting, and/or pivoting were recruited for this study. Prior to participation in this study, all enrolled participants signed an informed consent agreement. This study was approved by our institutional review board. The participants were divided into two groups. Group I consisted of fifteen patients with an isolated (no associated ligament, meniscal, or chondral injury and no degenerative changes), chronic ACL tear (defined as one that had been present for more than three months) confirmed arthroscopically, with a mean follow-up of nine months (range, four to eighteen months) in one knee and no injury or disease of the contralateral limb or of the hip or ankle of the involved limb. All of the patients followed a supervised home physical therapy program for at least three months after the ACL tear. None of the patients were able to return to their previous level of sports because of knee instability when pivoting. We did not include any patient who compensated for his or her instability after a physical therapy program. All patients were evaluated for the pivot shift with use of the Losee test (the tibia in internal rotation)[7] and the Clancy test (the tibia in external rotation)[8], with the patient awake and under anesthesia, and the pivot shift was graded as 1+ (glide), 2+ (jump), and 3+ (a transient lock). The pivot-shift test was grade 2+ in twelve patients, grade 3+ in one patient, and no pivot shift was found in two patients, either during the examination while awake or under anesthesia, even though both patients had instability when practicing soccer. Group II consisted of fifteen healthy subjects free of injury in both limbs with no history of traumatic injury of the lower extremities and matched by sex, age, height, weight, and activity level to the patients in Group I. To determine which limb was dominant, the participants were asked, "With which leg do you kick a ball? With which leg do you fake, jump, or pivot?"

Kinetic Analysis Instruments and Dynamometric Platforms

Kinetic analysis was performed with use of the dynamometric platform Dinascan/IBV (Instituto de Biomecánica de Valencia, Valencia, Spain), installed flush within the floor[9]. When a force acts on the dynamometric platform, it is distributed among transducers and the generated torque is also transmitted to the knee by means of the tibia. The dynamometric platform registers the forces exerted by the subject against the ground and determines the exact point of application underneath the foot, which is called the center of pressure. We consider that the moment registered with the platform could be a good estimation of the real torsional moment of the knee because the center of pressure nearly coincides with the vertical projection of the center of rotation of the knee, as we demonstrated after stereophotogrammetric studies (unpublished data).

Tasks Proposed for Evaluation of the Pivot-Shift Phenomenon

One way to twist the knee around a vertical axis is to twist the body while standing with the same foot planted. We proposed two tasks for evaluating the pivot-shift phenomenon: (1) jumping on one foot and pivoting with internal tibial rotation, and (2) jumping on one foot and pivoting with external tibial rotation. The first task reproduces the pathomechanics of an ACL injury and the classic Losee test[7]. The second task reproduces also the pathomechanics of ACL injury and the Clancy and Petermann tests[8,10]. Subjects perform these provoking activities on dynamometric platforms with both the injured and healthy limbs. We measure the force that the patient can tolerate while actively stressing the knee, simulating the mechanism that reproduces the patient's symptoms.

The Problem: What Should We Compare?

There is great variability in pathological motion in ACL-deficient knees. Liu and Maitland[11] speculated that it is multifactorial, possibly including the degree of ACL injury, mechanical properties of the remnant tissue, muscle strength around the knee, the unique articular anatomy (especially the slope of the tibial plateau) of the patient, or the contribution of unrecognized additional soft-tissue injury. Thus, the injured and normal knees were compared.

Laboratory Procedures

The subject is placed in a standing position on the platform, facing a reference point with the arms extended alongside the body. When indicated by the examiner to start the motion, the subject lifts up the uninvolved limb and keeps the one under study in full knee extension. Next, the subject flexes the involved knee and rotates the body in the direction opposite to the intended spin, in order to reach the joint's maximum contrary rotation, a maneuver termed the loading phase. The second part is the pivoting phase, which begins when the loading phase is completed. The subject begins rotating in the intended spin direction while extending the knee to push him or herself upward. For the analysis to be effective, the pivoting phase has to be fast and explosive to achieve maximum rotation demand on the knee. Our protocol requires a maximum effort on behalf of the patient when performing the jumping with pivoting. We define maximum effort as the energetic use of the maximum intensity of physical strength to perform jumping with pivoting. The biomechanical effort to perform the twist with the jumping and pivoting test is directly related to the body twist angle that determines the impulse or energy with which the test is performed. After a preliminary study, we decided not to include patients with a body twist angle of <90° (unpublished data).

The participants performed three practice trials prior to data collection followed by five tests using suitable sport shoes. We considered footwear to be adequate if the shoes had soles in good condition to avoid sliding during the performance of the pivoting gesture. The sequence of testing with the uninvolved and involved lower extremity was randomized to prevent an order effect[12].

Inclusion and Exclusion Criteria

To be included in our study group, all of the patients had to perform the jumping with pivoting test without pain. Moreover, they all responded yes to the following question: "Do you believe that your limitation when performing the test is because you think that your knee is going to give way?" In all cases, the limitation when performing the test was "the fear of instability or giving-way." None of the patients subjectively thought that muscle weakness limited their test performance. The evaluation of the proprioceptive relationship between the healthy limb and the injured limb, with use of the dynamometric platform, did not indicate any alteration in proprioception.

Data Analysis

We measured the torques and forces produced on the platform by the limb being tested during the jumping phase, immediately prior to the flying phase. Kinetic parameters are expressed in a curve with two humps: one positive and one negative (Fig. 1). For curves to be comparable, we normalized the moments with the moment of inertia. We removed the curves obtained from gestures that did not follow the established protocol, and recalculated a coherent average curve using a spline-fitting technique to enable curve shape comparison.

We calculated the following parameters: (1) loading slope—the speed with which the subject develops the torque on the platform during the loading phase; (2) loading moment—the maximum torque generated by the foot standing on the dynamometric platform during the loading phase; (3) loading impulse—the area enclosed by the curve during the loading phase; (4) pivoting slope—the speed with which the torque is developed during the pivoting phase; (5) pivoting moment—the torque generated during the pivoting phase; (6) torque amplitude—the difference between the loading moment and the pivoting moment; (7) pivoting impulse—the areas enclosed by the different sections of the curve describing the pivoting phase; (8) percentage of pivoting with load (Fz); and (9) the maximum body rotation angle during the test.

Statistical Analysis

Kinetic data from the five trials for each subject were averaged. The Student t test was performed to compare the results between two categories of the same variable; in this case, one limb was compared with the contralateral limb. A p value of <0.05 was considered significant. The power analysis was completed before our study was performed. The number of subjects necessary to obtain a beta value of 0.8 and an alpha value of 0.05 was ten per group. However, we recruited fifteen patients per group to compensate for unpredictable losses, as occurred in Group II, in which four patients were lost.

Source of Funding

There was no external funding source.

Results

Control Group

During the jumping and pivoting with external tibial rotation test, we observed no significant difference between the dominant and nondominant limb with regard to the following parameters: loading moment ($p = 0.065$), loading slope ($p = 0.387$), loading impulse ($p = 0.100$), pivoting moment

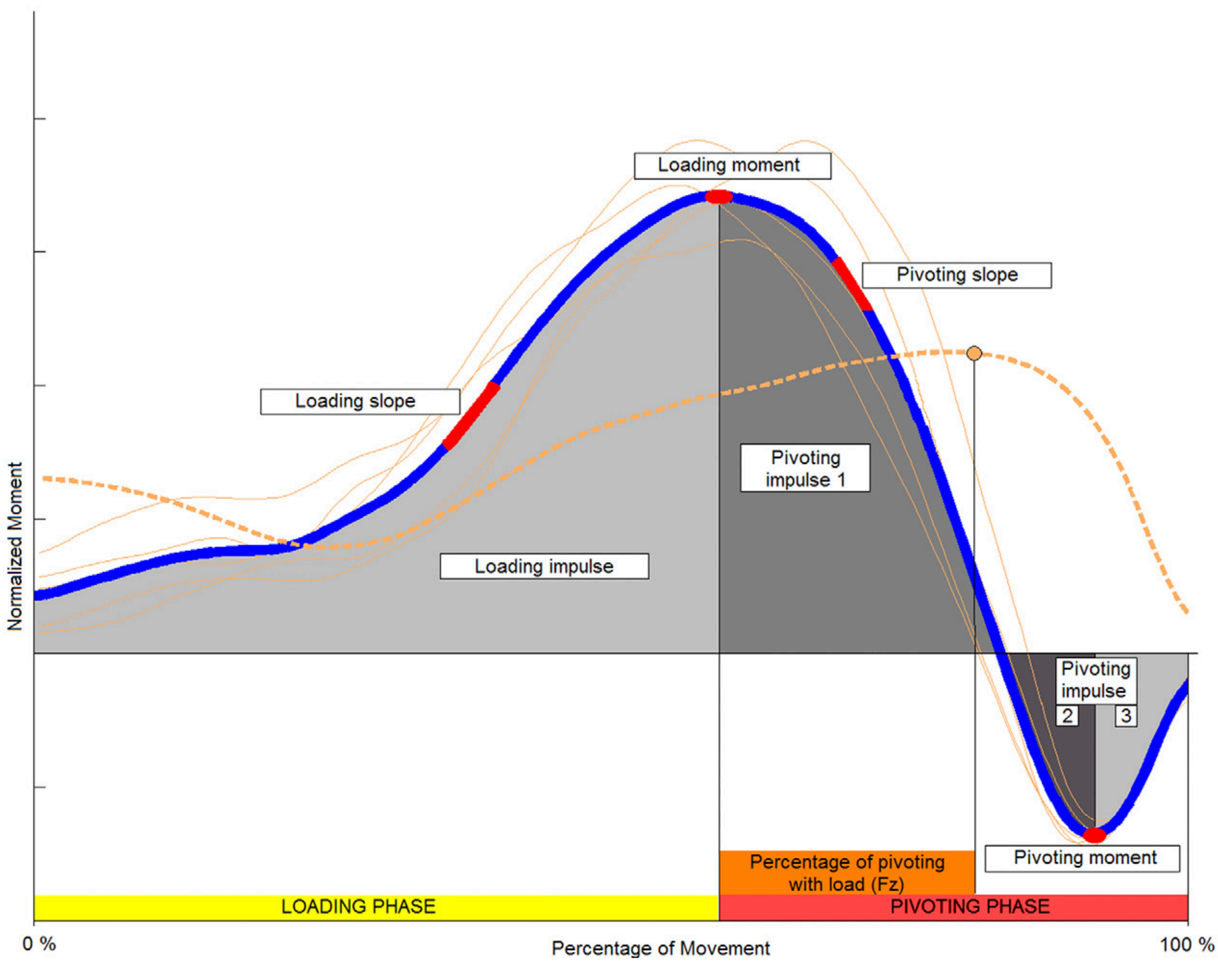

Fig. 1

Kinetic parameters analyzed.

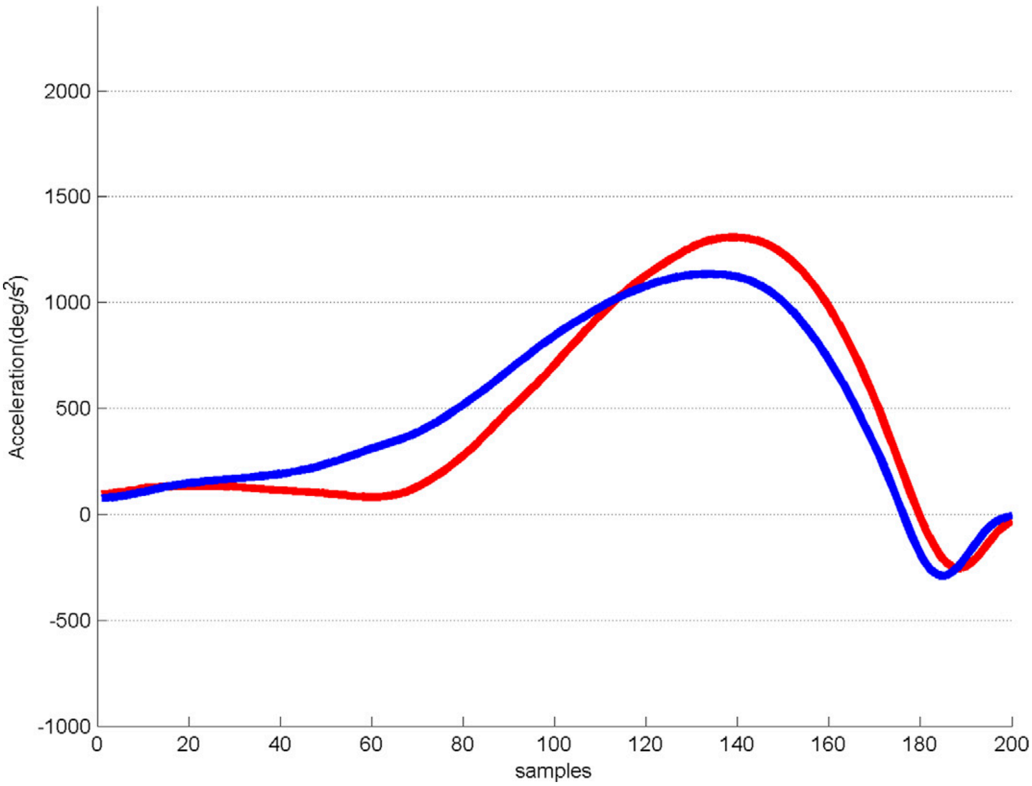

Fig. 2-A

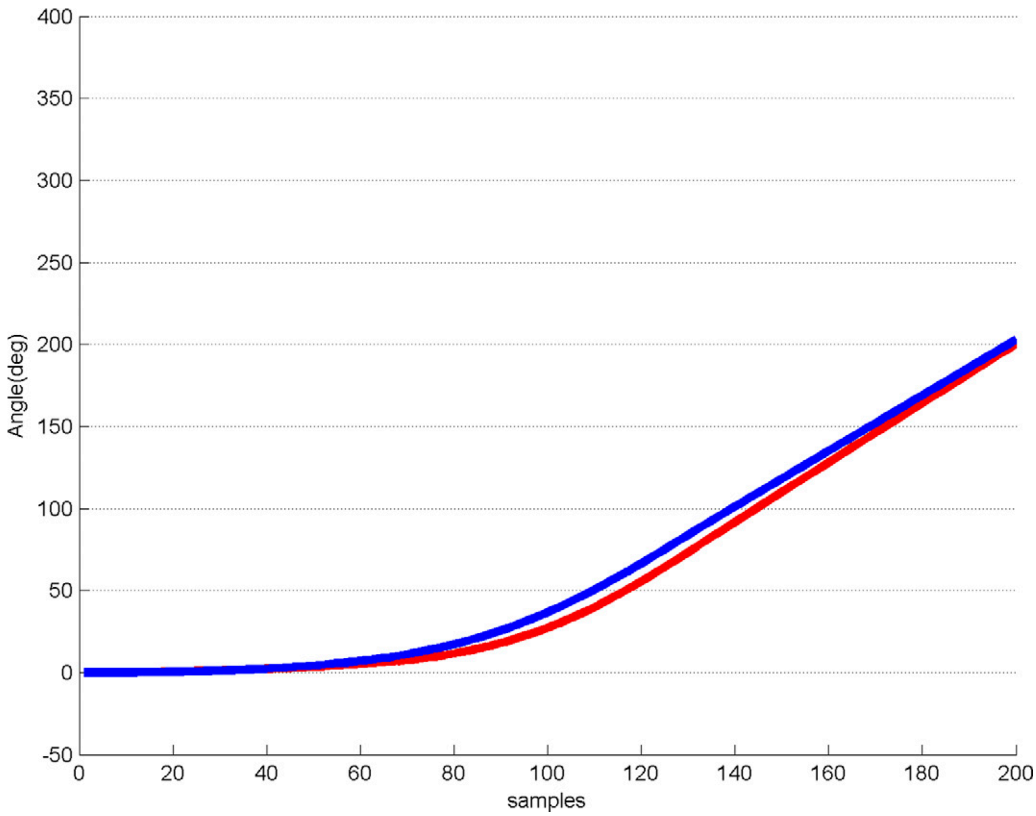

Fig. 2-B

Figs. 2-A and 2-B Plot of findings in a volunteer subject with normal knees. The graph shown in Fig. 2-A represents the curves for the normalized moments while jumping with pivoting and external tibial rotation. The graph shown in Fig. 2-B represents the body twist angle during the same task. The red line indicates the right knee, and the blue line indicates the left knee.

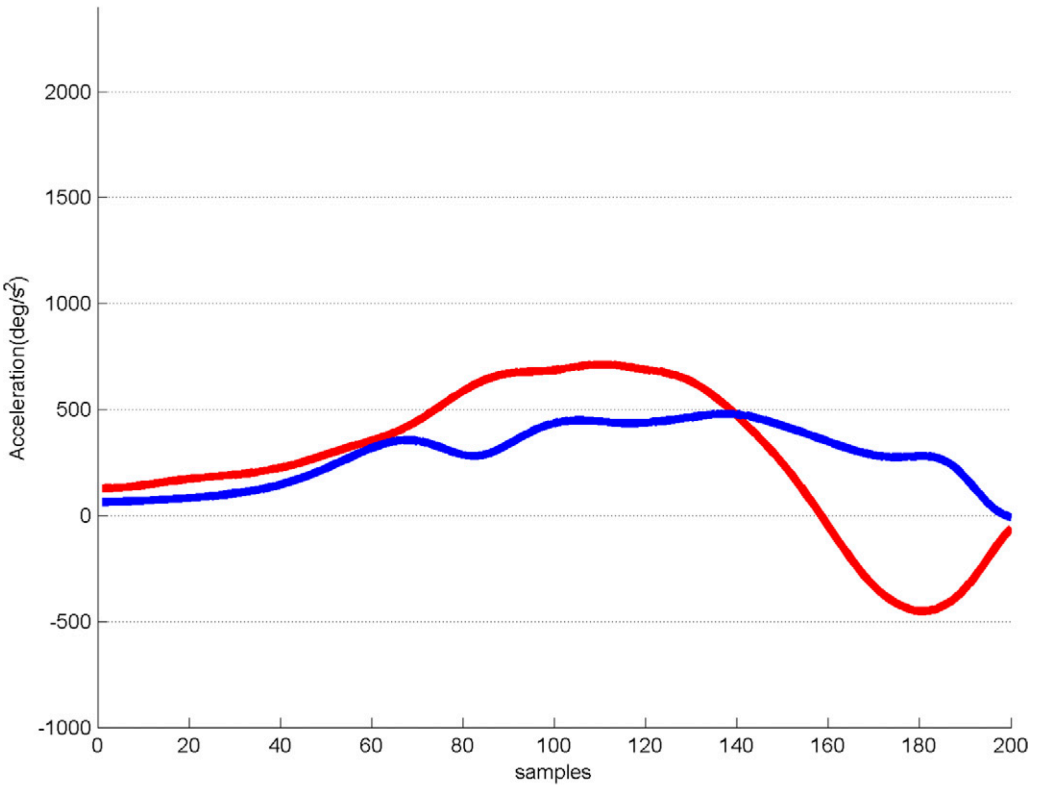

Fig. 3-A

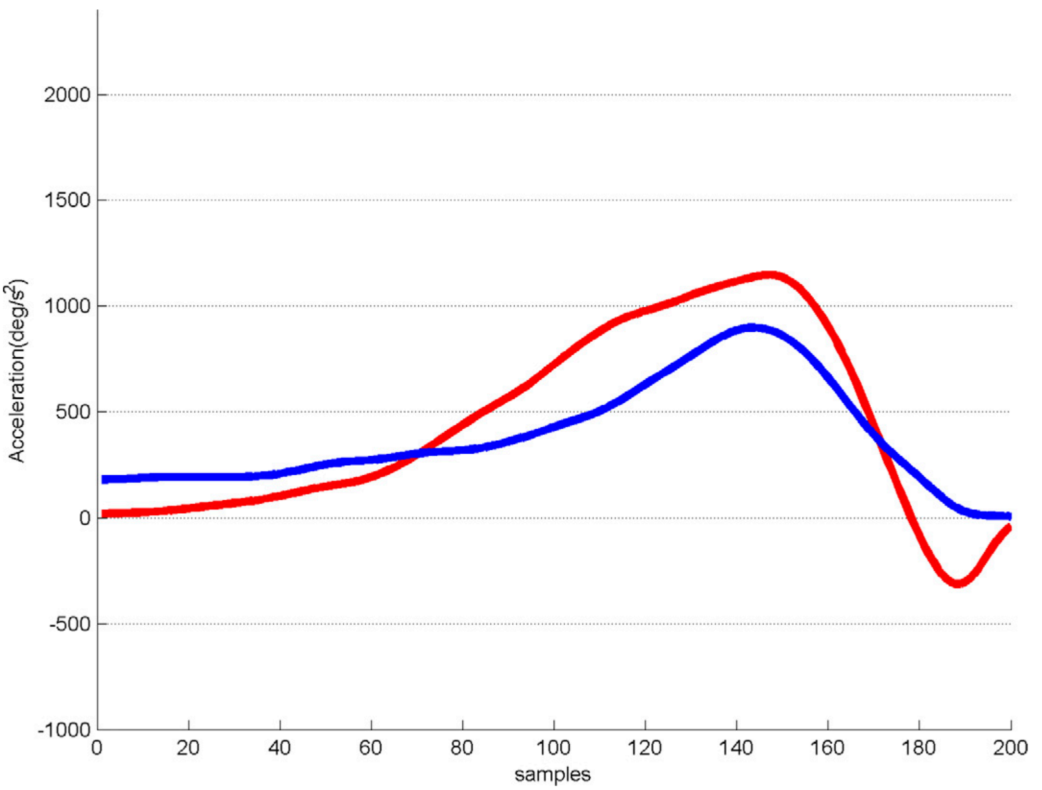

Fig. 3-B

Figs. 3-A and 3-B. Graphs showing results for a sixteen-year-old male patient with an isolated chronic ACL tear in the left knee. The right knee is dominant. The pivot-shift test was grade 3+ with the patient awake. **Fig. 3-A** The graph represents the curves for the normalized moments and the vertical reaction force (Fz) registered during the jumping and pivoting with internal tibial rotation test. **Fig. 3-B** The graph represents the same curves during the jumping with pivoting and external tibial rotation. The red line indicates the right knee, and the blue line indicates the left knee.

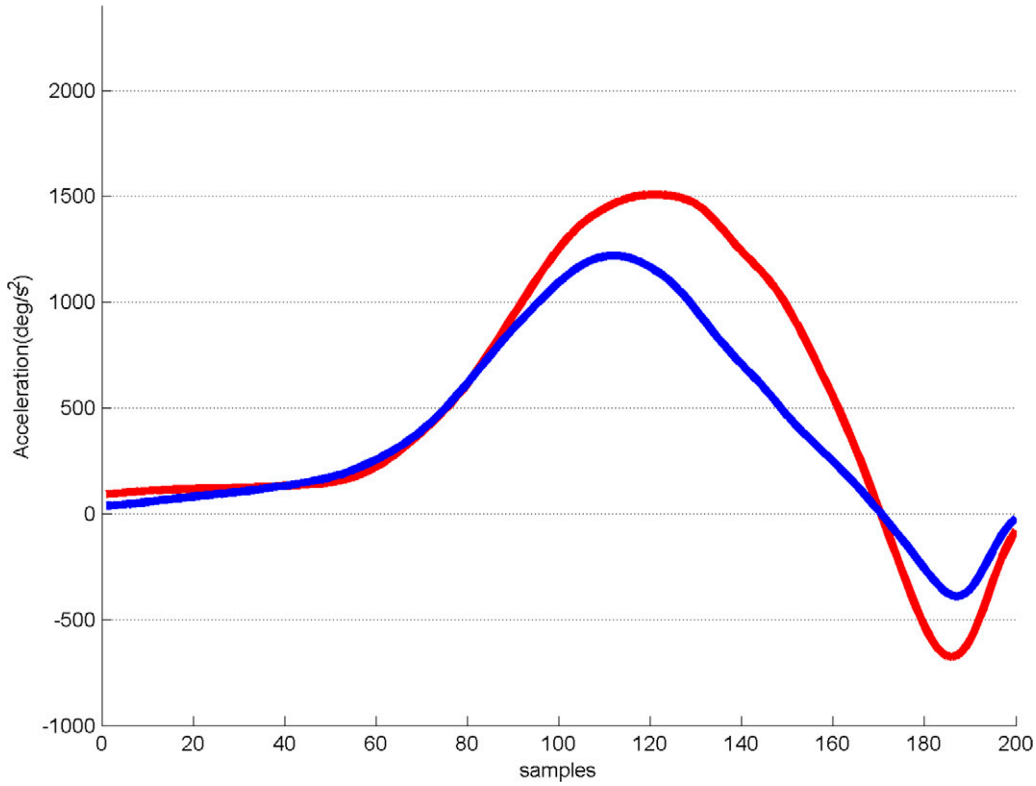

Fig. 4-A

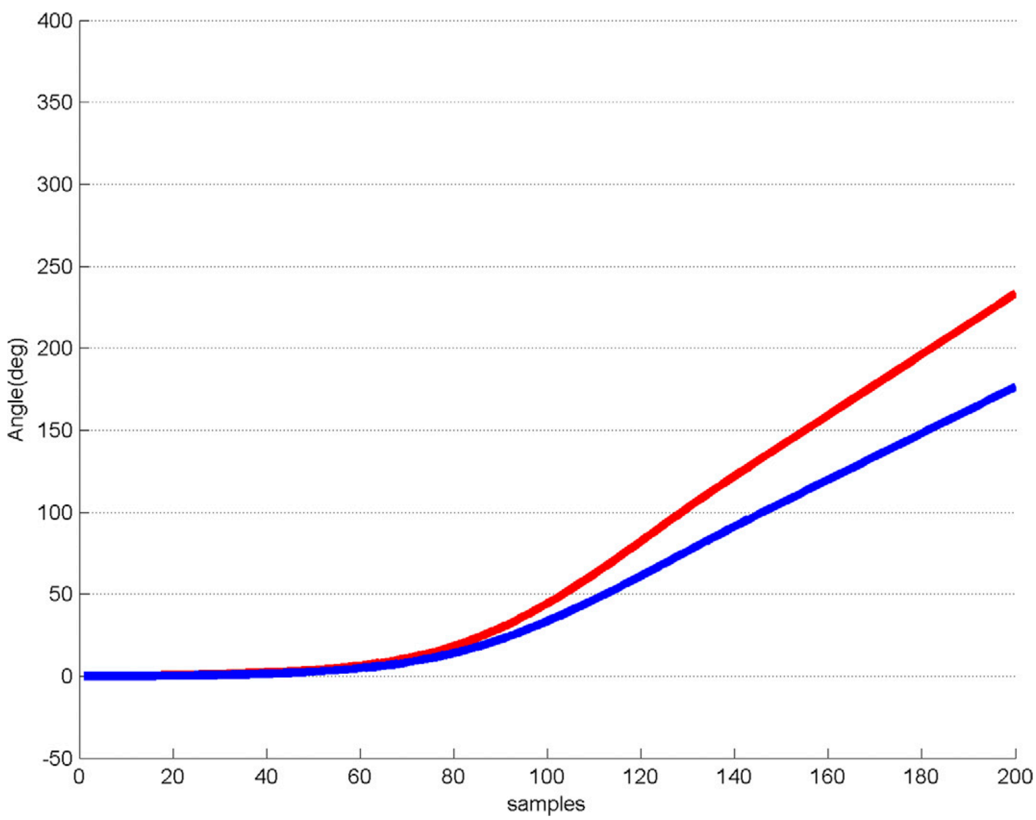

Fig. 4-B

Figs. 4-A through 4-E A patient with left limb dominance who had an isolated chronic ACL tear in the left knee. A positive pivot-shift test with the patient awake was increased with tibial external rotation. The red line indicates the right knee, and the blue line indicates the left knee. **Fig. 4-A** Curves for the normalized moments registered during the jumping with pivoting and external tibial rotation test. **Fig. 4-B** Body twist angle during the same task.

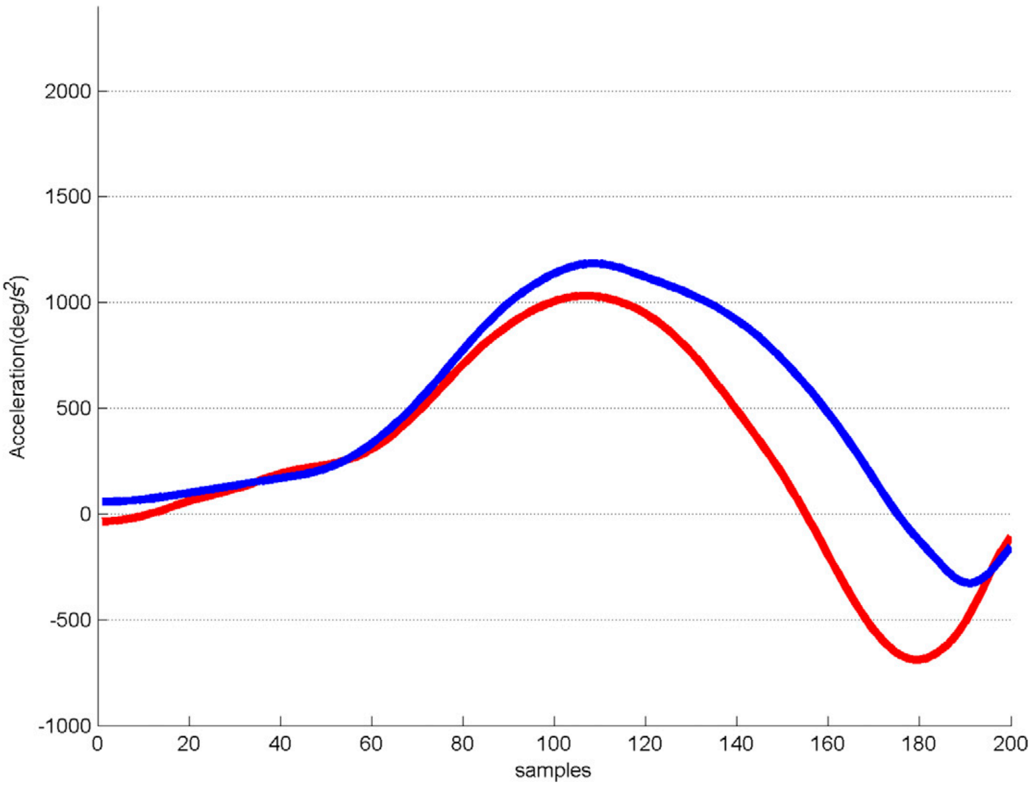

Fig. 4-C

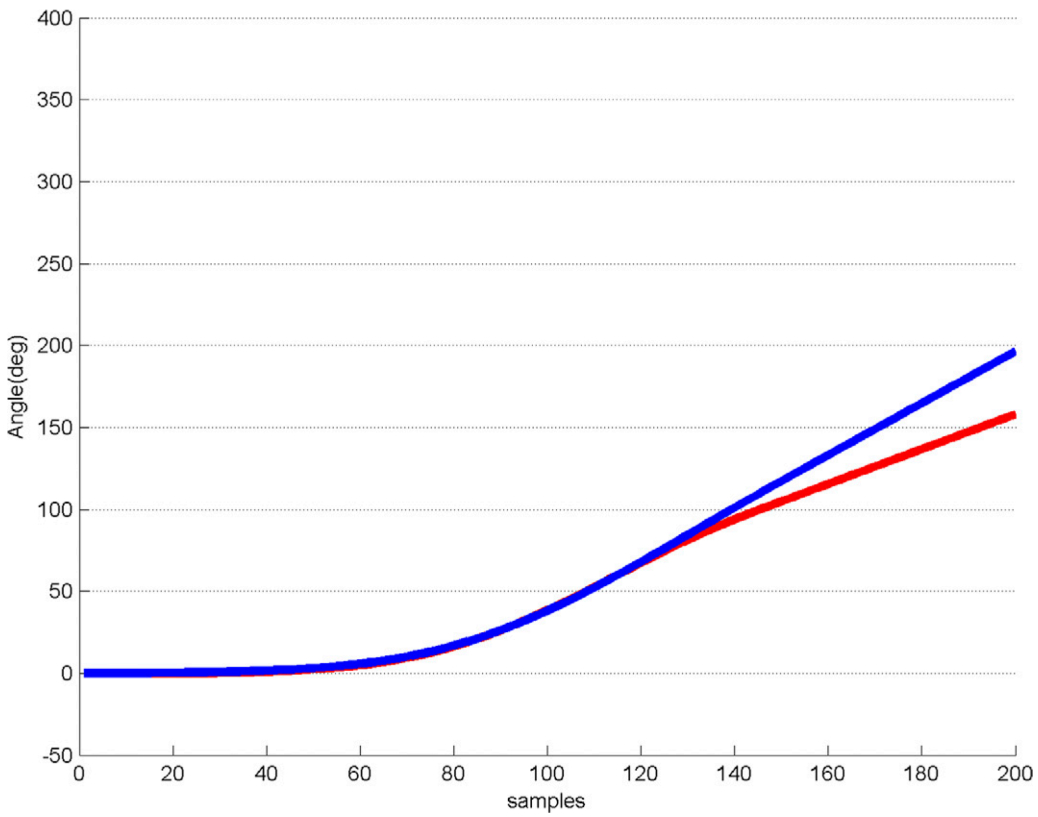

Fig. 4-D

Fig. 4-C Curves for the normalized moments registered during the jumping with pivoting and internal tibial rotation test. **Fig. 4-D** Body twist angle during the same task.

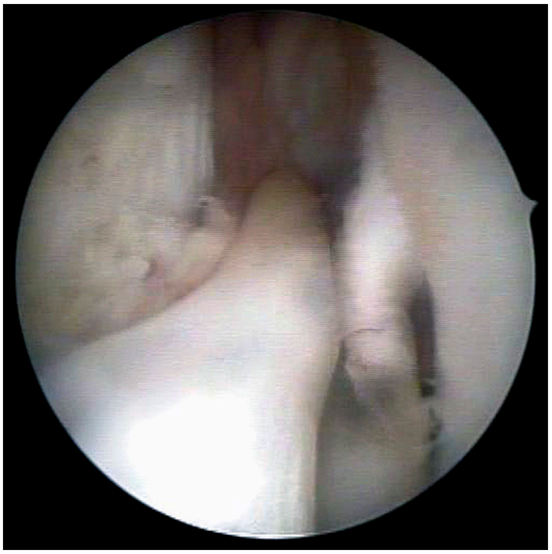

Fig. 4-E
The diagnosis of an ACL tear was confirmed arthroscopically.

(p = 0.805), pivoting slope (p = 0.716), pivoting impulse 2 (p = 0.858), pivoting impulse 3 (p = 0.873), and torque amplitude (p = 0.105). The remaining kinetic parameters (pivoting impulse 1, percentage of pivoting with load, and maximum body rotation angle) demonstrated significant differences ($p < 0.05$) influenced by limb dominance. Therefore, the parameters not influenced by limb dominance are the ones used for comparative studies (Figs. 2-A, 2-B, and Appendix).

In the jumping and pivoting with internal tibial rotation test, we observed no significant difference between the dominant and nondominant limb with regard to the following kinetic parameters: loading moment (p = 0.057), loading impulse (p = 0.306), pivoting moment (p = 0.331), pivoting impulse 2 (p = 0.323), pivoting impulse 3 (p = 0.260), torque amplitude (p = 0.317), pivoting slope (p = 0.452), body rotation angle (p = 0.077), and percentage of pivoting with load (p = 0.981). The other parameters (loading slope and pivoting impulse 1) showed significant differences ($p < 0.05$) influenced by limb dominance. The parameters not influenced by limb dominance were used for comparative studies (see Appendix).

ACL-Deficient Group

The kinetic study was normal in two of the fifteen patients with an ACL injury. Both patients had rotatory instability only when practicing soccer. They had a negative pivot-shift test during physical examination, and the kinetic parameters with the tests performed with maximum effort were also normal. Both patients indicated the tests were not as demanding as their activity during soccer. We excluded two patients because they made no special effort during the test, performing it with a body twist angle of <90° (25° for one patient and 50° for the other patient). In both patients, despite the rotational instability with a positive pivot-shift test during physical examination and the effect on the activities of daily living, the kinetic parameters did not reflect the impact on daily activity, possibly because of the small impulse these patients used during testing. Therefore, the results of our study are based on the eleven remaining patients.

The shape of the curve obtained while jumping and pivoting with external tibial rotation is highly reproducible (Figs. 3-A through 5-D). With this test, there are more altered kinetic parameters than while jumping and pivoting with internal tibial rotation. In most patients, the feeling of subluxation by the examiner during the physical examination was increased with external rotation, both with the patient awake and while under anesthesia, although the grade of the pivot shift remained unchanged. The sensitivity of the shape of the curve to evaluate the pivot-shift phenomenon was 84.6%, similar to the sensitivity of the physical examination with the patient under general anesthesia (87.5%), and much higher than the sensitivity of the physical examination with the patient awake (37.5%).

With the jumping and pivoting with external tibial rotation test, we observed a significant decrease in the parameters not influenced by limb dominance: pivoting moment (p = 0.023), pivoting slope (p = 0.005), pivoting impulse 2 (p = 0.006), pivoting impulse 3 (p = 0.035), loading moment (p = 0.008), loading slope (p = 0.011), loading impulse (p = 0.039), and torque amplitude (p = 0.005) (see Appendix). In the jumping with internal tibial rotation test, we observed a significant decrease in the following parameters not influenced by limb dominance: pivoting impulse 2 (p = 0.041), pivoting impulse 3 (p = 0.025), and percentage of pivoting with load (p = 0.012) (see Appendix).

Discussion

Much of the current knowledge about ACL biomechanics has been derived from cadaveric studies under controlled laboratory conditions. However, only in vivo studies can assess the combined effects of tissue healing and neuromuscular control on joint function. Among all of the techniques available to analyze the rotational stability in vivo in the ACL-deficient knee, kinematic analysis is the most widely used[13]. However, this technique has a number of disadvantages: (1) the impossibility of measuring the internal knee torques, limiting the understanding of the internal stress on the knee during a task that involves rotation[14,15]; and (2) the movement of skin, fat, or muscle around the bone affects the marker position and can cause error in the analysis[16]. Other in vivo techniques, such as dynamic magnetic resonance imaging, computer-assisted navigation, and three-dimensional radiostereometric analysis, are limited to environments too restrictive to perform high-demand activities[17-19].

According to Strobel and Stedtfeld[20], functional tests are designed to reproduce the symptomatic subluxating process or to provoke an “avoidance behavior” to guard against subluxation, which likewise is interpreted as a positive sign. Kinetic analysis, with use of dynamometric platforms, allows us to evaluate in vivo the avoidance behavior of the injured knee under realistic loading conditions.

An objective measurement of a subjective concept like a so-called defense mechanism is difficult and can be influenced by many variables. We were concerned initially that pain, muscle weakness, and a decrease in proprioception in patients with a chronic ACL tear could negatively influence the performance of

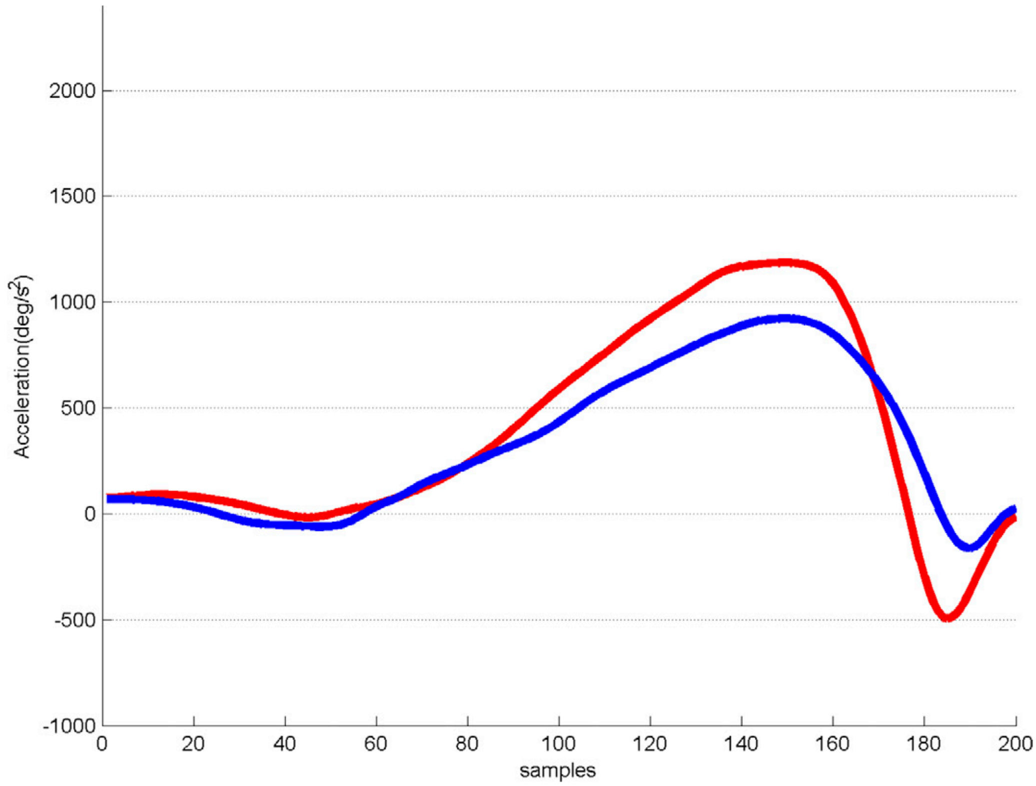

Fig. 5-A

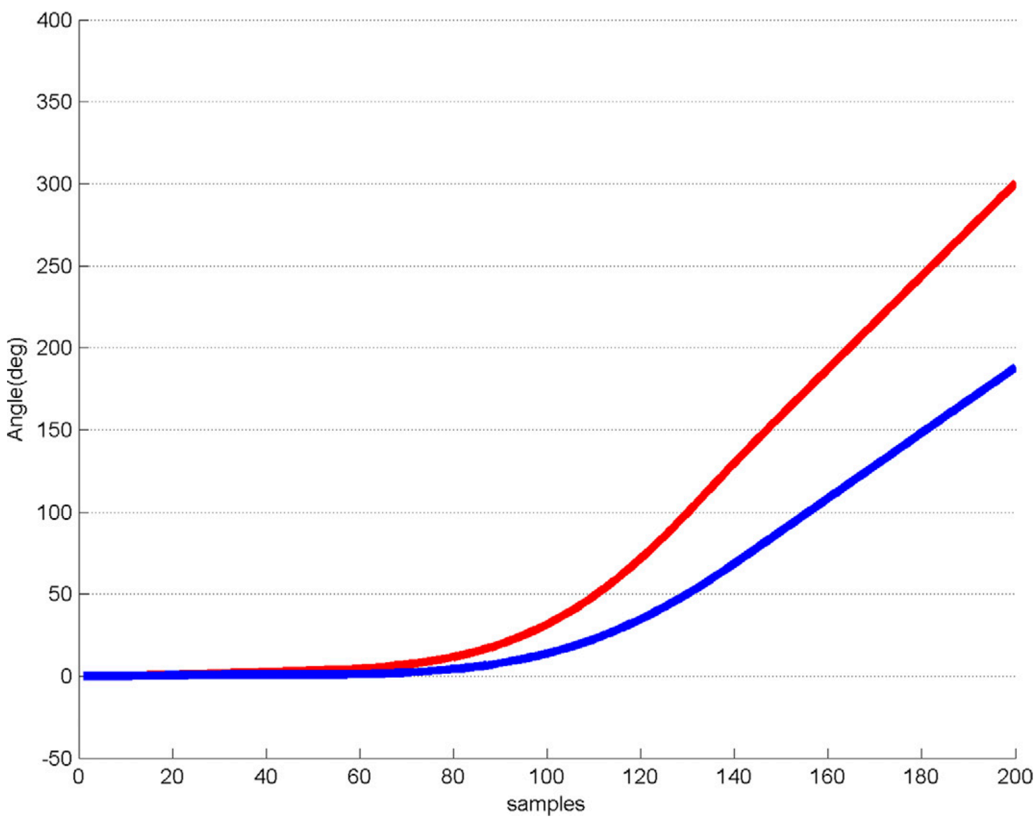

Fig. 5-B

Figs. 5-A through 5-D A patient with an isolated ACL tear in the left knee who had six months of follow-up. Rotatory instability occurred only when playing football. The right limb was dominant. The patient had a positive pivot-shift test under anesthesia with an extra amount of compression applied to the lateral compartment of the knee by an assistant during testing. When the patient was awake, the pivot-shift test was negative. The red line indicates the right knee, and the blue line indicates the left knee. **Fig. 5-A** Curves for the normalized moments registered during the jumping with pivoting and external tibial rotation test. **Fig. 5-B** Body twist angle during the same task.

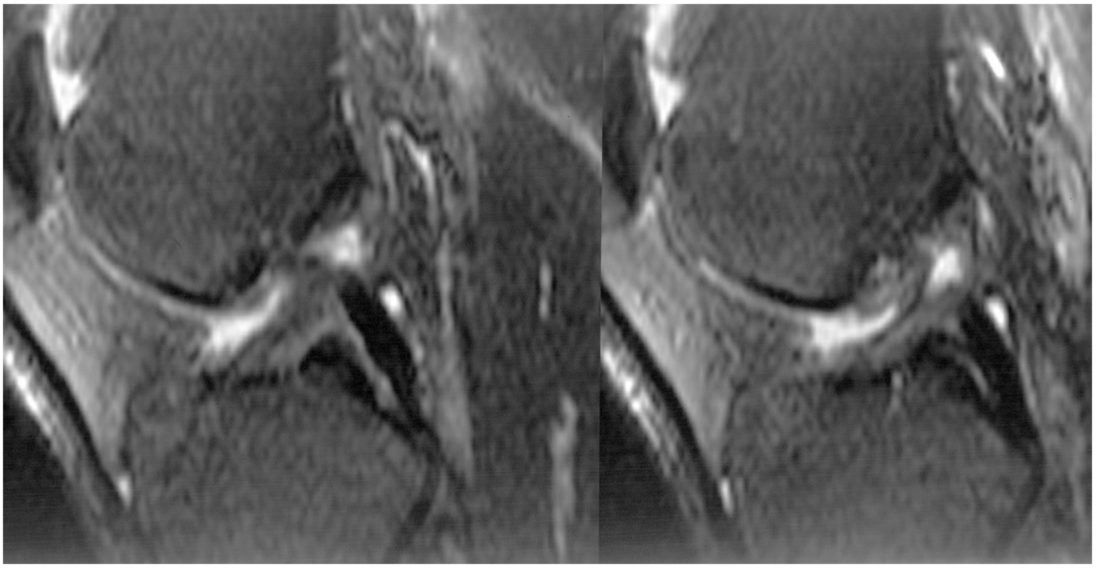

Fig. 5-C

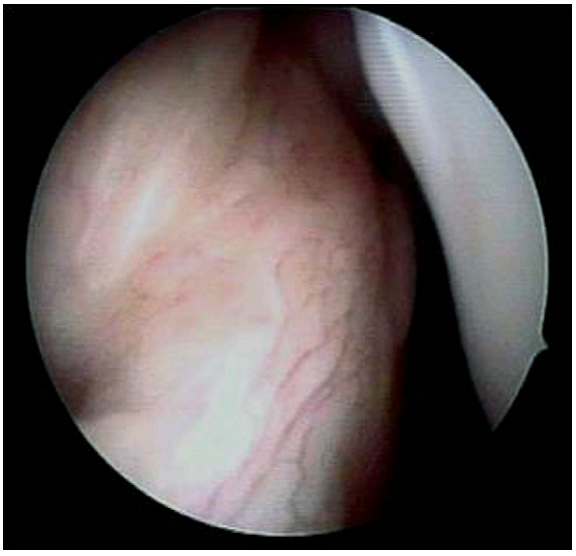

Fig. 5-D

Fig. 5-C T2-weighted magnetic resonance image showing the ACL adhered to the posterior cruciate ligament. **Fig. 5-D** The diagnosis of an ACL tear was confirmed arthroscopically.

the tasks and result in altered kinetic parameters. To be included in this study group, all of the patients had to perform the test without pain. While none of the patients subjectively believed they had muscle weakness that limited their test performance, we have not performed an objective evaluation of muscle strength using isokinetics. Tsepis et al.[21] examined the strength of the quadriceps and the hamstrings in amateur soccer players with an ACL-deficient knee and noted that the strength deficit of the hamstrings (19.2%) was an indicator of poor knee function, since they were significantly weak only in the group with a low Lysholm score. In a preliminary study (unpublished data), we did not note a direct relationship between a reduction in hamstring muscle strength (50%) and a significant reduction of the kinetic parameters in pivoting. Also, we did not note a direct relationship between the reduction of quadriceps muscle strength (20%) and a significant reduction of the kinetic parameters in pivoting. We included only patients with normal proprioception because it has been reported that decreased proprioception in patients with an ACL deficiency reduced their functional ability[22,23]. Finally, we included only patients with isolated ACL tears so that associated lesions could not influence the kinetic parameters studied.

Our proposed tasks duplicate muscle forces[7] (the sling-shot effect and neutral anterior shift effect) and rotational loads caused by sports movements (higher than the load applied to the knee during the clinical pivot-shift test). This is crucial because muscle forces play an important role in knee stability, especially in the ACL-deficient knee[24].

Kinetic tests were performed by specialized personnel in a specialized biomechanics laboratory for our study. Currently, this method is not available for routine use in daily clinical practice. Another drawback is the high cost of the platform (US$35,000 and installation costs).

Our results supported our hypothesis that, if there is a rotational instability in the knee, the patient would avoid reaching the high moments generated by the foot standing on the dynamometric platform during the pivoting phase in extreme pivoting activities as a precaution and safety measure, and therefore the ground reaction moment would be reduced. The analysis of the shape of the torque-time curves obtained after measuring the action-reaction loads in the dynamometric platform shows an important decrease in the moment in the pivoting phase in the ACL-deficient knees. We also noticed a decrease in the pivoting impulse and thus in the energy absorbed by the ligament during the pivot, i.e., a mechanism that makes the ligament work less. We also observed a significant decrease in the slope of the curve during the pivoting phase, implying that the patient performs the pivoting with less speed as a defense mechanism. Finally, the patient avoids reaching high axial forces (Fz) during pivoting activities as a defense mechanism. It is important to remember that an axial load of the knee is necessary for the pivot shift to be a symptomatic functional limitation[7]. We observed a significant decrease in the percentage of pivoting with load in the jumping and pivoting with internal tibial rotation test in ACL-deficient knees compared with the healthy, contralateral knee.

We also observed kinetic false-negative results. Fetto and Marshall[25] sectioned the ACL in thirty-seven fresh cadaver knee specimens and produced a positive pivot-shift test in only thirty-three (89%). A positive pivot-shift test indicates not only ACL laxity but also injury to secondary extra-articular ligament restraints, such as the iliotibial band and lateral capsule[7].

As expected, we found similar avoidance behaviors during jumping and pivoting with internal tibial rotation and during the same test with external tibial rotation, since both reproduce the ACL injury mechanism and therefore the subluxation test. However, the number and grade of altered kinetic parameters was significantly higher in the test performed with external tibial rotation. Our kinetic findings are in accordance with the clinical findings[9,10]. Finally, although the kinetic analysis is a very sensitive test (84.6%), it is completely nonspecific and the results are similar to those observed in patients with lateral patellar instability (unpublished data).

We did not attempt to identify a correlation between the clinical grade of the pivot shift and the magnitude of the kinetic parameters. A positive pivot-shift test, independent of the grade, is indicative of a functionally deficient ACL[26], so we believe it is not important to correlate the pivot-shift grade with the magnitude of the kinetic parameters.

This study provides support for the proposition that kinetic analysis appears to be an objective and useful research tool that allows us to study the pivot-shift phenomenon and rotational stability in ACL-deficient knees. However, kinetic analysis cannot be used for an acute ACL injury, in the presence of marked muscle weakness, and with bilateral knee injury. Currently, kinetic analysis for ACL injury assessment is a research tool that may be applicable to daily clinical practice in the future.

Appendix

eA Tables showing the measurements for the dominant and nondominant limbs in the control group and for the injured and healthy limbs in the pathologic group during the jumping and pivoting with external tibial rotation and internal tibial rotation tests are available with the online version of this article at jbjs.org. ■

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