Instrumented Arthrometry for Diagnosing Partial Versus Complete Anterior Cruciate Ligament Tears

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Abstract:

Nineteen patients with the clinical diagnosis of anterior cruciate ligament injury were examined by KT-1000 arthrometry before arthroscopy in an effort to differentiate partial from complete tears. To this end, the KT-1000 arthrometer was equipped with a strain gauge and processor that permitted the required force to increase the anterior displacement by 1-mm increments, to be read on a light-emitting diode. The measured force has been plotted against anterior displacement expressed in nonlinear increments along the x-axis to allow for the viscoelastic nature of the ligament. The results show that stress-strain diagrams of partially torn and completely torn ligaments are similar to those obtained by graded stress radiography. Using arthroscopy as the standard of measurement, partial tears can be differentiated from complete tears with a sensitivity of 80% and a specificity of 100%. The figures for complete tears versus partial tears are 100% and 80%, respectively. Graded arthrometry with x-y recording of the force-displacement relationship that allows for the viscoelastic qualities of ligament further extends the capabilities of instrumented arthrometry.

Ligament testing devices are capable of objectively quantitating the clinical grading of knee joint laxity, particularly in patients with injury to the ACL.[9] Diagnostic cutoff values have been established for tests performed at 15- pound (67 N) and 20-pound forces (89 N), and similar data are available for the compliance index, which measures the difference between results of the 89 and 67-N tests. [3,4] In addition, side-to-side differences measured between the injured and the contralateral uninjured knees have been routinely reported for both acute and chronic ACL-deficient knees.[9]

None of these tests, however, specifically addresses the problem of the differentiation of partial and complete ACL tears. It has been well established that significantly different clinical outcomes can be expected from nonoperative treatment of acute partial tears and complete tears.[2] addition, large partial tears show the increased risk of leading to a complete tear.[6] It is obvious, therefore, that a ligament testing technique that could assess the extent of a partial tear would be most useful in the decision between conservative management and surgery.

Using a modified KT-1000 arthrometer, we have examined 19 patients with clinical suspicion of ACL injury in an effort to determine the stress-strain pattern of the injured ACL and that of the opposite normal knee. Previous work on the use of graded stress radiography in distinguishing partial from complete tears has shown that, for small elongations, the stress-strain behavior of ACL ligaments follows the same pattern as that observed for ideal rubber.[8] Here, the force required to stretch the length 1_0 of the unstretched ACL, assumed to be 38 mm, to length I is ex- pressed by F = G (α — 1/$α^2$), where a equals $l/_{lo}$ and G represents the elastic modulus of the ligament. According to the viscoelastic theory of rubber elasticity, G is proportional to the number of elastic elements per volume unit of ligament.[10] In vitro stretching of the ACL has shown that the ligament follows viscoelastic theory for as much as 20% stretch over its relaxed length. Also, by selectively severing the ligament, it could be shown that the value for G de- creased proportionally to the percentage transection of the ligament. For 100% tears, there is a complete breakdown in the stress-strain behavior, and the observed values for the in vivo ACL then reflect contributions of structures other than the ACL. These findings and considerations form the physical basis for the distinction between normal ligaments and those that are partially or completely torn. In addition, redundancy or slack in an otherwise normal ACL can be accurately assessed.

The graded stress radiography technique involves taking radiographs of the lateral aspects of the knee with varying pressures applied to the calf using a commercially available stress device. The anterior displacement is measured from the films with the femoral and tibial condyles serving as reference marks. From the observed displacements, values for (α — 1/$α^2$) can be calculated. To expedite the nu-merous calculations, we use preprinted graph paper that presents (α — 1/$α^2$) in linear increments along the lower x-axis and the corresponding displacements in nonlinear increments along the upper x-axis (Figs. 1 and 2).

According to the above equation, a plot of force F against (α — 1/$α^2$) would give a straight line that goes through the origin with a slope equal to G. For partial tears, values of G are reduced. Slack in the ligament shows as a straight line intersecting the x-axis at a value for (α — 1/$α^2$) for which F equals zero. Complete tears, on the other hand, show relationships with large displacements, often nonlinear, that do not extrapolate to the origin of the graph. The validity of these concepts has been tested on a resected ACL in vitro and in 55 patients who had arthroscopic verification of their ACL injury. When calculated against &dquo;all others,&dquo; complete tears could be determined with 88% sensitivity and 75% specificity. The numbers for partial tears were 20% and 90%, respectively. This low percentage for sensitivity is possibly related to uncertainties in assessing partial tears by arthroscopy when the synovium has remained intact.[8]

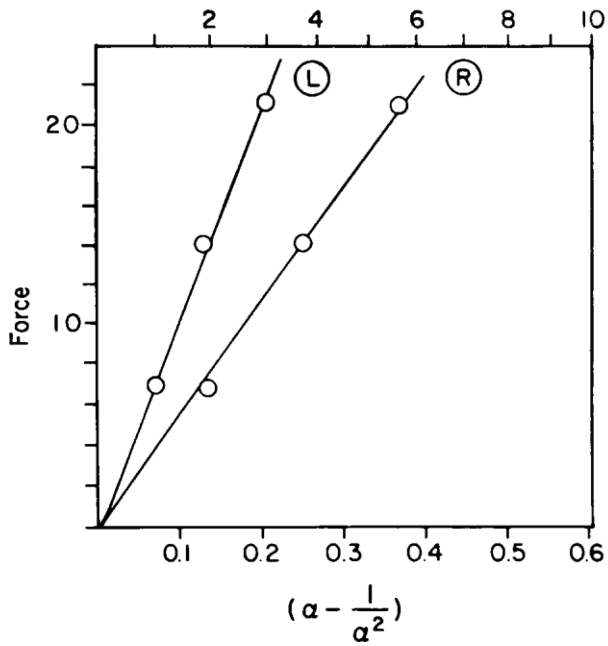

Figure 1. Radiographic stress diagram in a patient with partial tear of the right ACL, confirmed by arthroscopy (force in decanewtons)

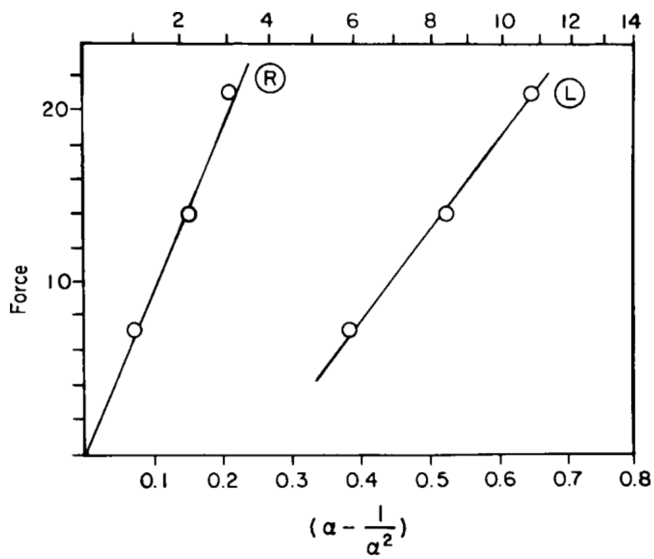

Figure 2. Radiographic stress diagram in a patient with a complete tear of the left ACL, confirmed by arthroscopy (force in decanewtons)

In the present study, we have examined the applicability of the graded stress technique to instrumented arthrometry with emphasis on differentiating partial and complete ACL tears. This study is part of our effort to investigate the role of imaging modalities for the evaluation of joint instability.

PATIENTS AND METHODS

Nineteen consecutive patients (6 women and 13 men) with a clinical diagnosis of ACL injury were examined by modified KT-1000 arthrometry on the day before arthroscopy. The patient's condition was described as acute when the injury at the time of examination was less than 6 weeks old, subacute when the injury was between 6 weeks and 3 months old, and chronic when the injury was older than 3 months. Five patients had acute, 4 had subacute, and 10 had chronic injuries. Patients with known injury or previous surgery to their contralateral knee were excluded from the study. Seven patients had been evaluated by magnetic resonance imaging, and 6 patients had graded stress radiography. Of these patients, 4 had both studies. The patients ranged in age from 17 to 32 years with an average of 22 years.

A KT-1000 arthrometer (MedMetric Co., San Diego, CA) was equipped with a model LCCB-50 strain gauge on line with a DP41-V processor (Omega Technologies, Inc., Stamford, CT) that permits continuous readouts, calibrated in pound-force, from a light-emitting digital diode. Using this arrangement, the forces required to increase the anterior displacement by 1-mm increments, as read from the dial gauge, were recorded in the range from 0 to 30 pounds for both the injured and the contralateral knees. All patients tolerated the procedure well.

RESULTS

The force-anterior displacement relationships for each of the 38 knees examined were plotted on preprinted graph paper that presents ($\alpha — 1/\alpha^2$) in linear increments along the lower x-axis. The displacement in millimeters, as read on the dial gauge, is plotted in corresponding nonlinear increments along the upper x-axis (Figs. 3 and 4). Three graphical patterns could be identified: 1) the normal, contralateral knees showing a linear relationship extending to approximately a 6-mm displacement corresponding to approximately a 12-pound force, which continues with a sharply increased slope up to 30 pounds, 2) a pattern similar to pattern 1 for the injured knee but with the slope increasing less sharply (Fig. 3), and 3) the straight line for the injured knee extending to approximately a 10-mm displacement, corresponding to about a 15-pound force, at which point the slope increases sharply (Fig. 4).

The same pattern for all normal knees was found without exception although a patient-to-patient variability was apparent in the slopes and the points of angulation. Greater variability was observed in patterns 2 and 3. Four patients were identified with pattern 2, all of whom were found to have a partial tear of the ACL by arthroscopy. Their points of angulation did not stray from those of the contralateral knees by more than a 1.6-mm drawer. Pattern 3 was observed in 15 patients, of whom 14 had a complete tear of the ACL and 1 had a partial tear. The points of angulation occurred at drawers ranging between 2.8 and 11.2 mm beyond those of the opposite knees. Arthroscopic confirmation of the condition of the ACL in the normal contralateral knees obviously was not available.

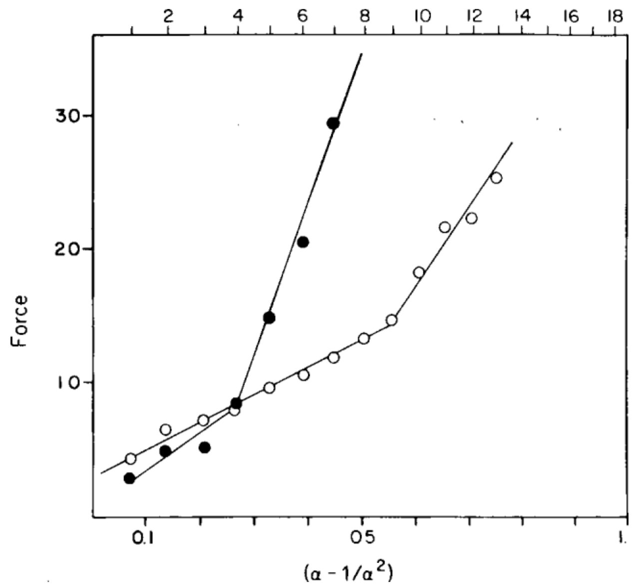

Figure 4. Plot of force (pounds) against ($\alpha — 1/\alpha^2$) in a patient with a complete tear of the left ACL (open circles). The right ACL is normal (solid circles). Same patient as in Figure 2.

TABLE 1
Mean and standard deviation (SD) of the side-to-side differences in anterior drawer at the point of angulation of KT-1000 arthrometer stress diagrams

	Mean (mm)	SD (mm)	Total
Partial tears	**1.40**	**2.14**	7.0
Complete tears	**6.37**	**2.48**	89.2

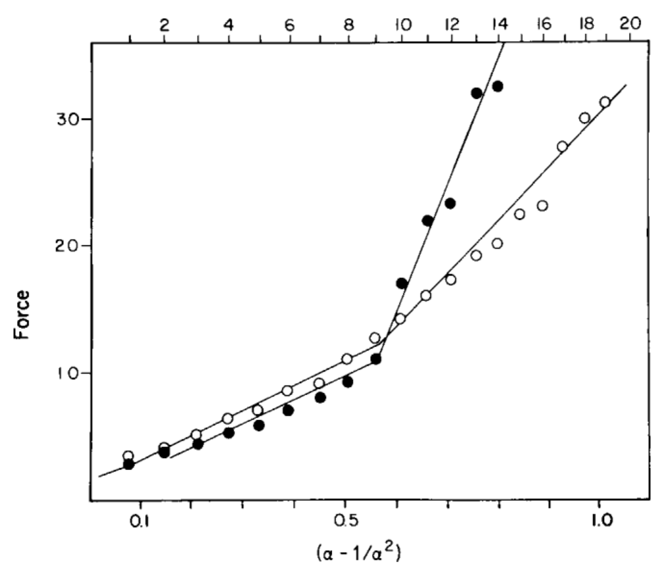

Figure 3. Plot of force (pounds) against ($\alpha — 1/\alpha^2$) using modified KT-1000 arthrometry showing partial tear of the right ACL (open circles). The left ACL is normal (solid circles). Same patient as in Figure 1.cases.

DISCUSSION

The force-anterior displacement relationships for partial and complete tears as described by patterns 2 and 3, respectively, are characteristic for each type of ACL injury and can be differentiated from normal ligaments in all cases. Partial tears can identify with a sensitivity of 80% and a specificity of 100%. The figures for complete tears are 100% and 80%, respectively. Because of large patient-topatient variabilities, only side-to-side comparison can provide diagnostic distinction and then only in the presence of a normal opposite knee. Specifically, the difference between the anterior drawers, observed for the points of angulation in the diagrams of each knee, determines whether a partial or complete tear is present. For partial tears, this difference is small and has a mean of 1.4 mm, whereas for complete tears this difference ranges between 2.8 and 11.2 mm in this series of patients. Table 1 presents the single variable statistics that include one false-negative case of a partial tear. Therefore, the technique described above, based on the viscoelastic stress-strain behavior of the ACL, appears to allow successful diagnosis of partial versus complete tears and to further extend the capabilities of the KT-1000 arthrometer in the evaluation of knee joint instability.

The similarity of the above patterns to the radiographic stress-strain diagrams (Figs. 1 and 2) is striking and provides insight into the sequence of events occurring on ACL testing. The initial linear part represents compression of the soft tissues of the calf that precedes effective stretching of the ACL and is essentially equal for both knees. The linearity suggests that soft tissue compression is a viscoelastic process as well and that it differs from ligamentous stretching only in the value of its elastic modulus. Soft tissue compression is not demonstrated in the radiographic diagrams because in these the bony landmarks relating to the points of attachment of the ACL were used to measure ligament stretching. The second linear parts in Figure 3 represent, in addition to further soft tissue compression, ACL stretching with different slopes for the normal and the partially torn ACL, identical to the radiographic diagrams. From the reduction of the slope of the line for the injured ACL, the percentage of the tear can, in principle at least, be calculated. A complete tear shows as the failure of the ACL stress-strain diagram to materialize. Instead, after further compression of the soft tissues, stretching of other knee structures such as capsule and collateral ligaments that are normally shielded in the intact knee is observed. This stretching shows as a belated increase in slope and correlates closely with radiographic findings.

No significant differences between acute, subacute, and chronic ACL injuries were demonstrated in this series. Such differences as have been recorded between acute and chronic injuries at 20 pounds of pressure[1] are small and are obscured by the large patient-to-patient variability in soft tissue compression. Similarly, slack in the injured ligaments and the contralateral ACLs cannot be separately identified.

The above observations and results are of general validity and are not restricted to the use of the KT-1000 arthrometer alone. Other types of arthrometers such as the Genucom (FARO Medical Technologies, Inc., Montreal, Canada) and the Knee Laxity Tester (Smith & Nephew DonJoy Inc., Carlsbad, CA) that are capable of measuring force-anterior displacement relationships are equally suitable for this purpose. A recent improvement in the KT-1000 arthrometer, marketed as the model KT-2000 arthrometer, involves the addition of an x-y recorder that directly plots the applied force against displacement in linear increments on graph paper (Fig. 5). The observed curve, including the relaxation part, can be shown to be a direct reflection of the algebraic form of equation1 For small displacements, that is, for values of a slightly larger than 1.0, a and 1/a’ are of the same order of magnitude and, therefore, the initial part of the curve rises steeply; however, as a increases, 1/a2 rapidly decreases, and the curve levels to a linear relationship when 1/a2 becomes negligible. For very large extensions, the viscoelastic relationship no longer holds, and the line again rises to a point where rupture of the ligament would occur. On relaxation, the same path is retraced but for a small measure of hysteresis. In Figure 6, we have further demonstrated the validity of this interpretation by plotting the displacement at 5-, 10-, 15-, and 20-pound forces, intrapolated from the curve in Figure 5, in terms of $(\alpha — 1/\alpha^2)$. A straight line that is identical to the ones for the normal contralateral knees in Figures 1 and 2 is obtained with a slope equivalent to the elastic modulus of a normal ACL. Thus, the advantages of the KT-2000 arthrometer arrangement of providing visualization and documentation of the force-displacement relationship would be further enhanced by plotting $(\alpha — 1/\alpha^2)$ in-

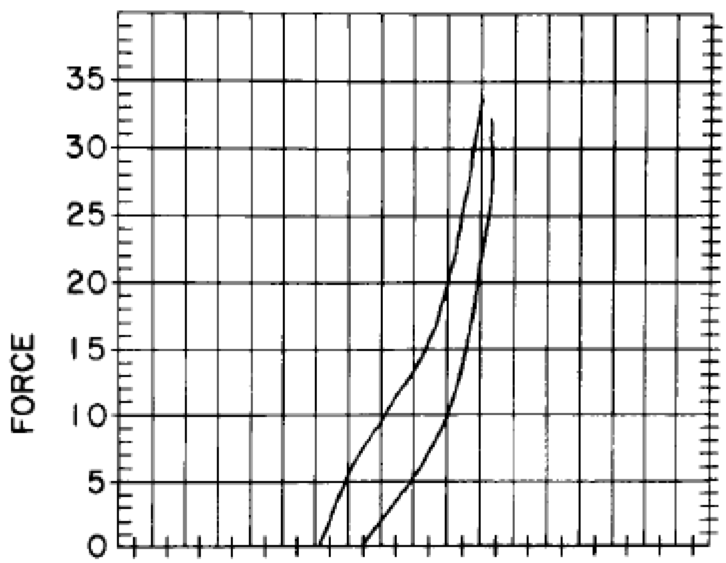

Figure 5. This x-y plot using KT-2000 arthrometry of a normal ACL shows force (pounds) plotted against linear increments (millimeters) of the anterior displacement (Daniel DM, personal communication). The right curve represents the relaxation curve.

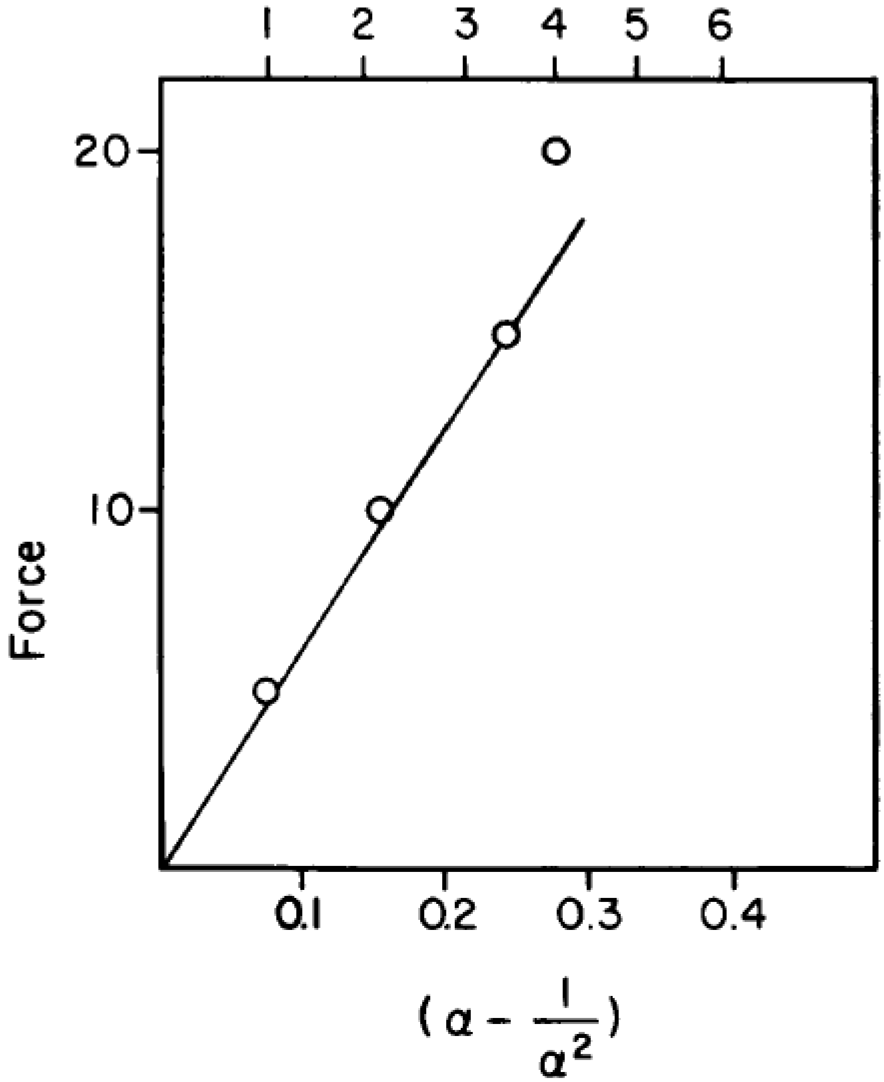

Figure 6. Plot of force (pounds) against ($\alpha — 1/\alpha^2$) using points intrapolated from the x-y curve in Figure 5. Compare this with the normal contralateral ACLs of Figures 1 and 2.

stead of plotting displacement in linear increments along the x-axis. Such a presentation would permit a direct graphical diagnosis of partial versus complete tears as distinct from normal ones (our patent pending).

The proposed technique also possibly can be applied to the examination of posterior cruciate ligament (PCL) injury. The arthrometry techniques, used by Parolie and Bergfeld[7] and by Fowler and Messieh[5] for the diagnosis and followup of PCL injury, as well as the data provided by the manufacturers of the KT-2000 arthrometer model, support this notion. However, we have not been able to study PCL injury systematically because no arthroscopic verification of this relatively rare injury was available to us at the time of this study.

One of the main problems in defining the cruciate ligament lesion, and in deciding whether to operate or to manage conservatively, centers on what constitutes a partial tear in arthroscopic terms. The usual criterion is the visualization of residual ligamentous continuity, but such arthroscopic partial tears may have normal function or can be indistinguishable from complete tears (Daniel DM, personal communication). Noyes et al.[6] postulated that the arthroscopic assessment of a partial tear can be estimated at best as the amount of gross tearing that could be observed: one-fourth, half, or three-fourths tearing. However, it has been recognized that such estimates do not define the actual damage because the ligament may sustain microscopic injury without gross disruption. Arthroscopy may, therefore, not be an ideal standard for examining the efficacy of functional tests such as instrumented arthrometry and graded stress radiography, but it remains the only means available for our purpose. It is conceivable that a combination of morphologic features, determined by arthroscopy or magnetic resonance imaging, and functional parameters, as derived from instrumented arthrometry or graded stress radiography, ultimately could define cruciate ligament injury in terms of knee instability and could provide the necessary criteria for the decision-making process.

In summary, by extending the arthrometric examination of cruciate ligaments over a range of forces applied to the knee and by plotting the applied force against $(\alpha — 1/\alpha^2)$ in linear increments, a diagnostic distinction between partial and complete tears can be made with a satisfactory degree of sensitivity and specificity. The results also suggest that a functional tear of the ACL cannot always be identified as such by arthroscopy.

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