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Arthrometric Curve-Shape Variables to Assess Anterior Cruciate Ligament Deficiency

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Abstract

Background—Instrumented measurement of asymmetry in anterior-posterior knee laxity is commonly used to assess anterior cruciate ligament integrity. Significant advances in arthrometric technology and data visualization have occurred since first generation arthrometers. However, little has changed with regard to diagnostic criteria employed. To our knowledge, no investigations have assessed the shape of laxity curves to diagnose anterior cruciate ligament (ACL) deficiency. We hypothesized that linear stiffness and compliance after positive curve inflection would be more sensitive and specific to anterior cruciate ligament injury than current measures and would require data from the involved limb only.

Methods—Laxity curves were obtained from 130 knees on 65 subjects (Anterior Cruciate Injured n=15, Controls n=50) using a CompuKT Knee Ligament Arthrometer. Traditional diagnostic variables and novel descriptive curve-shape variables [(1) inflection point, (2) pre- and post-inflection linear stiffness and (3) a modified compliance index based on the post-inflection linear stiffness] were assessed for sensitivity to anterior cruciate ligament deficiency. Statistical interactions were evaluated using 2-by-2 ANOVA.

Findings—Significant interactions (p<0.001) were identified for laxity symmetry, stiffness, compliance index and modified compliance index. Modified compliance index predicted anterior

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cruciate ligament deficiency with the highest sensitivity (93%) and specificity (100%). For a test performed on a single limb, modified compliance index demonstrated 98% sensitivity and 80% specificity.

Interpretation—The modified compliance index is a highly sensitive and specific measure to diagnose anterior cruciate ligament deficiency, and may serve as a simple and accurate diagnostic tool for individuals without a healthy contralateral limb.

Keywords

knee laxity; ACL; knee injury; knee arthrometer

INTRODUCTION

The anterior cruciate ligament (ACL) is the primary restraint to anterior tibial translation relative to the femur, providing approximately 85% of passive anterior tibial restraint. (Butler et al. 1980) Clinical assessment of anterior translation using the Lachman's exam has been identified as the most valid approach to identify ACL deficiency with sensitivity (Sn) of 85% and specificity (Sp) of 94%. (Benjaminse et al. 2006) However, instrumented measurement of anterior-posterior (AP) knee laxity (arthrometry) is also a well-established, commonly used diagnostic approach. Some clinicians prefer to use an arthrometer because it provides objective, quantitative, and accurate information that cannot be obtained from a Lachman's exam. These qualities and the fact that the data from an arthrometer is continuously distributed (not discreet as in a Lachman's grade) have also made them an important tool in knee biomechanical research. While a number of devices have been developed, validated and assessed for reliability, the KT arthrometer series (KT-1000, KT-2000, CompuKT, MEDmetric Corp., San Diego, CA) remains the most commonly used and most accurate and reliable device for assessing ACL integrity. (Anderson and Lipscomb 1989, Anderson et al. 1992, Balasch et al. 1999, Pugh et al. 2009, Queale et al. 1994, Riederman et al. 1991, Robnett et al. 1995, Wroble et al. 1990[1], Wroble et al. 1990[2]) Although the KT has been used for over three decades, the fundamental approach to assessment remains unchanged, despite advances in the technology. (Daniel et al. 1985 AJSM, Pugh et al. 2009) Namely, the use of side-to-side differences in AP displacement between knees at set, arbitrary forces, which do not account for inter-patient variability in knee laxity, remains the standard for laxity-based clinical and research assessment of ACL deficiency. (Daniel et al. 1985 JBJS, Daniel et al. 1985 AJSM, Highenboten et al. 1992, Pugh et al. 2009) In this paper, we present a new method for analyzing KT arthrometric data that generates objective, quantifiable laxity data with increased diagnostic accuracy compared to traditional arthrometric protocols. The diagnostic accuracy is also an improvement over the previously reported sensitivity and specificity of the Lachman's exam. (Benjaminse et al. 2006)

The current KT arthrometer methodology limits its potential applications since assessment of displacement asymmetry at a "manual maximum force" is reported as the most sensitive and specific "force" for the determination of ACL deficiency. (Bach et al. 1990, Daniel et al. 1985 AJSM, Highenboten et al. 1992, Pugh et al. 2009) Bach et al. reported 77% Sn and 90% Sp for this test using a 3 mm side-to-side difference as the diagnostic cutoff point for the manual maximum force test in acute ACL tears. (Bach et al. 1990) Similar values have been reported by Highenboten et al. and Daniel et al. for the manual maximum test. (Daniel et al. 1994, Highenboten et al. 1992) The manual maximum force does not currently have a defined value and may be highly variable within and between testers. This may account for the variability in reliability data reported for the KT arthrometers, particularly between raters (ICCs range=0.38–0.86). (Forster et al. 1989, Hanten and Pace 1987, Myrer et al. 1996) In addition, the need for side-to-side comparisons poses a limitation for patient populations without an “unaffected” contralateral limb. Currently, no highly sensitive and specific arthrometric diagnostic criteria exist for patients who do not have a healthy contralateral limb. Given that reports of rates of graft failure and/or contralateral ACL tear can be as high as one in four ten years post-reconstruction, or even higher in competitive athletes, this presents a diagnostic conundrum. (Paterno et al. 2010, Pinczewski et al. 2007) Development of more sensitive and specific arthrometric protocols that allow for single limb assessment could increase the diagnostic capacity of the KT and still provide the clinician with the insight offered by objective, quantitative data.

The KT-2000 was the initial graphing unit that offered a force-displacement plotter, and was subsequently modified to an electronic plotter in the CompuKT. Despite the significant improvements in data visualization techniques, few studies have analyzed other potential variables to assess ACL integrity. (Fleming et al. 1993) Daniel et al. proposed the use of a ‘compliance index’ (CI), defined as the difference in displacements at 67N and 89 N of anterior force. (Daniel et al. 1985 AJSM) Subsequently, this measure has been used as an objective way to quantify asymmetry in the “endpoint” of anterior translation felt during a Lachman exam. (Anderson et al. 1992, Bach et al. 1990, Daniel et al. 1985 JBJS, Daniel et al. 1985 AJSM, Myrer et al. 1996, Skinner et al. 1986) Highenboten et al report a sensitivity of this measure of 79%, but report no value for the specificity of this measure. (Highenboten et al. 1992) However, the assumption of a linear force-displacement relationship in this range of applied forces does not account for the high variability in laxity curve-shape between patients. (Liu et al. 2002)

The purpose of the current study was two-fold: To develop an accurate, reliable method for analysis of AP knee laxity curve shapes, and to identify variables that detect ACL deficiency with higher sensitivity and specificity than current diagnostic criteria. The primary hypothesis tested was that the linear stiffness and compliance after a positive curve inflection would discriminate between an ACL-intact knee and an ACL-deficient individual with high sensitivity and specificity, and that the inter-rater reliability of these measures would be high. The secondary hypothesis tested was that stiffness and compliance after positive curve inflection would demonstrate diagnostic utility for arthrometric data from a single limb, which would eliminate the need to assess the contralateral limb. Current diagnostic protocols in arthrometry generally require the patient to have at least one unaffected limb. High rates of graft failure and contralateral limb injury, especially in active populations, preclude use of current arthrometric techniques for patients who have already suffered a previous injury.

METHODS

Patient Population

KT knee arthrometer data of 65 subjects, which included 15 ACL-deficient (ACLD) subjects and 50 healthy controls (CTRL) without history of knee ligament injury, were used for analysis. The ACLD subjects consisted of patients with a complete tear of the ACL confirmed by MRI and/or arthroscopy. No ACLD subjects reported contralateral limb ACL or PCL injury. Descriptive statistics of the patient groups are shown in Table 1. Informed consent and assent was obtained from all control subjects and their legal guardian (for minors) using a consent form and study protocol approved by our Institutional Review Board (IRB). Data on ACL-deficient subjects was obtained via an approved clinical chart review.

Arthrometric Evaluation

All patients were examined using a CompuKT Knee Ligament Arthrometer (MEDmetric Corp, San Diego, CA) by a single experienced, highly-reliable licensed physical therapist (ICC=0.92). Patients were positioned supine with knees flexed over a standard, manufacturer issued wedge. Pilot testing revealed a mean knee flexion angle of 22.3 ± 2.4 degrees in this position with no significant side to side difference in knee flexion angle noted ($p=0.194$) and extremely high repeatability for repeated measures of knee flexion within subjects (ICC=0.971, $p<0.0001$). The knee was placed in a neutral alignment using the support bar included with the arthrometry kit. External tibial rotation was restricted throughout the testing as recommended by the manufacturer. (Cannon 2002, Daniel et al. 1985 AJSM) A 134 N posterior force was applied to establish the limit of posterior tibial displacement prior to application of a 134 N of anterior force. Arthrometric force-displacement curves were acquired using the manufacturer's internal A/D settings (60Hz). Bilateral digitized raw data was exported from the manufacturer's acquisition software to Microsoft Excel and the force-displacement plot was created. No filtering, averaging, or other modification of the data was performed. The reasoning for not filtering the data was partially due to observable effects of filtering previous curves on the curve shape, but was primarily to test and illustrate the relative ease with which the proposed technique can be performed and to increase the generalizability of the study to the average KT user.

Reliability of Force-Displacement Plot Analysis

Consistency within and agreement between two novice analysts who were given minimal instruction (described below) was assessed. A summary of the reliability methodology is shown in Figure 1.

Data Analysis and Identification of Variables

AP knee laxity curves were assessed in a standard fashion by a single analyst after the reliability of the analytical methodology was verified. The analyst used digitized force-displacement data visualized on a computer screen to identify the regions of linear stiffness of each plot for CTRL and ACLD subjects. Instructions were to identify the x-coordinate at which the analyst felt the linear region of stiffness began and ended, and to then use a line of best fit on those points, and all points in between. The stiffness of a given region was then defined as the slope of the line of best fit, or the change in force divided by the change in displacement. There is an initial, high stiffness region in the transition phase from a posterior to anterior force in all KT arthrometer curves. This region is not due to properties of the ACL as the ACL is not tensioned at this point. Thus analysts were instructed to identify the region of initial linear stiffness (S_1) as the first linear region that originated in the positive-positive quadrant of the force-displacement plot. Instructions were the same for the post-inflection stiffness (S_2), except that it was to be defined as the first linear region after an increase in force from the S_1 region and that the ending point was to be at or prior to the application of 134 N of anterior force. The inflection point was operationally defined as the point of intersection of the lines of best fit for the linear regions (Figure 2). The inflection point consisted of a displacement coordinate (X) and a force coordinate (Y). The last variable introduced by the authors was the modified compliance index (MCI). The MCI was defined as the amount of displacement over a 22N interval *after* the inflection point. If no inflection point could be identified, the MCI was defined as the displacement over a 22N interval for the initial stiffness, since this value of net change in force permits direct comparison to traditional compliance measures. (Daniel et al., 1985 AJSM) Variables investigated that were previously reported in the literature included displacement (mm) at 0, 67, 89, and 134 N of anterior force (DF_0, DF_{67}, $DF_{89,}$ and DF_{max}, respectively), the compliance index ($CI=DF_{89}-DF_{67}$), and the net displacement at 134 N ($DF_{net} = DF_{max}-DF_0$). (Anderson et al. 1992, Daniel et al. 1985 JBJS, Daniel et al. 1985 AJSM) The variables introduced by the authors included the initial linear stiffness (S_1, N/mm), the post-inflection linear stiffness (S_2), the X (mm) and Y (N) coordinates at the point of inflection and the modified compliance index (MCI). Each of these variables are illustrated in Figure 2.

Statistical Analysis

The tests used to assess reliability of this method of curve analysis included tests for intra-analyst consistency and inter-analyst agreement of the descriptive variables introduced by the authors. Intra-class correlation coefficients (ICCs) were calculated for each variable and a Hotelling's T^2 test was used as described in Figure 1. For intra-analyst consistency, ICCs of three separate analyses were compared for each variable. For inter-analyst agreement, each analyst's results were used to calculate ICCs between analysts. Hotelling's T^2 tested the null hypothesis that the mean of the differences between analyses was zero.

Clinical Study

Analysis of normality for each variable was tested using skewness and kurtosis tests, as well as a Shapiro-Wilk normality test. All statistical tests and reported p-values were performed on log transformed data at the recommendation of a biostatistician. This transformation was performed because log transformed data showed stronger agreement with normal distribution than non-transformed data and because a parametric mixed model was the most appropriate statistical approach. Raw values are used for descriptive reporting in this manuscript for clinical relevance and clarity. Two-by-two repeated measures analysis of variance (ANOVA) was used to investigate the interactions of group (ACLD vs. CTRL) and side (involved vs. uninvolved) with alpha=0.05. For the analysis of between-limb differences two-tailed, paired t-tests were performed. In ACLD subjects, Side 1 was defined as the involved limb and Side 2 was defined as the uninvolved limb. In controls, Side 1 was defined as the dominant limb and Side 2 was defined as the non-dominant limb. Dominance was determined by querying each subject which leg they would use to kick a ball as far as possible. A receiver operating characteristic (ROC) analysis was performed for single leg and between limb differences on the continuous variables for $DF_{max,}$ DF_{net}, compliance index and MCI.

RESULTS

Group-by-side effects were observed for a number of variables. Main effects of group and side were also observed, however post-hoc testing revealed that these effects were driven by the affected limb in ACL-deficient subjects for all variables. The predictive strength for four between-limb and two single limb variables for comparison of ACLD and normal knees is presented in Table 3. Eight variables demonstrated statistically significant group-by-side interactions between all healthy (n=115) limbs including controls, and affected limbs (n=15). Descriptive statistics for the five variables that demonstrated the strongest group-by-side differences are shown in Table 4.

Based on the strength of the statistical interactions, boxplot and ROC analyses were used to determine the most sensitive and specific variables to the condition of the ACL. Figures 3A, B, and C demonstrate the difference in distributions for the values of S_2, traditionally defined compliance index and the modified compliance index. The MCI demonstrated the greatest sensitivity and area under the ROC curve (AUC), a common measure for the quality of a diagnostic algorithm.

Variables that did not show significant group by side differences were the X [p=0.17, Affected: 10.63 (SD 4.49) mm; Unaffected: 7.57 (SD 1.9) mm] and Y [p=0.14, Affected:

65.57 (SD 30) N; Unaffected: 59.93 (SD 16.98) N] coordinates of inflection, and displacement at 0 N [p=0.86, Affected: 2.87 (SD 1.25) mm; Unaffected: 2.16 (SD 0.97) mm] and 67 N [p=0.16, Affected: 8.65 (SD 4.23) mm; Unaffected: 7.31 (SD 1.96) mm] of anterior force. A one-way ANOVA of all healthy limbs (CTRL dominant, CTRL non-dominant, ACLD uninjured) revealed no significant differences in any variable for any group (range p-values; 0.14–0.90). In ACLD subjects S_1, X, Y, DF_0, and DF_{67} showed no significant side-to-side differences during paired t-tests (Range p-values: 0.10–0.94).

The results of the reliability analysis are summarized in Table 2. Intra-analyst consistency was excellent for S_1 [Analyst 1: mean 9.97 (SD 3.38) N/mm Max RMS Error = 0.53 N/mm; Analyst 2: mean 9.73 (SD 3.04) N/mm Max RMS Error = 1.28 N/mm], X [Analyst 1: mean 8.88 (SD1.53) mm Max RMS Error = 0.16 mm; Analyst 2: mean 8.74 (SD 1.63) mm Max RMS Error = 0.919 mm], and Y [Analyst 1: mean 64.01 (SD 14.87) N Max RMS Error = 1.04 N; Analyst 2: mean 62.23 (SD 15.74) N Max RMS Error = 5.77 N], and was good to excellent for S_2 [Analyst 1: mean 39.66 (SD 4.06) N/mm Max RMS Error = 3.69 N/mm; Analyst 2: mean 39.88 (SD 5.12) Max RMS Error = 5.33]. Inter-rater agreement was excellent for $S_{1,}$ X, and Y, and was fair to good for S_2. In all cases, Hotelling's T^2 test failed to reject the null hypothesis that the difference in means was equal to zero (range p-values: 0.49–0.98).

DISCUSSION

This study outlines an accurate, reliable method to assess ACL integrity using arthrometric data from a single limb. The primary hypothesis tested was that linear stiffness and compliance after a positive curve inflection would discriminate between a healthy and ACL-deficient individual with higher sensitivity and specificity than currently used measures. The results demonstrated increased diagnostic accuracy in ACL injury for the modified compliance index compared to traditionally defined arthrometric measures such as the manual maximum test. Since our method accounts for inter-patient variability in laxity and anterior displacement prior to engagement of the ACL, the results demonstrate much greater consistency within the population of healthy limbs examined. The sensitivity and specificity (Sn = 0.933, Sp = 1) of limb asymmetry in the MCI was greater than previously reported values for the manual maximum test, which supported our primary hypothesis. The secondary hypothesis tested in study was that the variables based on the stiffness/compliance after a positive curve inflection would be diagnostically useful for data from a single limb. Sensitivity and specificity for the modified compliance index as a single limb diagnostic tool (Sn = 0.98, Sp = 0.80) are comparable to commonly used measures that compared between limb differences. Thus our results support the applicability of this approach in a single limb and support our secondary hypothesis.

The compliance index has been used in a number of studies and was the first protocol that measured stiffness to assess the integrity of the ACL. (Anderson et al. 1992, Bach et al. 1990, Daniel et al. 1985 JBJS, Daniel et al. 1985 AJSM, Myrer et al. 1996, Skinner et al. 1986) However, the arbitrary recommendation to use 67 and 89 N of anterior force as the beginning and end points of the measure fails to account for the high probability that the tangential stiffness (the instantaneous slope of the force displacement curve) is changing in this range. This study shows that a change in stiffness occurred at an anterior force greater than 67 N in approximately one third (38/115) of healthy limbs. This concept is further illustrated by the difference in distributions between the compliance index and the modified compliance index in Figure 3. Of the 115 healthy limbs tested in this study, all but one demonstrated a positive inflection point prior to the application of 134 N of anterior force. Thus, in a normal, healthy limb the perceived compliance over this 22 N interval (from 67 N to 89 N) would be considerably higher than that reflected by the post-inflection linear region if a significant increase in stiffness occurred within or above that interval. The results of the current study indicate greater asymmetry within an ACL-deficient subject in the modified compliance index [1.15 mm 95% confidence =0.93–1.36) compared to the traditional compliance index (0.99 mm (0.79–1.19)]. Furthermore, these results show that use of the MCI reduces the standard deviation within a population of all healthy limbs (n=115) by almost 40% (0.42mm to 0.26mm) compared to the traditional knee arthrometer compliance index. While these small changes in mean values and the reduction in variance may not be clinically meaningful by themselves, the resulting changes in sensitivity and specificity between the MCI and the compliance index demonstrate strong clinical significance.

The degree of variability in AP laxity and curve-shape characteristics between individuals makes the identification of a “healthy” range of stiffness or compliance useful and appealing for two major reasons: 1) A significant portion (approximately 21.1% at 10 years postoperative) of individuals who suffer a primary ACL injury go on to suffer a second ACL injury (either to the contralateral limb or graft failure). (Paterno et al. 2010, Pinczewski et al. 2007) Since AP displacement of a grafted limb differs from that of a limb with a native ACL, traditional side-to-side asymmetry assessments may not be possible in the event of ACL injury to the contralateral (initially uninjured) limb. This represents a situational limitation to the traditional diagnostic use of the knee arthrometer that can be overcome by the approach presented in this paper. 2) Identification of a normal range of force-displacement stiffness in an AP laxity curve may provide both clinicians and researchers with a means to compare individuals to one another in a way that is not currently possible. These results indicate stronger predictive accuracy based on AUC for the single limb values of the modified compliance index than for traditional diagnostic measures comparing asymmetries. (Bach et al. 1990, Daniel et al. 1985 AJSM, Highenboten et al. 1992) Though a more thorough assessment would need to include a population of ACL reconstructed patients, this method may also be useful and accurate for assessment of ACL injury in patients with a previous contralateral reconstruction.

Few studies have examined KT arthrometric data using linear stiffness as a diagnostic measure. In 2002, Liu et al. conducted a modeling study to determine the utility of assessment of stiffness and the rate of change in stiffness to diagnose a partial tear of the ACL. The model results showed that it may be possible to differentiate a mild partial ACL injury from the normal knee, or a severe partial ACL injury from an ACL-deficient knee based on the analysis of the force-displacement measurement. (Liu et al. 2002) It should be noted that a single model was used for all simulations. In a clinical evaluation, the value of the stiffness, compliance index and tibial anterior translation vary markedly between subjects. (Daniel et al. 1985 AJSM)

Fleming et al. performed an *in vivo* assessment of the strain in the anteromedial bundle (AMB) of the ACL using arthroscopically inserted Hall Effect strain transducers during anterior drawer using the Knee Signature System (KSS) arthrometer. The results showed a significant correlation between tibial displacement and measured anteromedial band strain (R^2=0.59). However, the authors point out in the discussion that ‘to make an accurate prediction of AMB strain from tibial displacement requires a high r^2, more likely higher than 0.59.’ (Fleming et al. 1993) Although a definitive conclusion is beyond the scope of the current study, those results indicate that the inflection point in an AP laxity curve is likely the point of engagement of the ACL. In previous studies, the point of initial engagement of the ACL during anterior drawer was defined as the “just-taut” point. (Fleming et al. 1993) Fleming et al. indicated in five live subjects that a mean anterior load of 17.1 (SD 11.6) Newtons is necessary for the ACL to reach its just-taut length. (Fleming et al. 1993)Our results indicate that there is a great deal of variability between individuals in the amount of force required to engage the ACL. These observations illustrate the importance in accounting for individual to individual variability in laxity curve shape for analysis of ACL deficiency.

Although the data presented in this study show a strong interaction between the newly introduced modified compliance index and the condition of the ACL, there are limitations to the results and interpretation of these findings. A number of factors, including muscle relaxation, arthrometer placement, flexion angle and speed and angle of force application may influence stiffness and/or displacement variables. (Gross et al. 2004) Another limitation to this study is the use of a single KT operator. While this approach allows for high reliability of measurements within this individual operator, we lack the ability to confirm these results between raters for this patient population. Several studies verify a reasonable inter-rater repeatability with regard to endpoint displacement, especially in experienced users. (Anderson et al. 1992, Ballantyne et al. 1995, Berry et al. 1999, Myrer et al. 1996, Queale et al. 1994, Wroble et al. 1990[2]) However, no studies examine stiffness values in KT curves as presented here. Future work should focus on the characterization of the relationship between the modified compliance index and the integrity of the ACL. The efficacy of the MCI for distinguishing between complete and partial tears, and native and reconstructed tissues, is particularly intriguing given the simplicity and cost effectiveness of laxity testing. In addition, further work should be conducted to clarify the benefits and limitations of diagnosing an ACL injury using data from a single limb.

CONCLUSION

This study introduces a new method for assessment of AP knee translation curves and demonstrates the value of the MCI as a diagnostic indicator of ACL injury. The MCI is both a highly sensitive and specific predictor of ACL deficiency. This measure may serve as an accurate, objective, and quantitative diagnostic tool to assess ACL integrity and provide a method to assess AP knee laxity in a single limb in an individual without a healthy contralateral limb.

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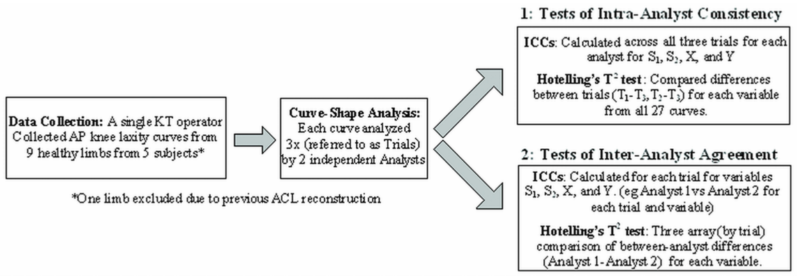

Figure 1.

Methodology for the reliability portion of this study consisted of tests for agreement and consistency between and within two analysts, respectively.

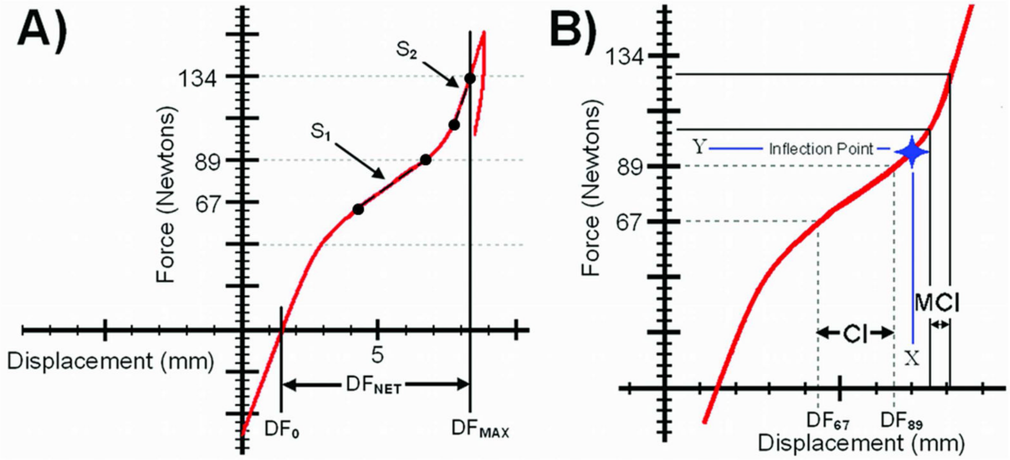

Figure 2.

A) A representative illustration of S_1, the slope of the linear region in the first quadrant after an initial decrease in stiffness from the posterior-to-anterior force transitional region, and S_2, the slope of the linear region in the first quadrant after an increase from S_1, as well as DF_{net}, DF_0, and DF_{max}. Linear stiffnesses S_1 and S_2 are determined by the slope of a line of best fit for all points between visually identified starting and ending points of linearity. B) A typical example of the AP displacement (mm) at which the transition from S_1 to S_2 occurs (X) and the force (N) at which that transition occurs (Y). Together, these coordinates make up the Inflection Point. Also shown is the difference between the traditionally defined Compliance Index (CI) and the Modified Compliance Index (MCI).

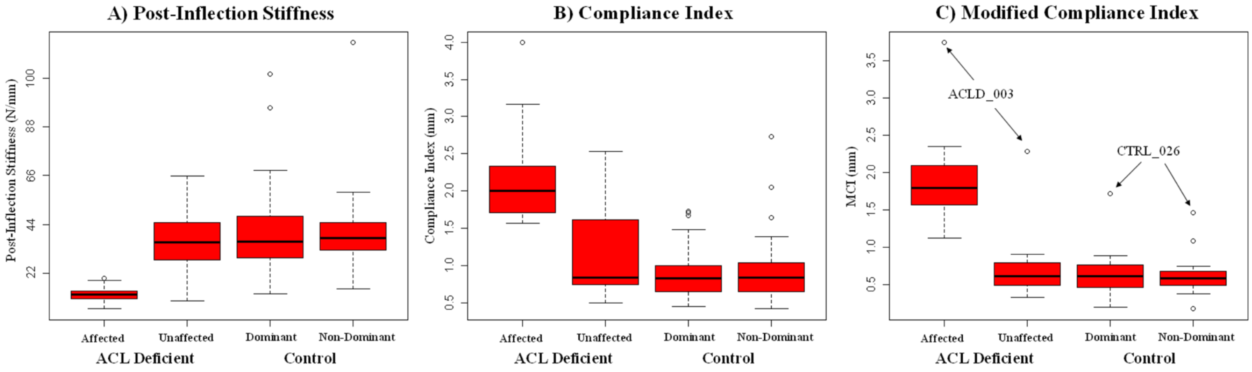

Figure 3.

Differences by limb in distributions between S_2 (Fig 3A), compliance index (Fig 3B), and modified compliance index (Fig 3C). ACLD n=15, CTRL n=50. Large variability in the distributions for S_2 and the compliance index for healthy limbs (ACLD Side 2, CTRL Side 1, CTRL Side 2) is greatly reduced using the MCI, or the compliance over a 22N interval after curve-inflection. MCI reduces the overlap in distributions between healthy and ACL-deficient limbs. Four of 115 healthy limbs (outliers) demonstrated a false positive test for ACL deficiency based on data from a single limb. False positives can be compared to the contralateral limb as a verification technique, as demonstrated by the subject specific nature of these outliers.

Table 1

Age and sex of subjects in the control and ACL deficient groups.

CTRL	n=	Average Age	St. Dev	ACLD	n=	Average Age	St. Dev
Female:	35	16.74	2.44	**Female:**	10	16.72	3.47
Male:	15	16.73	2.89	**Male:**	5	15.95	5.39
Total	50	16.74	2.55	**Total:**	15	16.42	4.10

Table 2

Intra-class Correlation Coefficients (ICCs) for the intra-analyst reliability and inter-analyst agreement using the described curve analysis methodology

	Intra-Analyst ICCs (95% Confidence Interval)			
	S1	**S2**	**X**	**Y**
Analyst 1	0.99 (0.98–0.99)	0.90 (0.82–0.95)	0.99 (0.99–0.99)	0.99 (0.99–0.99)
Analyst 2	0.96 (0.93–0.98)	0.92 (0.85–0.96)	0.99 (0.99–0.99)	0.99 (0.98–0.99)
	Mean Inter-Analyst ICCs Over 3 Trials (Mean Lower Bound-Mean Upper Bound)			
	S1	**S2**	**X**	**Y**
Agreement	0.97 (0.93–0.99)	0.81 (0.63–0.91)	0.99 (0.98–0.99)	0.98 (0.96–0.99)

Table 3

Results of Receiver Operating Characteristic (ROC) analysis for ACL deficiency for measures of asymmetry and single limb variables.

	Side-to-Side Comparisons (Affected-Unaffected)				**Single Limb Data**	
	CI	**MCI**	**Dfnet**	**DF_{max}**	**CI**	**MCI**
Sensitivity (Sn)	0.67	0.93	0.73	0.99	0.60	0.98
Specificity (Sp)	0.96	1.00	0.98	0.47	0.97	0.80
Max Sn	0.80	0.93	0.93	0.80	1.00	1.00
Max Sp	0.94	1.00	0.86	0.77	0.91	0.97
Optimal Cutoff	0.48	0.55	1.50	10.80	1.55	1.10
Area Under ROC Curve	0.89	0.99	0.93	0.87	0.96	0.98

Table 4

Descriptive statistics [mean (SD)] of the most significant variables between ACL-deficient and ACL-intact limbs and results of statistical assessments.

	ACL Deficient (n=15)		Controls (n=50)		
	Affected	**Unaffected**	**Dominant**	**Non-Dominant**	**All ACL-Intact Limbs**[*]
DF_{max} (mm)	14.75 (4.66)[†]	10.22 (3.17)	9.32 (1.78)	9.25 (1.78)	9.41 (2.02)
DF_{net} (mm)	11.88 (3.82)[†]	7.33 (2.13)	7.26 (1.45)	7.21 (1.35)	7.24 (1.50)
Compliance Index (mm)	2.18 (0.67)[†]	1.19 (0.61)	0.89 (0.33)	0.92 (0.41)	0.94 (0.42)
Modified Compliance Index (mm)	1.89 (0.63)[†]	0.74 (0.46)	0.61 (0.24)	0.59 (0.19)	0.62 (0.26)
S_2 (N/mm)	12.78 (3.59)[†]	36.16 (13.29)	41.87 (17.82)	41.17 (15.51)	40.82 (16.28)

[*] One way ANOVA between all populations of healthy limb revealed no significant differences for any variable

[†] Significant difference*($p<0.001$) from population of all healthy limbs