Bench Testing of a Knee Joint Arthrometer

MASSIMO G. BARCELLONA, PHD; TONY CHRISTOPHER; MATTHEW C. MORRISSEY, ScD, PT

abstract

The KT1000 and KT2000 knee joint arthrometers (MEDmetric Corp, San Diego, California) have been shown to overestimate the measurement of knee joint sagittal laxity. The purpose of this study was to investigate the accuracy of the KT arthrometers as measures of anterior and posterior linear displacement. The anterior and posterior linear displacements of 3 KT arthrometers (2 KT1000 arthrometers and 1 KT2000 arthrometer) were compared with the simultaneous displacement measured by a precision linear Vernier Dial Test Indicator (Davenport Ltd, London, United Kingdom). The displacement calculated using the analog output of the KT2000 was also compared with the values on the KT2000 displacement dial.

Compared with the Vernier Dial Test Indicator, the KT arthrometers overestimated anterior linear displacement by between 22% and 24%. True anterior displacement for all 3 arthrometers, as recorded by the Vernier Dial Test Indicator, was found by multiplying the KT value by 0.79. When compared with the Vernier Dial Test Indicator, the KT arthrometers underestimated posterior linear displacement by between 18% and 19%. True posterior displacement, as recorded by the Vernier Dial Test Indicator, was found by multiplying the KT1000 value by 1.17 and the KT2000 value by 1.16.

The internal apparatus of the KT2000 and KT1000 knee joint arthrometers overestimates anterior displacement and underestimates posterior displacement with a predictable relative systematic error. Future validation studies should use these correction equations to assess the accuracy of the KT arthrometers. Sagittal plane knee laxity measured with the KT devices requires systematic correction for optimal accuracy.

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The authors have no relevant financial relationships to disclose.

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doi: 10.3928/01477447-20130724-14
Because the anterior cruciate ligament (ACL) is the primary restraint to anterior translation of the tibia at the knee, assessment of knee joint sagittal laxity is accepted as a method for evaluating the integrity of the ACL. Objective quantification of knee sagittal laxity is important in the diagnosis of ACL injury and allows for the evaluation and comparison of different operative and nonoperative interventions.

Benefits of the KT arthrometers (MEDmetric Corp, San Diego, California) are that they are fully portable and noninvasive and, like Roentgen stereophotogrammetric analysis, can detect changes in knee laxity over time. They also allow for results to be compared with previously published literature. For these reasons, KT arthrometers remain the devices of choice to measure sagittal laxity in the knee in large-scale multisite intervention studies. A thorough understanding of the factors that contribute to the inaccuracy of KT arthrometers is necessary.

Kowalk et al reported that a KT1000 arthrometer produced a maximal mean error of 0.3 mm and a maximal absolute error of 0.6 mm when bench tested using aluminum plates of known thicknesses across a range of 15-mm anterior to 15-mm posterior displacement in increments of 2 to 3 mm. The authors concluded that the KT1000 demonstrated relatively small errors for the measurement of tibial anteroposterior displacement despite the existence of a statistically significant difference ($P < .05$) in the data obtained from the dial of the KT1000 and the known displacements determined using the aluminum plates. It remains unknown whether the error reported is inherent to all KT arthrometers, systematic, so that it may be corrected for, and inherent to the dial of the KT arthrometers and not to the voltage output from the newest KT model (KT2000).

The following procedures were designed to test for systematic error of the KT2000 and KT1000 arthrometers when used to measure anterior and posterior linear displacement. The primary hypothesis was that the absolute values given for displacement of the tibial reference pad in both the anterior and posterior directions by 3 KT arthrometers would not differ from the simultaneous values obtained using a gold standard linear displacement measurement device (Vernier Dial Test Indicator; Davenport Ltd, London, United Kingdom). The secondary hypothesis was that the displacement shown on the dial of the KT2000 would not differ from the displacement calculated from the voltage output of the KT2000.

**MATERIALS AND METHODS**

The experimental setup for assessing the accuracy of the KT2000 arthrometer to measure anterior displacement is shown in Figure 1. The main body of the KT2000 was fixed to a horizontal surface using its 2 hook-and-loop straps. The patella reference pad of the KT2000 was fixed using a retort clamp, and the arm of the tibial reference pad was aligned with the arm of the patella reference pad, as would occur during clinical testing of patients.

A precision linear Vernier Dial Test Indicator with a resolution of 0.01 mm and a range of 13 mm was used to measure upward displacement of the tibial reference pad of the KT2000 (Figure 1). This device was calibrated from 0 to 13 mm using 1-mm–increment steel gauge blocks (Mitutoyo UK Ltd, Andover, United Kingdom) and was accurate to within 0.01 mm. The readings on the displacement dial of the KT2000 and the displacement dial of the Vernier Dial Test Indicator were set to 0 mm. The examiner (M.G.B.) used a retort stand with a boss head as an adjustable mechanical stop to fix the tibial reference bar at the level of each 1-mm increment on the displacement dial of the KT2000 arthrometer. This allowed the corresponding linear displacement to be recorded from the dial of the Dial Test Indicator. Twelve trials were performed, and the experimental setup was recreated between each trial. Each trial consisted of measurements at 1-mm increments from 0 to 11 mm (as indicated on the displacement dial of the KT2000 arthrometer).

To correct for possible hysteresis in the system, the examiner ensured that the readings on the displacement dial of the KT2000 and the Dial Test Indicator dial returned to 0 between the acquisition of data at each 1-mm increment.

To corroborate and compare the results, the same examiner repeated the experimental procedures described above with a KT1000 arthrometer, and 3 examiners repeated the procedures with another KT1000 arthrometer. In addition, the KT2000 and the 2 KT1000 arthrometers were checked for accuracy and linearity.
according to the guidelines provided by the manufacturer.

By performing the procedures described above and using the experimental setup shown in Figure 2, one examiner assessed the accuracy of the KT2000 and 1 of the KT1000 arthrometers for measuring posterior linear displacement.

To assess whether systematic error may have been isolated to the displacement dial and not the analog output from the KT2000, the authors compared anterior displacement at 5, 10, and 15 mm as shown on the dial of the KT2000 with the displacement calculated from the analog output of the KT2000. The mean of all 3 trials at each displacement point was used for comparison. The analog voltage output from the KT2000 was sampled using a Power1401 (CED Ltd, Cambridge, United Kingdom) analog-to-digital converter and Signal 2.14 software (CED Ltd).

Statistical analysis was performed using SPSS version 16.0 software (SPSS, Inc, Chicago, Illinois). The 12 trial means and SDs of the readings on the Vernier Dial Test Indicator at the KT displacement dial 1-mm increments from 0 to 11 mm were calculated.

Descriptive statistics were computed and the data were tested for normality using the Kolmogorov-Smirnov test and by observing the Q-Q plots. Two-tailed paired t tests (α = .05) were used to assess the difference between the values for displacement on the KT arthrometers and the corresponding mean values on the Vernier Dial Test Indicator and for the difference in displacement as calculated from the voltage output of the KT2000 to that shown on the displacement dial of the KT2000. Levels of agreement between the results from the KT displacement dial and the Vernier Dial Test Indicator were plotted and assessed as recommended by Bland and Altman.\(^5\)\(^6\)

The relationship between the mean values of the Vernier Dial Test Indicator and the corresponding value on the dial of the KT arthrometers at each 1-mm increment was determined using 2-tailed Pearson’s correlation coefficients, and the coefficient of determination ($R^2$) was calculated.

RESULTS

Pearson’s correlation coefficients for the KT arthrometers relative to the Vernier Dial Test Indicator were significant at the $P<.01$ level, with $R$ values of 1.000 ($R^2=0.999$). The differences between displacement on the KT arthrometers and the corresponding values on the Vernier Dial Test Indicator were significant at the $P<.001$ level.

The KT arthrometers overestimated anterior displacement (mean bias range, 22%-24%) (Figure 3) and underestimated posterior displacement (mean bias range, 18%-19%) (Figure 4).
The regression equation for the determination of absolute KT arthrometer linear anterior displacement was $y = 0.79x$ when using data sets from either the KT2000 or both KT1000s (where $y =$ Vernier Dial Test Indicator value and $x =$ KT displacement dial value). The regression equation for the determination of absolute KT arthrometer linear posterior displacement was $y = 1.17x$ when using the data set from the KT1000 and $y = 1.16x$ from the KT2000 data set (where $y =$ Vernier Dial Test Indicator value and $x =$ KT displacement dial value). Figure 5 shows the relationship found for anterior displacement when using the KT1000 data set as gathered by 3 examiners and the relationship found for posterior displacement using the KT2000 data set for 1 examiner.

The anterior and posterior displacements as calculated using the analog output of the KT2000 were not different ($P > .05$) from the respective 5-, 10-, and 15-mm increments, as set by the examiner on the dial of the KT2000 (Table 1).

**Discussion**

The current study showed that the KT2000 and KT1000 arthrometers have an in-built relative systematic error across the range of 0 to 11 mm, leading to a 22% to 23% overestimation of anterior linear displacement and an 18% to 19% underestimation of posterior linear displacement.

The original experimental procedures used to assess the accuracy of the KT2000 arthrometer were conducted for both posterior and anterior displacement across a force range of 14 to 112 N at approximate 20-N intervals. Anterior and posterior displacement were calculated by taking an average of the motion of the medial and lateral aspects of the femur relative to the tibia using a pair of linear variable differential transformers. The tests were repeated a total of 32 times on 2 cadaveric knees, and the skeletal tracking system was unconstrained to all degrees of tibial rotation and displacement. The results of these in vitro studies demonstrated a 0.97 correlation coefficient between the arthrometer readings and the readings from the linear variable differential transformers, with an SD of error of 0.44 mm. The current SD of error for the difference between anterior displacement on the dial of the KT2000 and anterior displacement on the Vernier Dial Test Indicator dial was 0.76 mm. However, based on the current results, the authors recommend not using
the SD of error to represent this type of systematic error because, with a percentage error, the absolute error depends on the range of values tested (ie, the larger the values, the greater the amount of error). The current data also show that correlation coefficients are not representative of absolute agreement. The current authors had correlation coefficients of 1.000 for their comparisons and poor absolute agreement.

The current study was limited to investigating a range of KT displacement dial values from 0 to 11 mm due to the maximum range of the Vernier Dial Test Indicator. Daniel et al.\(^2\) reported the force test range, not the displacement range, of 2 uninjured cadaveric knees used to test KT accuracy. However, with a maximum force of 112 N and because the 2 cadaveric knees were ACL intact, the current authors would not expect the maximum displacement to be as great as the 11-mm maximum in the current experiments. Thus, the SD of error from the 2 reported experiments was not comparable for this reason. Comparing the current results of KT accuracy to those reported by Daniel et al.\(^2\) was also problematic because the current experiment was designed for direct measurement of linear displacement, whereas the experimental procedures designed by Daniel et al.\(^2\) were performed without constraining anteroposterior displacement to the sagittal plane.

Table 2 is a summary of studies that investigated the inherent accuracy and concurrent validity of the KT1000 or KT2000 arthrometers. The current results appear to conflict with those of a previous bench testing study.\(^4\) Kowalk et al.\(^4\) reported a mean error of 0.3 mm at approximately the 9-mm anterior displacement point of the KT1000. In contrast, the current data show that at the 9-mm anterior displacement point of the KT, the mean error may be as large as 1.9 mm (based on the linear regression \(y=0.79x\) correction factor). The discrepancies in these results may be partly due to differences in the experimental setup. Kowalk et al.\(^4\) used displacement of the tibial reference pad relative to the displacement of the patella reference pad at the level of the joint line indicator on the KT1000 as the reference point for the gold standard, whereas the current setup relied on the measurement of displacement at the tibial reference pad relative to the patella reference pad. Discrepancies in these data may have also been due to true differences in the original calibration of the KT arthrometers.

The results of previous studies differ with regard to the reported direction of the error when the KT arthrometer was used to measure sagittal laxity compared with measurements made using radiostereometric analysis (RSA) (Table 2). These discrepancies may be due to differences in the testing forces used when comparing the KT arthrometer test values with those of other devices, such as RSA.\(^7,8\) In studies where the translation forces used with either the KT or RSA techniques were equal, the consistent finding was that the KT arthrometers overestimated the measurement of sagittal knee laxity (Table 2).\(^3,9\) Overestimation of sagittal laxity has also been reported in studies on other external measurement devices, including the Stryker Knee Ligament Tester (Stryker, Mahwah, New Jersey), the CA-4000 electrogoniometer (OS, Inc, Hayward, California) and the Genucom Knee Analysis System (FARO, Lake Mary, Florida), relative to radiographic techniques and at forces ranging from 88 to 180 N.\(^11,13,14\)

The overestimation of anterior-to-posterior translation at the knee by using external measurement devices has been attributed to the effect of soft tissue deformation\(^5,16\) and anterior-to-posterior movement of the patella relative to the femur\(^5\) because anterior-to-posterior translation, as measured by the majority of external devices available, is determined by the relative displacement between the tibia and the patella. A study of 2 cadaveric knees using a custom-built external laxity tester and simultaneous RSA measurement reports that this anterior-to-posterior motion of the patella relative to the femur accounts for 1% to 3% of an approximate 10% overestimation error.\(^9\) A more recent cadaveric study of 8 human ACL-injured knees supports the proposed sources of error between the KT arthrometers and more accurate RSA techniques by showing that the total anterior-to-posterior laxity was not significantly different for the KT1000 arthrometer compared with the RSA technique (KT1000, 15.71 ± 2.31 mm; RSA, 15.07 ± 3.15 mm) with the soft tissue and the patella removed.\(^15\) Although these results suggest that the majority of the error between KT arthrometric and RSA measurements is accounted for by soft tissue deformation and patellofemoral motion, the current results suggest that

<table>
<thead>
<tr>
<th>Test</th>
<th>Mean Anterior Displacement, mm</th>
<th>Mean Posterior Displacement, mm</th>
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<tbody>
<tr>
<td></td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td>1</td>
<td>5.20</td>
<td>10.19</td>
</tr>
<tr>
<td>2</td>
<td>4.99</td>
<td>10.24</td>
</tr>
<tr>
<td>3</td>
<td>5.07</td>
<td>10.10</td>
</tr>
<tr>
<td>Mean</td>
<td>5.08</td>
<td>10.18</td>
</tr>
</tbody>
</table>

\(^a\)MEDmetric Corp, San Diego, California.
### Table 2

Summary of Studies Investigating the Accuracy of KT Arthrometers

<table>
<thead>
<tr>
<th>Study</th>
<th>Comparison</th>
<th>Methodological Considerations</th>
<th>Results</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brandson et al&lt;sup&gt;6&lt;/sup&gt;</td>
<td>KT1000 vs RSA in ACLI knees preop and 1 y after reconstruction (n=9)</td>
<td>89-N test forces (KT1000) vs 150-N test forces (RSA)</td>
<td>Significant side-to-side difference in mean anterior translation, mm. Preop: KT1000, 2.6; RSA, 6.4. Postop: KT1000, 0.2; RSA, 1.0. (P not reported.)</td>
<td>Different test forces used.</td>
</tr>
<tr>
<td>Daniel et al&lt;sup&gt;2&lt;/sup&gt;</td>
<td>2 cadaveric knees: 32 tests on each knee comparing anterior and posterior displacement between LDVTs and KT1000</td>
<td>LDVTs; average lateral and medial compartment motion measured across force range of 14 to 112 N (approx 20-N intervals) and compared with KT1000</td>
<td>$R=0.97$ correlation coefficient between KT1000 and LDVT measurements (SD of error=0.44 mm).</td>
<td>LDVTs unconstrained to all degrees of rotation and displacement of the tibia. Measurements made according to force, not displacement.</td>
</tr>
<tr>
<td>Fleming et al&lt;sup&gt;11&lt;/sup&gt;</td>
<td>KT1000 vs RSA in patients after ACLR (n=15)</td>
<td>Mean total AP laxity ($-90$-to-+$130$-N forces) across 4 repeat measurement times during 1-y FU after ACLR</td>
<td>Significant differences existed for the 3 techniques ($P&lt;.001$). Mean laxity, mm: KT, 11.4±3.0; PSR, 10.2±3.3; RSA, 6.9±3.0.</td>
<td>Only KT1000 and RSA detected increases in laxity across the 4 measurement times ($P=.04$).</td>
</tr>
<tr>
<td>Isberg et al&lt;sup&gt;15&lt;/sup&gt;</td>
<td>KT1000 vs RSA in ACLI patients (n=22)</td>
<td>Evaluated side-to-side differences in total AP laxity ($-90$-to-+$130$-N forces) preop and 2 y after ACLR</td>
<td>Total AP laxity side-to-side difference, mean (range), mm. Preop ($P&lt;.0001$): KT1000, 4 (0-10); RSA, 7.4 (2.2-17.4). Postop ($P&lt;.0001$): KT1000, 0.5 (1.5-4.0); RSA, 2.8 (1.8-10.7).</td>
<td>Greater overestimation of total AP laxity in intact vs injured knees pre- and postop, mean (range), mm. Preop: injured knee (NS): KT1000, 11.0 (6.0-18.0); RSA, 10.9 (6.2-19.6); intact knee ($P&lt;.0001$): KT1000, 8.0 (6.0-10.0); RSA, 3.1 (0.2-8.6). Postop: injured knee ($P&lt;.0001$): KT1000, 9.5 (7.5-14.0); RSA, 6.5 (2.4-14.1).</td>
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<tr>
<td>Jonsson et al&lt;sup&gt;7&lt;/sup&gt;</td>
<td>KT1000 vs RSA in 86 intact, 39 ACLI, and 55 ACLR knees</td>
<td>89-N test forces with KT1000 vs 150-N test forces with RSA</td>
<td>Mean anterior translation: KT1000 vs RSA, respectively, mm. Intact knees: 5.9 vs 5.5 ($P&gt;.05$); ACLI knees: 11 vs 13 ($P&lt;.01$); ACLR knees: 7.5 vs 9.5 ($P&lt;.001$).</td>
<td>Different test forces used.</td>
</tr>
<tr>
<td>Khan et al&lt;sup&gt;11&lt;/sup&gt;</td>
<td>ACL-deficient human cadaveric knees; RSA vs KT2000 vs Instron&lt;sup&gt;6&lt;/sup&gt; materials testing device (n=8)</td>
<td>Total displacement ($-90$-to-$90$-N forces) at 20° and 90° knee flexion</td>
<td>Median (range), mm. 20° knee flexion: RSA, 15.1 (11.5-21.2); KT2000, 15.0 (13.4-20.2); Instron, 19.1 (16.2-27.6). 90° knee flexion: RSA, 10.4 (8.4-17.2); KT2000, 11.3 (7.3-18.8); Instron, 15.1 (11.4-23.9). Device correlations: 20° knee flexion: RSA vs KT2000, $R=0.79$; RSA vs Instron, $R=0.81$; KT2000 vs Instron, $R=0.70$; 90° knee flexion: RSA vs KT2000, $R=0.95$; RSA vs Instron, $R=0.90$; KT2000 vs Instron, $R=0.99$</td>
<td>Mean Instron measurements significantly higher (3-4 mm) than RSA and KT2000.</td>
</tr>
<tr>
<td>Kowal et al&lt;sup&gt;8&lt;/sup&gt;</td>
<td>KT1000 vs aluminium plates of known thickness</td>
<td>15-mm anterior to 15-mm posterior displacement in 2-3-mm increments</td>
<td>KT1000 vs aluminium plates significantly different ($P&lt;.05$). Maximal mean error=0.3 mm; maximal absolute error=0.6 mm</td>
<td>Low measurement error reported.</td>
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</table>

**Abbreviations:** ACLI, anterior cruciate ligament injured; ACLR, anterior cruciate ligament reconstruction; AP, anteroposterior; approx, approximate; FU, follow-up; LDVT, linear variable differential transformers; NS, not statistically significant; postop, postoperatively; pre, preoperatively; PSR, planar stress radiography; RSA, radiostereometric analysis.

<sup>1</sup>MEDmetric Corp, San Diego, California.

<sup>2</sup>Instron, Norwood, Massachusetts.
an additional KT arthrometer-inherent source of error exists. The extent of this relative systematic anterior translation error may be masked if total anterior-to-posterior translation is considered instead of anterior translation alone because a proportion of the total anterior-to-posterior laxity will be due to laxity in the posterior direction, which is underestimated by the KT arthroimeters in the current results.

Discrepancies in the results of studies comparing the measurement of sagittal knee laxity with the KT arthrometers relative to concurrent measurements made using RSA may also be influenced by differences in the coordinate systems used to define the bony segments of the knee during RSA. Beardsley et al reported an RSA-based measurement study comparing 2 translation measurement paradigms in 153 radiographic anterior-to-posterior laxity examinations from individuals after ACL reconstruction. Their results showed that the use of an anatomical femoral coordinate system based on the knee joint center of rotation led to sagittal laxity values that were an average of 4.2 mm greater than values obtained using a femoral cluster coordinate system based on the centroid of the implanted femoral tantalum bead cluster.

A potential limitation of the current study was that setting the analog displacement dial at 1-mm increments between 0 and 11 mm on the KT arthrometers was achieved manually, with the examiners positioning the tibial reference pad so that the indicator on the analog dial was as close as possible, as noted by visual observation, to the 1-mm increment line on the dial. In view of the low variation in the results at every 1-mm increment across the 12 trials for both KT arthrometers (maximum SD, KT2000=0.08, KT1000=0.11) and the almost identical results for all 3 KT arthrometers, the effect of this was considered small. Another potential limitation of these findings was that the almost identical relative error of the studied KT arthrometers may be due to chance. Although this is unlikely, this simple experimental procedure should be recreated by those using KT arthrometers to measure anterior translation in the clinical and research fields. Researchers should also use these findings to help inform the results of future and past KT arthrometer validation studies. These results support the reasoning that proposes the use of side-to-side differences as the favored method of reporting the results of knee laxity testing because, unlike the absolute values, this will not be affected by the systematic error described.

REFERENCES