Validity and Intrarater Reliability of 2-Dimensional Motion Analysis Using a Handheld Tablet Compared With Traditional 3-Dimensional Motion Analysis

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Context: Lower-extremity landing mechanics have been implicated as a contributing factor in knee pain and injury, yet cost-effective and clinically accessible methods for evaluating movement mechanics are limited. The identification of valid, reliable, and readily accessible technology to assess lower-extremity alignment could be an important tool for clinicians, coaches, and strength and conditioning specialists. Objective: To examine the validity and reliability of using a handheld tablet and movement-analysis application (app) for assessing lower-extremity alignment during a drop vertical-jump task. Design: Concurrent validation. Setting: Laboratory. Participants: 22 healthy college-age subjects (11 women and 11 men, mean age 21 ± 1.4 y, mean height 1.73 ± 0.12 m, mean mass 71 ± 13 kg) with no lower-extremity pathology that prevented safe landing from a drop jump. Intervention: Subjects performed 6 drop vertical jumps that were recorded simultaneously using a 3-dimensional (3D) motion-capture system and a handheld tablet. Main Outcome Measures: Angles on the tablet were calculated using a motion-analysis app and from the 3D motion-capture system using Visual 3D. Hip and knee angles were measured and compared between both systems. Results: Significant correlations between the tablet and 3D measures for select frontal- and sagittal-plane ranges of motion and angles at maximum knee flexion (MKF) ranged from $r = .48$ ($P = .036$) for frontal-plane knee angle at MKF to $r = .77$ ($P < .001$) for knee flexion at MKF. Conclusion: Results of this study suggest that a handheld tablet and app may be a reliable method for assessing select lower-extremity joint alignments during drop vertical jumps, but this technology should not be used to measure absolute joint angles. However, sports medicine specialists could use a handheld tablet to reliably record and evaluate lower-extremity movement patterns on the field or in the clinic.

Keywords: kinematics, lower extremity, landing, injury prevention

Lower-extremity pathologies often result from improper mechanics. Inadequate muscle strength or altered activation patterns can lead to abnormal joint alignments that are associated with increased risk of injury.1–3 Inadequate hip and knee flexion during landing activities have been associated with anterior cruciate ligament (ACL) injury risk, and altered frontal-plane mechanics have been linked to ACL injury and patellofemoral pain syndrome.1–3 Three-dimensional (3D) motion analysis is the gold standard in identifying faulty mechanics and assessing efficacy of training protocols.4 However, 3D motion analysis is impractical in a clinical or field setting due to space requirements of the camera system and expertise for data collection and analysis. Two-dimensional (2D) motion analysis is acceptable for measuring lower-extremity alignment of selected tasks.5 Angles commonly assessed include hip and knee motion in the sagittal plane and frontal-plane projection angle (FPPA).5–9 FPPA, while not an anatomical joint angle, is correlated with knee-abduction angle and torque and is a common 2D measure for assessing knee-injury risk.5–7 However, these 2D analyses require using tripods and computers, which are not amenable to the clinical setting.

Technology advances provide opportunities for using handheld tablets in analyzing motion. A variety of apps are available that allow video capture and movement analysis on a tablet or smartphone. However, there is little evidence of the reliability and validity of a tablet and app. Therefore, the aim of this study was to examine the validity and intrarater reliability of a handheld tablet and app for assessing hip and knee flexion and FPPA during drop-vertical-jump (DVJ) landings.

Methods

Twenty-two healthy subjects (11 women and 11 men, mean age 21 ± 1.4 y, height 1.73 ± 0.12 m, mass 71 ± 13 kg) completed the study after screening to ensure safe
participation in DVJs. All subjects gave informed written consent (Ithaca College human subjects review board).

After instruction and practice, 6 DVJs were captured by the tablet and 3D motion-analysis systems simultaneously. Twenty-nine reflective markers were placed on anatomical landmarks (Figure 1[A]). Subjects dropped off a 31-cm box onto 2 force plates, followed by a maximum vertical jump focusing on an overhead target.

A 7-camera (240-Hz) ViconNexus system (Englewood, CO) synchronized with 2 AMTI (Watertown, MA) force plates (1200 Hz) captured the 3D data. Kinesio-Capture (Spark Motion) on an iPad2 held by a researcher with the camera lens at eye level parallel to the plane of motion captured the 2D data (30 Hz).

3D marker coordinates and force data were processed in Visual 3D (C-Motion Inc, Germantown, MD). Data were filtered with a low-pass fourth-order Butterworth filter using a 6-Hz cutoff frequency for the 3D coordinate data and 20 Hz for the force data. A 7-segment model (pelvis, bilateral thighs, shanks, and feet) was created from a static trial with the local axis systems originating at the proximal joint centers. Longitudinal axes (z) were defined by the distal joint centers, with the medial lateral axes (x) defined by the anatomical markers. The hip centers were defined from the pelvis markers.10 The knee- and ankle-joint centers were defined as the bisection of the medial and lateral joint markers. Joint angles were calculated using Euler angles (y, z, x).

Knee-flexion (3DKneeFlex) and hip-flexion (3DHipFlex) angles at initial contact (IC) and maximum knee flexion (MKF) corresponding to the 3 iPad sagittal-plane trials were averaged. Knee abduction (3DKneeAbd) and hip abduction (3DHipAbd) at IC and MKF corresponding to the 3 iPad frontal-plane trials were averaged. 3D IC was defined as when the vertical force increased above 20 N. MKF was calculated from 3D data. iPad IC was the first frame where the feet contacted the ground. MKF was the frame before visualizing knee extension. Range of motion (ROM) was calculated by subtracting IC values from MKF values.

Angles from the KinesioCapture app were obtained in the sagittal and frontal planes separately. One student researcher educated in anatomy and musculoskeletal examination with some clinical experience measured FPPA from the frontal-plane trials and hip and knee flexion from the sagittal trials, positioning the angle tool with a fingertip on the touch screen using standard goniometric alignments for sagittal-plane angles (Figure 1[B]). FPPA was measured by aligning the proximal arm along the midline of the anterior thigh, the distal arm along the midline of the anterior shank bisecting the malleoli, and the axis at the midpoint of the patella (Figure 1[C]). Averages of the 3 sagittal and 3 frontal DVJ trials were calculated. To determine the intrarater reliability of the KinesioCapture measures, a random trial from each subject was analyzed twice by the same researcher, blinded to the initial measures.

Data were analyzed using SPSS (version 22, SPSS Inc, Chicago, IL) and were statistically explored, identified outliers were visually inspected, and raw data were checked. Remaining outliers were removed for subsequent analyses; the actual n used for each analysis is in Tables 1 and 2. Since the iPad measures a projected 2D angle and there are important non-sagittal-plane motions in a DVJ, variances for the iPad and 3D angles may not be equal, so Pearson product–moment correlations were used.

Figure 1 — (A) Graphics of 3D marker setup, segment axis systems, global axis system, and 6 medial anatomical markers removed for the drop-vertical-jump trials shown in black; (B) 2D sagittal-plane angles, where δk and δH are angles as measured in KinesioCapture; and (C) frontal-plane projection angle (FPPA), where δF is the frontal-plane angle as measured in KinesioCapture. KneeFLEX
Reliability of a Tablet for Measuring Joint Angles

Results

Means and standard deviations for all variables are provided in Table 1. Significant correlations were found between FPPAIC and 3DKneeAbdIC (r = .48, P = .036), FPPAMKF and 3DKneeAbdMKF (r = .69, P = .001), FPPAROM and 3DKneeAbdROM (r = .77, P < .001), 2DKneeFlexIC and 3DHipFlexIC (r = .48, P = .028), 2DKneeFlexMKF and 3DHipFlexMKF (r = .51, P = .022), and 2DKneeFlexROM and 3DHipFlexROM (r = .73, P < .001).

FPPAs were significantly different from 3DKneeAbd at IC (P = .002) but not at MKF (P = .337) or for ROM (P = .097). Standardized differences (dIC = 1.00) from MKF were significant (dROM = 0.27) to dROM = 0.04. 2DKneeFlex measures at IC and ROM were significantly different from 3DKneeFlex measures at IC (P = .001) and ROM (P = .010) with large standardized differences (dIC = 1.26 and dROM = 0.67). 2DKneeFlexMKF was not significantly different from 3DKneeFlexMKF (P = .054) with a standardized difference of dMKF = 0.29. All three 2HipFlex measures were significantly different from the 3HipFlex measures (IC P = .001, MKF P < .001, ROM P < .001) with large standard differences (dIC = 0.82, dMKF = 1.73, dROM = 1.25). Bland-Altman plots are provided in Figures 2, 3, and 4. There was a systematic bias noted by the positive slope of the regression line in FPPAIC (R^2 = .71).

Intrarater reliability was good (.7–.9) to excellent (> .9) for all measures (Table 2). Values ranged from ICC_{2.1} = .73 (P < .001) for 2DKneeFlexMKF to ICC_{2.1} = .94 (P < .001) for FPPAMKF. MDCs ranged from 2.7° to 7.2° for FPPA, 4.9° to 7.1° for KneeFlex, and 4.7° to 7.6° for HipFlex. MDC was greater at MKF than at IC for all 3 angles.

Table 1 2-Dimensional (2D) and 3-Dimensional (3D) Lower-Extremity Measures for the Drop-Vertical-Jump Task With Pearson r Values and Coefficients of Determination (100 × r^2) for Each Pair of Measures

<table>
<thead>
<tr>
<th></th>
<th>2D, Mean ± SD (°)</th>
<th>3D, Mean ± SD (°)</th>
<th>r</th>
<th>r^2 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FPPAIC (3D KneeAbdIC), n = 21</td>
<td>-3.7 ± 4.7^b</td>
<td>0.6 ± 3.7</td>
<td>.17</td>
<td>3</td>
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<tr>
<td>FPPAMKF (3D KneeAbdMKF), n = 19</td>
<td>0.7 ± 16.6</td>
<td>4.1 ± 4.4</td>
<td>.48^a</td>
<td>23</td>
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<td>FPPAROM (3D KneeAbdROM), n = 19</td>
<td>2.9 ± 13.8</td>
<td>-3.3 ± 2.2</td>
<td>.69^a</td>
<td>48</td>
</tr>
<tr>
<td>KneeFlexIC, n = 22</td>
<td>30.5 ± 6.1^b</td>
<td>21.5 ± 7.6</td>
<td>-23</td>
<td>5</td>
</tr>
<tr>
<td>KneeFlexMKF, n = 22</td>
<td>89.8 ± 9.1</td>
<td>87.2 ± 8.5</td>
<td>.77^a</td>
<td>59</td>
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<tr>
<td>KneeFlexROM, n = 22</td>
<td>59.3 ± 9.7^b</td>
<td>65.6 ± 18.6</td>
<td>.35</td>
<td>12</td>
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<tr>
<td>HipFlexIC, n = 21</td>
<td>33.6± 8.8^b</td>
<td>25.5 ± 10.3</td>
<td>.48^a</td>
<td>23</td>
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<tr>
<td>HipFlexMKF, n = 20</td>
<td>88.0 ± 15.6^b</td>
<td>63.5 ± 11.7</td>
<td>.51^a</td>
<td>26</td>
</tr>
<tr>
<td>HipFlexROM, n = 22</td>
<td>56.2 ± 17.0^b</td>
<td>37.8 ± 9.4</td>
<td>.73^a</td>
<td>49</td>
</tr>
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</table>

Abbreviations: FPPAIC = frontal-plane projection angle (FPPA) at initial contact (IC); FPPAMKF, FPPA at maximum knee flexion (MKF); FPPAROM, FPPA range of motion (ROM); KneeAbdIC, knee-abduction angle at IC; KneeAbdMKF, knee-abduction angle at MKF; KneeAbdROM, knee-abduction ROM; KneeFlexIC, knee-flexion angle at IC; KneeFlexMKF, knee-flexion angle at MKF; KneeFlexROM, knee-flexion ROM; HipFlexIC, hip-flexion angle at IC; HipFlexMKF, hip-flexion angle at MKF; HipFlexROM, hip-flexion ROM. Note: 2D are measures from the iPad tablet.

^a Significant correlation between iPad and 3D measure (P < .05). ^b Significant difference between iPad and 3D measure (P < .05).

Table 2 Intrarater Reliability for the KinesioCapture Measurements

<table>
<thead>
<tr>
<th></th>
<th>ICC_{2.1}</th>
<th>SEM (°)</th>
<th>MDC (°)</th>
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<tr>
<td>FPPAIC, n = 19</td>
<td>.80^a</td>
<td>1.9</td>
<td>2.7d</td>
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<tr>
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<td>.94^a</td>
<td>5.1</td>
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<td>2D HipFlexMKF, n = 22</td>
<td>.80^a</td>
<td>5.4</td>
<td>7.6</td>
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</tbody>
</table>

Abbreviations: FPPAIC, frontal-plane projection angle (FPPA) at initial contact (IC); FPPAMKF, FPPA at maximum knee flexion (MKF); 2D KneeFlexIC, 2-dimensional (iPad) knee-flexion angle at IC; 2D KneeFlexMKF, iPad knee-flexion angle at MKF; 2D HipFlexIC, iPad hip-flexion angle at IC; 2D HipFlexMKF, iPad hip-flexion angle at MKF; SEM, standard error of measurement; MDC, minimal detectable change.

^a Significant at P < .01.

used to determine associations between the tablet and 3D measures. Significant differences between the iPad and 3D measures were determined with paired t-tests, and Bland-Altman plots were created. Intrarater reliability for the remeasured KinesioCapture trial was determined with intraclass correlation coefficients (ICC_{2.1}). Standard errors of measurement (SEM) were calculated for the tablet measures using the ICCs: SD times the square root of (1 − ICC). Minimal detectable changes (MDC) were calculated by multiplying SEM by the square root of 2 (to account for measurement error on 2 scores). Alpha was set at .05.
Inadequate trunk, hip, and knee flexion during landing activities has been associated with increased risk of injury to the ACL, and altered frontal-plane mechanics have been linked to ACL injury and patellofemoral pain syndrome.1–3 This study suggests that specific lower-extremity kinematics measured with an iPad are correlated with 3D motion analysis and can be reliably measured using the KinesioCapture app. Fair to good correlations were found for both frontal and sagittal ROM and MKF measures between the iPad and 3D angles. The FPPA correlations were slightly higher than those reported ($r = -0.381$) for 2D video of a DVJ.5 Only 1 significant correlation was found at IC, which may be related to difficulty in measuring IC angles due to the iPad’s slow frame rate and fixed shutter speed.

2D intratester reliability was good to excellent for all but KneeFlexMKF, which was fair. Results are similar to intratester reliability for measuring 2D angles during sit-to-stand.12 Landmarks that were occasionally obscured by the arms may have resulted in lower KneeFlexMKF reliability.

Although most tablet and 3D measures were correlated, there were large standardized differences between the 2 methods for some variables. In addition, differences between FPPAMKF and 3D knee-abduction angles were related to the magnitude of FPPA ($r = 0.83$), which could be due to conceptual differences in a 2D frontal-plane projected angle versus actual 3D joint alignment when nonsagittal motion is present. This suggests that iPad angles are not a valid substitute for actual 3D joint angles. Moreover, changes in FPPA in clients with extreme FPPA alignment may not equate to similar changes in
knee-abduction angle as for clients with more neutral FPPA. Future research is needed to determine how this may relate to knee-abduction torque or knee-injury risk.

In this study, the tablet was held parallel to the planes of motion. Caution should be used with the orientation of the tablet when collecting data to ensure accurate measures. Use of a stylus to align the angle tool may also result in greater accuracy. While males and females were included to provide a range of landing postures, results are limited to the population, and landing task and may be affected by sample size. Future studies should examine different populations and movement skills in addition to the effect of tablet positioning on validity.

Significant correlations for most measures and good ICCs suggest that the iPad and KinesioCapture app may be a reliable tool for evaluating 2D MKF and ROM landing kinematics; while the iPad and 3D measures are related, the 2D measures do not provide a valid substitute for measuring actual joint alignment. Use of a tablet and app provides an all-in-one system to record, document, and store movement patterns for sports medicine practitioners to evaluate client status and progress.

Acknowledgments
This study was approved by the Ithaca College Review Board for Human Subjects Research (#0213-10).

References

**Figure 4** — Bland-Altman plots for (A) hip flexion at initial contact (HipFlexIC) and (B) hip flexion at maximal knee flexion (HipFlexMKF).

