Reliability of Kinematic Measurements of Rear-Foot Motion

The purpose of this study was to examine the ability of a video-based, computer-interfaced motion analysis system to provide reliable data. Ten subjects with no significant orthopedic or neurological dysfunction and ranging in age from 22 to 45 years ($\bar{x}=29.6$, $SD=7.8$) were tested. Reflective markers were placed on the posterior shank and foot of each subject. Footswitches were attached to the plantar forefoot and rear foot. A video camera was placed behind the subject, and video data were collected while the subject walked on a treadmill. One representative gait cycle for each subject was selected and processed 10 times with a video processor and analysis software. Three intraclass correlation coefficients (ICCs) were calculated for variables generated by the analysis software, one for two individual measures and one each for the mean of three and five repeated measures. Except for temporal variables, processing data introduced additional variability into the measurement process, particularly for angular velocity data.

Measurement of all variables was highly reliable (ICC values $\geq 0.95$) when based on the mean of at least three repeated measures. Although a single measure of temporal and angular position variables may be considered reliable, we recommend using an average of three trials for angular velocity variables. Additional research is needed to determine tester and subject variability and validity of the measures.

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Recently, there has been considerable interest in quantifying motion at the subtalar joint because dysfunction at this joint is believed to contribute to foot and ankle overuse injuries. Several investigators$^{1-4}$ have analyzed the kinematics of the rear foot during walking and running with the use of one or more cameras positioned to the rear of the subject. Such studies primarily have been conducted in laboratory settings, but as equipment that provides automated analysis becomes more readily available and easier to use, greater application in clinical settings is feasible. Prior to the use of such equipment in any setting, however, the reliability and validity of the obtained measurements must be demonstrated.

In any measurement, error potentially can be attributed to a variety of sources including the subject, the tester, and the test equipment. Ideally, the equipment would introduce no additional error, but the reliability of the obtained measurements should be tested, not assumed. Kinematics of the rear foot have been measured using high-speed cinematography with digitization of the individual frames.$^{1-4}$
Figure 1. Motion analysis equipment and procedural setup for collecting video data on subjects. (LED=light-emitting diode, VCR=videocassette recorder.)

Engsberg and Andrews\textsuperscript{4} reported a Pearson Product-Moment Correlation Coefficient of .39 when performing a test-retest experiment on a series of six consecutive cinematographic frames digitized on five separate occasions. Frame-by-frame digitization, however, is very tedious and time-consuming. Recently, microcomputer-based systems (hardware and software) that provide various kinematic measures of rear-foot motion have become available commercially.

The purpose of this study was to assess the ability of a specific video-based, computer-interfaced motion analysis system to provide reliable data. We hypothesized that equipment-related measurement error would be minimal, as indicated by acceptably high reliability coefficients.

Method

Sample

Ten volunteers (8 women, 2 men) with no significant orthopedic or neurological dysfunction were tested. The absence of significant orthopedic or neurological dysfunction was determined by the tester (MJM) and operationally defined as no pain, weakness, or instability resulting in an inability to perform normal activities of daily living. The subjects ranged in age from 22 to 45 years ($\bar{X}$=29.6, SD=7.8). No effort was made to determine each subject’s static foot and ankle alignment because we did not believe that either these or other subject-related factors would influence the ability of the system to process data reliably. All subjects gave informed consent to participate in the study.

Measurement System

The measurement system studied has both hardware and software components. The main hardware component, the Motion Analysis\textsuperscript{5} ExpertVision\textsuperscript{5} system, is a general purpose, video-based, microcomputer-interfaced, two-dimensional motion analysis system. The ExpertVision\textsuperscript{5} system includes the following components: a video camera and lens,$^1$ a spotlight, a video monitor, a video processor (VP-110),$^2$ a videocassette recorder (VCR),$^2$ and a microcomputer (Fig. 1). The video camera uses a CCD (charge-coupled device) solid-state imaging device to capture visual images and convert them to electrical signals. The camera’s electronic shutter operates at 30 frames per second, and the scanning mode is set at 2:1 noninterlaced to allow a sampling frequency of 60 fields per second. The camera was equipped with a video lens that has a 12.5-mm focal length.

The spotlight, a 30-W reflector bulb with a reflector hood, was attached to the tripod next to the camera (to maximize the amount of light reflected back to the camera from the retroreflective markers$^2$ secured to the subject). The video monitor was a conventional black and white monitor with a 50.5-cm (12-in) diagonal screen. The video processor has a maximum sampling rate of 60 Hz. The VCR is an industrial grade, 1.27-cm (0.5-in) VHS-type recorder/player. The VCR has several features that aid in locating appropriate data for processing, including pause, frame-by-frame advance, search modes, and audio event channels. The microcomputer is an IBM-PC$^4$-compatible system that incorporates an Intel 80836 processor chip.$^5$

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\textsuperscript{2}Ti-23A, NEC Corp, NEC Building, 33-1, Shiba 5-chrome, Minato-ku, Tokyo 108, Japan.
\textsuperscript{3}AG-630Cl, Panasonic, Audio-Video Systems Division, One Panasonic Way, Secaucus, NJ 07094.
\textsuperscript{4}International Business Machines Corp, PO Box 1328-W, Boca Raton, FL 33429.
\textsuperscript{5}Intel Corp, Robert Noyce Bldg, 2200 Mission College Blvd, Santa Clara, CA 95052.

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running at 16 MHz. The system contains 640K of random access memory (RAM), two floppy disk drives, a 40M hard disk drive with a 28-millisecond access time, and a VGA color graphics monitor and adapter card. The operating system for the microcomputer is DOS, version 3.3.

The software component of the measurement system is FootTrak, a set of computer programs designed to process the video data and produce various measures of rear-foot kinematics during standing and walking. In addition to FootTrak and the standard hardware components of the ExpertVision® system, the motion analysis system included a black metal box containing light-emitting diodes (LEDs), which were connected by wires to footswitches* on the plantar surface of the subject's foot. The footswitches are on-off devices that close when the foot makes contact with the floor. A specific LED is activated when the connected footswitch closes.

**Basic System Operation**

Retroreflective markers are placed on the subject in locations that permit measurement of specific variables of interest. The LED box and the subject are placed in the camera's field of view. The video camera, which is focused on both the subject and the LED box, captures a series of images that represent both movement of the markers and timing of foot-floor contact. The series of images is sent either directly to the video processor for processing or first to the VCR for recording and then to the video processor for processing. The video processor detects the edges of the markers and LEDs in the analog video signal and digitizes them. On command from the FootTrak software, the video processor sends the digital data representing the x and y coordinates of the edges of the markers and LEDs to the microcomputer. After the digitized data have been collected by the microcomputer, the FootTrak software locates the centroid (center) of each marker (and LED) in each image. The FootTrak software then creates a time-based representation of movement, referred to as a "path," by joining successive locations of each centroid (taken from successive images). Finally, the path data are processed further using conventional mathematical techniques to produce measures of temporal, angular position, and angular velocity variables.

**Procedure**

One tester (MJM) performed all procedures. Pairs of retroreflective markers were placed at the midline of the calcaneus and the distal one third of the leg bilaterally using the following procedure. Subjects were positioned prone on a firm plinth with their leg in neutral (neither medially nor laterally rotated). The calcaneus was held with the thumb on one side and the index finger on the other. The calcaneus was bisected visually, and two retroreflective markers were placed over the midline, one just above the plantar surface of the heel and one at the superior-posterior aspect of the heel just below the axis of the subtalar joint (determined visually by pronating and supinating the subtalar joint). The lower leg was then bisected visually, and two markers were placed over the midline, one each at 5 and 20 cm proximal to the malleoli (Fig. 2).

Thin, relatively pliable on-off footswitches were secured to the plantar surface of the forefoot (at the first metatarsal head) and rear foot (at the posterior lateral heel) bilaterally with double-sided adhesive tape and wrapped with paper tape (Fig. 2). The footswitches were connected via a thin, flexible cable to the LED box. The LED box was placed to the right of the posterior aspect of a treadmill in the camera's field of view (Fig. 1).

The camera and attached spotlight were placed 165 cm (65 in) behind the subject and 53 cm (21 in) above the ground. Although the FootTrak manual recommends placing the camera 140 cm (55 in) behind the subject and 38 cm (15 in) above the ground, preliminary testing on 10 subjects (by the first author) prior to the study indicated this camera placement often failed to record data during the late stance phase. Increasing the height and distance of the camera from the subject increased the field of view and allowed improved measuring during the late stance phase.

Video data required for calibration were obtained prior to testing each subject. A bar with a pair of retroreflective markers was placed across the rear of the treadmill, adjacent to the LED box. The camera was adjusted so that its field of view included the horizontal reference bar and the LED box. Room lighting, camera aperture, and threshold control of the video processor were adjusted to optimize the detection of the targets (ie, the retroreflective markers and the LEDs). Three seconds or more of calibration video data were then recorded on the VCR for subsequent processing.

Subjects practiced walking on the level treadmill with the footswitches secured to their feet. Subjects were allowed to take as much time as necessary to increase their walking speed slowly to 3.2 mph. During the acclimation period, the tester checked to ensure that all markers remained attached to the posterior leg and calcaneus, footswitches were attached to the plantar surface of the foot, and appropriate images of the reflective markers were displayed on the video monitor. When the subject was acclimated to walking on the treadmill, video data were collected on the VCR. The videotape was allowed to run for at least 8 seconds prior to the sampling period. A hand-held tone switch was used to place an audio event tone on the tape to mark the beginning of each sample. Data were collected for at least 2 minutes, with audio event marks placed approximately every 30 seconds.

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Data Processing

Recorded video data were processed using the video processor and the FootTrak software. First, the videotape was rewound to a point at least 8 seconds prior to a specified audio tone. Next, as the videotape was played, the video processor (1) detected the audio event tone, (2) began extracting data representing the edges of the markers and the LEDs, and (3) sent the data to the microcomputer. Then, using the dynamic treadmill analysis mode of the FootTrak software, one representative gait cycle from the data collected on a subject was selected to be used for repeated processing. A "representative gait cycle" was defined as a cycle that contained all necessary footswitch data and (2) visually showed similar kinematics to the mean of the multiple gait cycles displayed on the monitor. The selected gait cycle was processed 10 times; each time, processing began with rewinding the videotape to the same starting point (initiated by the audio tone) and playing the same segment of videotape to be processed.

Data used for analysis were taken from ASCII files generated by the FootTrak software instead of from the standard FootTrak printout because data on the FootTrak printout (1) were rounded to the nearest whole degree (which seemed to introduce additional error in preliminary testing) and (2) did not include standard deviations. Raw data (to 0.01° precision) from the ASCII files were collected and summarized in a separate file. The variables examined in this study and their operational definitions are presented in the Appendix. Names of variables are those provided by the FootTrak software.

Data Analysis

Intraclass correlation coefficients (ICC[3,1]) and standard deviations were used as indicators of the ability of the equipment to provide reliable data. As described earlier, the representative gait cycle for each subject was processed 10 times to yield 10 measures for each variable. Three ICCs were calculated for each variable, one based on 2 individual measures (first and second) and one each based on the mean of 3 (first 3 and second 3) and of 5 (first 5 and second 5) repeated measures of the variable. The standard deviation of all 10 measures of each variable was also determined. The criterion used for judging the acceptability of the reliability coefficients was ICC2.95. This relatively high criterion was chosen because we believed computer-assisted video analysis should introduce little error into the measurement.

Figure 2. Subject positioned prone on plinth showing placement of retroreflective markers and footswitches.
Table. Means, Standard Deviations, Coefficients of Variation, and Intraclass Correlation Coefficient Values

<table>
<thead>
<tr>
<th>Variable*</th>
<th>$X^a$</th>
<th>SD$^b$</th>
<th>CV</th>
<th>ICC$^d$</th>
</tr>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>SM 3M 5M</td>
</tr>
<tr>
<td>Calcaneus-to-tibia angle (*)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Angle at touch-down</td>
<td>8.10</td>
<td>0.86</td>
<td>10.62</td>
<td>.93 .99  1.00</td>
</tr>
<tr>
<td>Maximum pronation</td>
<td>12.06</td>
<td>0.42</td>
<td>3.48</td>
<td>1.00 1.00 1.00</td>
</tr>
<tr>
<td>Total pronation range of motion</td>
<td>5.36</td>
<td>0.86</td>
<td>16.04</td>
<td>.86 .99  .99</td>
</tr>
<tr>
<td>Time to maximum pronation (% of gait cycle)</td>
<td>23.31</td>
<td>3.64</td>
<td>15.61</td>
<td>.95 .98  .99</td>
</tr>
<tr>
<td>Toe-off angle (n=8)</td>
<td>5.55</td>
<td>0.80</td>
<td>14.41</td>
<td>.96 .99  1.00</td>
</tr>
<tr>
<td>Calcaneus-to-tibia angular velocity (°/s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Initial velocity</td>
<td>36.57</td>
<td>27.63</td>
<td>75.55</td>
<td>.50 .95  .97</td>
</tr>
<tr>
<td>Maximum pronation velocity</td>
<td>125.57</td>
<td>22.10</td>
<td>17.60</td>
<td>.88 .96  .96</td>
</tr>
<tr>
<td>Maximum supination velocity</td>
<td>203.64</td>
<td>34.18</td>
<td>16.78</td>
<td>.93 .98  .99</td>
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<tr>
<td>Temporal variable</td>
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<td></td>
<td></td>
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<tr>
<td>Swing</td>
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<td></td>
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<tr>
<td>Percentage</td>
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<td>0.00</td>
<td>1.00</td>
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<tr>
<td>Time (ms)</td>
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<td>0.00</td>
<td>1.00</td>
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<td>Stance</td>
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<tr>
<td>Percentage</td>
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<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Time (ms)</td>
<td>513.19</td>
<td>0.00</td>
<td>0.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

*Left leg only.

*a Grand mean of 10 measures on 10 subjects.

*Mean standard deviation for 10 measures on 10 subjects.

*Intraclass correlation coefficients (ICC[3,1]) on repeated single measures (SM), means of three repeated measures (3M), and means of five repeated measures (5M).

Results

The Table presents the means, standard deviations, coefficients of variation (CVs), and ICC values for the variables analyzed. Standard deviations were 0.00 and ICC values were 1.00 for all temporal variables. The ICC values for calcaneus-to-tibia angle measures were .86 to 1.00 for repeated single measures, .98 to 1.00 for means of three and five repeated measures. The ICC values for calcaneus-to-tibia angular velocity measures were .50 to .93, .95 to .98, and .96 to .99 for repeated individual measures, the mean of three repeated measures, and the mean of five repeated measures, respectively. The standard deviations were <1.00 degree for angular position variables and 22.1° to 34.2°/s for angular velocity variables.

Discussion

The values of the ICC (1.00) and standard deviation (0.00) for all of the temporal variables indicate that the motion analysis system did not introduce any error into the measurements of those variables; that is, the system processed temporal data from the same gait cycle identically all 10 times. The high level of reproducibility for the temporal measures probably is related to the fact that the system has to identify the time at which the LEDs (the source in the video images of the temporal data produced by the footswitches) turn on and off, not their exact location in terms of Cartesian coordinates.

There was more variability in the measures of angular position than in the measures of temporal variables. Although standard deviations were low (≤0.86) for repeated single measures, the ICC values of some repeated measures were unacceptable according to our a priori criterion (ICC≤.95). Using a mean based on three repeated measures increased all ICC values (ICCs≥.98).

In comparison with the other variables, there was notable variability in the measurements of the angular velocity variables. The ICC values were as low as .50, and standard deviations were as high as 34.2 (CV=17%-76%) for calcaneus-to-tibia angular velocity. Errors in angular velocity measures would be expected to be greater than errors in angular position measures because angular velocity measures are derived. They are derived from the angular position measures through the use of difference scores and the formation of ratios. Velocity is equal to position.
2 minus position 1, divided by the given time interval. Because each position measure may contain error, this process apparently compounded the original error and rendered the derived measure less reliable than the data from which it was derived. Indices of reliability improved markedly when the mean of either three (ICC≥.95) or five (ICC≥.99) repeated measures was used. Based on these data, we recommend using a mean of three repeated measures for all angular velocity variables.

A benefit of FootTrak’s printed report is an option that allows the user to choose kinematic data from either individual cycles or the mean of up to six trials. Unfortunately, the report values of each cycle are rounded to the nearest whole degree, and preliminary testing (by the first author) seemed to indicate that this rounding also introduced error. In addition, the printed report does not contain standard deviations for the trials. We believe the report would be much more useful to researchers and clinicians if rounding error were reduced and standard deviations were included.

Besides the dynamic treadmill report, FootTrak provides options for color graphic displays of angular position and velocity data and for animated stick figures on the monitor of the computer. One to six cycles (or a mean of all cycles) of left or right tibia-to-calcanear angle, tibia-to-calcanear velocity, calcaneus-to-vertical angle, and tibia-to-vertical angle may be viewed with or without event markers (ie, heel-off or toe-on). Figures on the screen can be printed at any time. These features may be useful in a clinical setting to visualize kinematic patterns and to assist in patient education or training situations. Further research is needed to determine meaningful parameters of these kinematics in pathological and nonpathological populations.

This study assessed the reliability of data generated by the dynamic treadmill analysis option of FootTrak. The FootTrak software also contains options for measuring resting calcaneus stance position and neutral calcaneus stance position. Although we did not analyze these measures, we would expect reliability for repeated processing of these static angular position measures to be similar to the reliability of the angular position measures examined in this study.

Given certain constraints regarding lighting and marker placement, the Motion Analysis® system allows the kinematic analysis of essentially any type of movement. Although flexible, use of the system requires some basic programming skills. A benefit of FootTrak software (especially to clinicians) is that no computer programming is required of the user. A limitation of the preprogrammed software is that it cannot be modified easily.

FootTrak software is designed to be used with the subject walking or running on a treadmill. The benefits of treadmill analysis are that it requires minimal space in a clinic or research laboratory and the field of view remains essentially stationary. Some patients, however, have difficulty adjusting to treadmill ambulation. In addition, ambulating on a treadmill may or may not be considered a legitimate simulation of normal walking. Kinematics of rear-foot motion may be different than kinematics of normal walking. Finally, integration of the FootTrak system with other movement analysis systems (ie, force platform or kinematics in the sagittal plane) would be dependent on the ability of the other systems to use a treadmill.

This study examined equipment performance. The same data (ie, the same gait cycle) were processed by the equipment multiple times. Placement of markers, footswitches, and foot and ankle alignment of the subjects were all constant and should have no influence on processing the same gait cycle repeatedly. Therefore, any variability in the measurements obtained in this study must be due to error introduced at intermediate stages of processing. Factors that are important in relation to accuracy, either at the level of acquisition of the raw video signal (eg, camera frame rate and resolution, speed of target movement, variations in lighting conditions) or at the later stages of processing (eg, type of filtering, methods for deriving values), cannot be addressed by our data. Our data also cannot address the errors that would be associated with the use of the equipment in applied settings.

The only relevant potential sources of error in this study would include the following: (1) reproduction by the VCR of the original analog video signal from the videocassette tape, (2) data acquisition and digitization by the video processor of the analog signal received from the VCR, and (3) acquisition and initial processing by the computer of the digitized data from the video processor (ie, creation of the video file). Walton reported a loss of system precision (defined as agreement among repeated observations made under identical conditions) when comparing data collected directly from the system camera with data collected from prerecorded videotape. He concluded that although there was some loss of precision, “these losses are insignificant when compared to other sources of error” and “storing raw video images on video cassettes has little or no impact on overall system performance.” We are unaware of any data that address the precision of either data acquisition and digitization by the video processor or data acquisition and initial processing by the computer system. Therefore, the degree to which each of the factors noted contributes to random error cannot be determined at this time.

In general, the primary purpose of these measures is to infer motion occurring at the subtalar joint. Variables generated by the FootTrak software and similar variables reported in the literature1-3 purport that the equipment is measuring pronation and supination. With this type of two-dimensional, video motion analysis system, however, data are taken only from the plane of motion that is parallel to the lens of the camera. Error
(as related to actual joint motion) will be introduced if the axis of the joint is not perpendicular to the midline of the camera lens. Because the axis of the subtalar joint is oblique and there is considerable variation among subjects, only a portion of the actual triplanar pronation or supination motion is being analyzed. The portion of motion viewed by a single camera would more closely approximate the frontal-plane motion of calcaneal inversion and eversion at the subtalar joint. Even this component of actual subtalar joint motion will be distorted as the leg rotates in the transverse plane or moves medially or laterally in the frontal plane. Additional research is needed to determine the reliability, validity, and clinical usefulness of these measurements.

**Conclusion**

Except for measures of temporal variables, the Motion Analysis® system and the FootTrak software introduced additional variability into the measurement process, particularly for angular velocity data. The reliability of all angular position and angular velocity measurements increased with the number of measures used. Measurement of all variables was highly reliable (ICC values ≥ .95) when taking a mean of at least three repeated measures. Although this study documents the reliability of measurements obtained under controlled conditions (ie, the equipment was the only source of error), additional research is needed to determine (1) the error attributable to tester and subject factors and (2) the validity of the measures.

**Acknowledgment**

The primary software used in this study, FootTrak, was furnished by Motion Analysis Corporation.

**References**