

A proposed test to support the clinical movement analysis laboratory accreditation process

John P. Holden^a, W. Scott Selbie^b, Steven J. Stanhope^{c,*}

^a US Food and Drug Administration, Center for Devices and Radiological Health, Rockville, MD 20850-3223, USA

^b C-Motion, Inc., Rockville, MD 20855, USA

^c Physical Disabilities Branch, National Institutes of Health, Building 10, Room 6s235, MSC 1604 Bethesda, MD 20892-1604, USA

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Abstract

This paper describes a testing methodology and resultant set of four variables that can be used to quickly and easily document the correct installation, configuration, and combined working status of force platform (FP) and three-dimensional (3D) motion capture components of a clinical movement analysis (CMA) laboratory. Using a rigid, rod-shaped testing device, CMA laboratory data are collected simultaneously from the FP and motion capture components (typically, video-based kinematic measurements) as the device is manually loaded while being pivoted broadly about a point on the FP. Using a computational method based on static equilibrium, it is possible to independently measure the rod's orientation and tip position during the moving trial, using FP derived data exclusively, and to compare these estimates to rod orientation and tip position estimates derived exclusively from the motion capture component. The motion laboratory accreditation test (MLAT) variables include: the difference (angle) between the orientation of the long axis of the testing device as independently determined from kinematic measures (motion capture component) and the FP derived data; and the difference (x , y , z) between the center of pressure position (FP derived) and the position of the testing device tip (motion capture derived) that loads the FP. A numerical dynamics model was explored to evaluate the appropriateness of the static equilibrium-based FP data model and to determine guidelines for testing device movement frequency and FP loading. The MLAT technique provides a simple means of detecting the combined presence of errors from many sources, several of which are explored in this paper. The MLAT has been developed to help meet one criteria of the CMA laboratory accreditation process, and to serve as a routine quality assessment tool.

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1. Introduction

Criteria for clinical movement analysis (CMA) laboratory accreditation in the United States and Europe are being developed in several areas, including measurement instrumentation, data collection, and data reduction [1]. One of the challenges in developing specific criteria in these areas is the need for a relatively simple, standardized method to assess and report the combined performance of the force platform (FP) and the system components dedicated to measuring movement (motion

capture component). Several approaches for checking and/or comparing system performance have been reported in recent years [2–19], but many of these methods have tended to be time-consuming and/or focused on a specific measurement system or application. For example, a method similar to that proposed for rapidly ‘spot checking’ for stereophotogrammetric errors [18] utilizes a tipped rod that is manually moved in a circular pattern, but does not include an evaluation of FP measures. More recently, a method for ‘spot checking’ FP location estimates that simultaneously measures and compares FP and kinematic data from a double tipped rigid rod [19] has been proposed. However, this method: (1) requires that the rod be kept almost vertical during each data set collection (minimally loading the FP shear components), (2) needs data

* Corresponding author. Tel.: +1-301-496-9891; fax: +1-301-480-9896

E-mail address: steven_stanhope@nih.gov (S.J. Stanhope).

sets from five different locations to test each FP, and (3) produces indices that are primarily sensitive to FP location. Therefore, the need remains to identify a rapid methodology that generates a minimal number of measures giving an immediate indication of whether or not all aspects of the measurement systems are configured, calibrated and implemented properly.

Inverse dynamics analysis is used routinely in CMA laboratories to calculate variables such as net joint moments and joint powers. To perform this analysis, motion and FP data are combined. The ground reaction forces (GRFs) measured using a FP must be correctly calculated and spatially transformed into the laboratory coordinate system (LCS), where they are expressed relative to the positions of body segments and joints measured by the motion capture components. If either the FP or the motion capture components are not configured or functioning properly, or if these devices are not correctly synchronized in time and space, then errors are introduced when the FP and motion data are combined in the inverse dynamics analysis.

Data inaccuracies can be introduced through the motion capture components, the force measurement system, or the synchronization of the motion and force data in time and space. FP measurement errors can exist due to the system's configuration (e.g. analog scale factors, and FP origin specification), its interface (e.g. FP channel connections and assignments), and/or estimates of FP alignment (e.g. the spatial transformation of FP data from the FP coordinate system into the LCS). Errors introduced by the motion capture components can be caused by uncorrected camera nonlinearities, poor three-dimensional (3D) external camera calibration, and/or target image distortions. In setting up and calibrating video-based systems, numerous parameter settings and measurement estimates must be properly made in order for the FP data to correctly reflect the location and orientation of the GRF relative to the objects measured by the motion capture components. Ideally, an accreditation test of these measurement systems will be sensitive to as many of the potential sources of error as possible, without extraordinary requirements for time or equipment. In addition, the method should lead to a rapid determination of the exact nature and cause of the system's poor performance.

The purpose of this paper is to describe a rapid testing methodology and a set of four variables that can quickly and easily document the correct installation, configuration, and combined working status of the combined FP and motion capture systems. The technique provides a simple means of detecting the presence of errors across a wide spectrum of system components, settings and configurations. The test also has limited use as an aid in trying to determine the specific source(s) of errors. The output variables incorporate data that are collected

simultaneously from the FP and the motion capture components, and they indicate the extent of spatial agreement between the two sets of data. This motion laboratory accreditation test (MLAT) technique has been expressly developed to meet one criteria of the CMA laboratory accreditation process, and to serve as a regular laboratory quality assessment tool.

2. Methods

The MLAT involves use of a rigid mechanical device similar to ones that have been described previously [3,15,16,19]. The test device includes a machined rigid rod that has a pointed tip at each end. Using a hand-held loading bar and base-plate, each with machined conical depressions (dimples), one can manually apply forces through the testing device rod to the FP with a negligible applied moment of a force couple. The rod was outfitted with five spherical, retroreflective targets; however, the authors believe the device design is amenable to alternative motion tracking technologies. Data are simultaneously sampled from the FP and motion capture components as forces are manually applied through the loading bar and the test device is pivoted about the tip mounted in the base-plate (Fig. 1). The testing device should be placed on the FP in a location that will effectively load all FP components. During the test, the manually loaded rod should be pivoted through a broad range of angles relative to the FP working-surface, including arcs in each of the two vertical planes defined by the LCS.

For the purpose of this report, the 3D position of the rod tip mated with the base-plate and the orientation (in the form of a unit vector) of the tip-to-tip long axis of the rod in the LCS, as determined using the motion capture component, (60 Hz video-based system) were calculated using a least squares fit of the unfiltered target locations to a model of the precisely machined device. FP derived (60 Hz) CoP locations were obtained from an AMTI (type OR6-5-1) FP. The FP origin parameter is a manufacturer supplied parameter that indicates the location of the center of the FP top working surface relative to the FP measurement origin. It is used in the calculation of $\text{CoP}_{(x,y,z)}$ locations in the FP coordinate system and during the spatial transformation of the CoP data from the FP coordinate system to the LCS. The FP origin parameter was adjusted to accommodate the base-plate thickness at the base of the dimple.

The coincidence of the rod orientation measurements and the rod tip-position/CoP measurements is indicated by four test variables (Fig. 2). The rod orientation variable ($\Delta\theta$) is the angle derived from the dot (scalar) product between the rod orientation (in the form of a unit vector) as independently determined from the

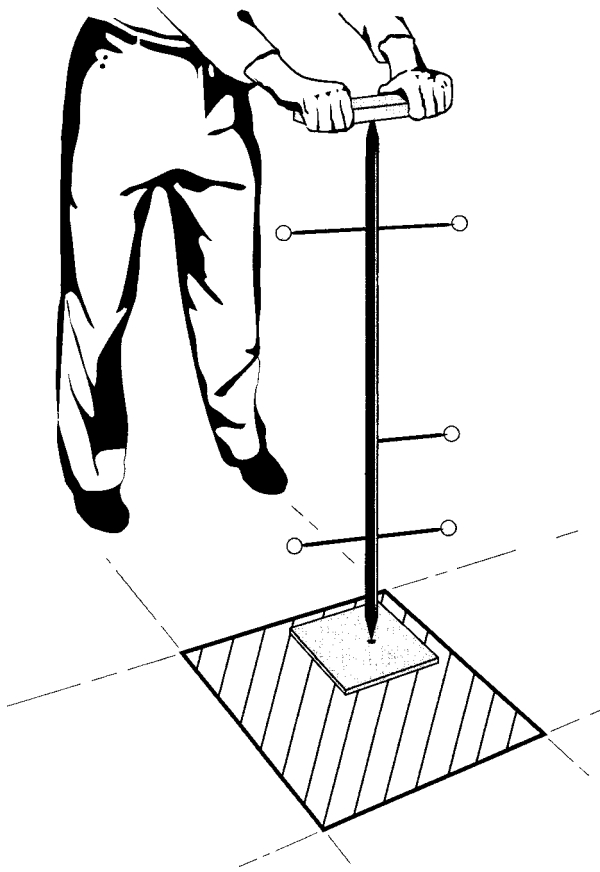


Fig. 1. A rigid mechanical device is used to apply forces to the FP. The device includes spherical, retroreflective targets attached to a machined rod having a pointed tip at each end. Using a hand held loading-bar and base-plate (shaded) with machined conical depressions, one can apply forces to the FP with a negligible applied moment. Data are sampled as the test device is manually loaded and slowly pivoted about the rod end on the base-plate.

motion capture and FP measures (Appendix A, section I). The three COP position variables ($\Delta\text{CoP}_{x,y,z}$) are the differences in the coordinates of the CoP location, i.e. the x , y , and z components of the displacement vector between the CoP location (determined from the FP measurements) and the tip of the test device rod location (determined from the motion capture component). For a given test trial, the mean, standard deviation, and range of these four variables are calculated for all cases in which a minimum GRF magnitude is exceeded.

A critical point of the proposed testing method is to obtain independent estimates of the testing rod's orientation from motion and FP data. To accomplish this, it is assumed that the FP data have been obtained from a loaded rod in a state of static equilibrium. However, execution of a comprehensive CMA laboratory test requires that the manually loaded rod be intentionally moved through all LCS planes to angles that substantially load the FP shear components of force. Validity of the static equilibrium FP data model was evaluated

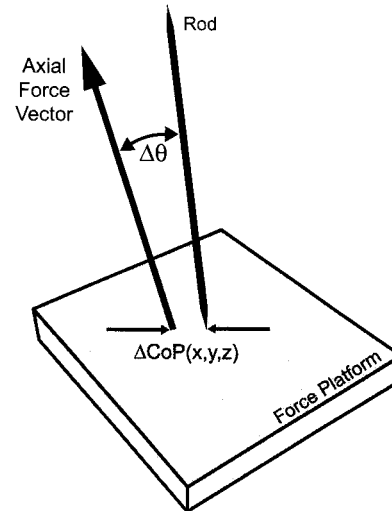


Fig. 2. The four test variables include: the rod orientation variable ($\Delta\theta$), the difference in spatial orientation (angle) of the rod as separately determined from FP measures (axial force vector) and kinematic measures of the rod (Appendix A, section I); and ΔCoP , the differences in the three coordinates of the CoP location, i.e. the x , y , and z components of the displacement vector between the CoP location determined from the FP and the tip of the testing rod as determined from the motion capture system.

using an equation that relates the dynamics of rod motion to errors in the rod orientation variable (Appendix A, section II, Eq. (6)). This equation was combined with a numerical model of a loaded inverted pendulum located in a gravitational field (dynamics model) that underwent simple harmonic motion with a maximum angular displacement from vertical of 0.5 rad (approximately 29°). The dynamics model was used to evaluate the influence of rod movement frequency and magnitude of the FP applied force (F_p) on the magnitude of the rod orientation variable ($\Delta\theta$) due solely to the missing inertial terms in the FP data model (variable β in Appendix A). Initially, the dynamics model was evaluated using a constant applied force of 100 N over a range of movement frequencies from 0.0 to 1.0 Hz. Finally, the dynamics model was evaluated at a constant movement frequency of 0.39 Hz over a range of FP applied forces from 16 to 100 N. Physical characteristics of the modeled rod were obtained from the test device rod (length = 1 m, mass = 1.5 kg). Rod inertial characteristics were obtained using a thin rod model (center of mass location = 0.5 m, $I_{cg} = 0.125 \text{ kg m}^2$).

In addition to calculating and reporting the descriptive statistics for the four test variables, an analysis program, developed specifically to support the MLAT process, displays an interactive 3D rendering of the test trial. The program renders models of the FP, the position and orientation of the mechanical testing device, and the CoP and FP derived rod orientation vector scaled to the applied load, all in a 3D scene. The movements of the testing device and aligned load, as

well as the locations of the rod tip and the CoP location, are displayed through an animation of the test scene, which can be viewed from any angle. Such data rendering assists in the interpretation of results, by allowing a visual assessment of the quality of the test data and of how (and possibly why) the four MLAT variables changed during the trial.

The ability of the technique to disclose several common sources of systematic errors was verified by individually altering the values of common parameters associated with actual CMA test data obtained using the test device. As explained in the following three paragraphs errors were incorporated in the following parameters: one FP alignment dimension, one FP analog scale factor, and the FP origin offset. The analysis program was executed on each set of data, with and without one of the introduced parameter errors.

The position and orientation (alignment) of the FP relative to the LCS must be accurately known. This information is used to determine the spatial transformation of the GRF data into the same coordinate system as the 3D motion data, in many cases, the alignment is specified by the 3D locations of the four FP corners in the LCS (Fig. 3). Errors can easily be made in determining these corner locations; such errors should add an offset to the mean value of the corresponding ΔCoP x , y , or z variable. As an example of such an error, the FP alignment test was performed by adding a value of 10 mm to the x coordinate of each FP corner location.

FP analog scale factors are used to convert raw data obtained from an analog-to-digital converter to physical units such as Newtons, meters, or Newton-meters. Correct scaling must be applied in order to obtain

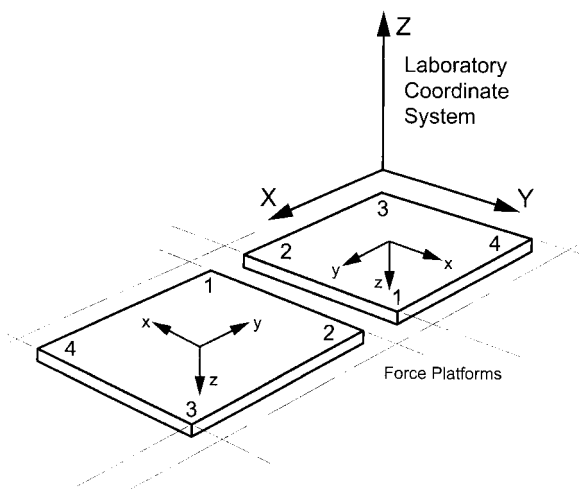


Fig. 3. The position and orientation of each FP coordinate system relative to the LCS is specified by the locations of the four FP corners in the LCS. These data are typically used to determine the transformation of the measured ground reaction forces into the LCS, i.e. into the same coordinate system as the 3D point data used to locate the test device.

accurate FP force, moment, and CoP measures. Measurement errors can result due to incorrect setting of an amplifier gain or excitation voltage, or incorrect calculation of the calibration conversion factor. Errors in the scale factors for the FP shear forces are reflected in the $\Delta\theta$ variable, and in one of the horizontal plane components of the ΔCoP variable (the particular component that is affected depends on the orientation of the FP relative to the LCS). To demonstrate this effect, the analog scale factor for the FP F_y channel was increased by a factor of two for a test in which the z direction was vertical in the LCS (FP scale factor test).

The location of the FP measurement origin, in relationship to the center of the FP working-surface, is usually specified by a vector (expressed in the FP coordinate system) from the FP measurement origin to the center of the working surface (Fig. 4). This convention was established along with the C3D file format [20], which was originally introduced in the 1980s. The FP coordinate system is often oriented with the z -axis directed downwards (i.e. away from the top working surface), in which case the sign of the z -component of the origin offset vector would be negative, according to the convention. However, not all CMA laboratories conform to this convention; rather, the negative of the vector (i.e. opposite sign for each component) is sometimes employed. Also, not all analysis programs interpret the origin location parameter in the same manner. If inconsistencies exist, the horizontal plane components of the ΔCoP variable will be erroneous; the magnitudes of the errors will depend on the magnitude of the origin location error and on the magnitude and direction of the applied force. To illustrate this effect well, the testing device was moved to form an inverted conical pattern

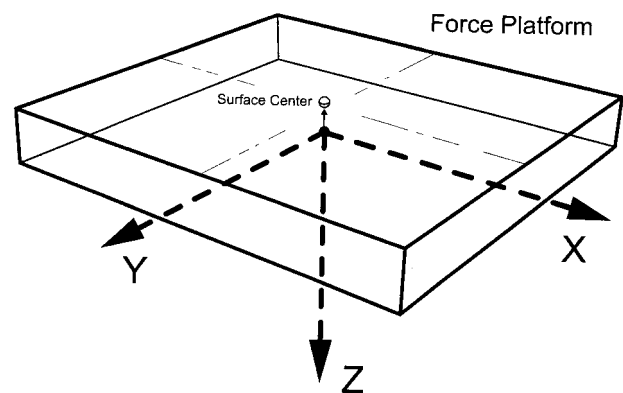


Fig. 4. The location of the measurement origin in the FP is usually specified by a vector from the FP measurement origin to the center of the top working surface, in the FP coordinate system. The FP coordinate system origin is below the surface, and the z -axis is directed downwards, so the sign of the z component is negative, according to the convention established in the 1980s. A problem can exist if the origin location is stored in one manner (e.g. with a positive z component), and the analysis software interprets the values according to the convention (i.e. with opposite sign).

during force application, and the analysis program was executed using correct and inverted values of the FP origin offset parameter (FP origin test).

3. Results

The dynamics model was evaluated to determine the influence of rod motion and net load applied to the FP on the magnitude of the rod orientation variable ($\Delta\theta$) due to the inertial terms (β). The range of modeled rod movement frequencies (0.0–1.0 Hz) produced a range of maximum rod accelerations from 0.0 to 20.7 rad/s² that coincided with the locations of maximum rod displacement (± 0.5 rad). Likewise, the magnitude of β increased exponentially with increased movement frequency (Fig. 5) to a maximum of 3°. A movement frequency of 0.39 Hz (2.98 rad/s²) resulted in a β value of slightly less than 0.5° while a frequency of 0.57 Hz (6.30 rad/s²) produced a value for β approximating 1°.

The influence of FP load on the rod orientation variable under the dynamic model conditions was evaluated using a set movement frequency of 0.39 Hz and range of applied forces from 16 N (slightly greater than the rod weight) to 115 N. The resultant maximum value of β decreased exponentially with an increase in applied load from a high of 4.9° to a low of 0.4° (Fig. 6). A FP applied load of 50 N was required to reduce the angular error in $\Delta\theta$ below 1°.

During laboratory experiments, an attempt was made to produce CMA laboratory data using the MLAT device under conditions that reduced the maximum influence of motion and load on the $\Delta\theta$ variable to below 1°. As anticipated, the FP alignment test shifted

the mean value of the ΔCoP_x variable by 10 mm. The endpoints of the range of ΔCoP_x were also shifted by 10 mm, while the magnitude of the range was unchanged. The standard deviation of ΔCoP_x was also unchanged as a result of the alignment test. The variable $\Delta\theta$ and the other CoP variables (i.e. ΔCoP_y and ΔCoP_z) were also unchanged.

Under the FP scale factor test conditions, whenever a shear force was applied along the FP Y axis, the inclination of the predicted axial force vector (Appendix A, Eq. (3), term A) away from vertical was always greater than the inclination of the testing rod. This effect was maximized by pivoting the testing rod primarily in the $y-z$ plane of the FP (Fig. 7, curve a). The $\Delta\theta$ variable with the correct F_y scale factor was $0.4 \pm 0.2^\circ$ (mean \pm standard deviation (S.D.)), with a range of 0.1–1.1°; reprocessing the same data file with an incorrect scale factor (offset by a factor of two), $\Delta\theta$ was $6.3 \pm 3.2^\circ$, and had a range of 0.1–11.8°. Also, because the shear forces are used in calculating the CoP location, errors were also detected by the ΔCoP_x variable (note: the FP Y axis was aligned with the LCS X axis). With the correct scale factor, Δ

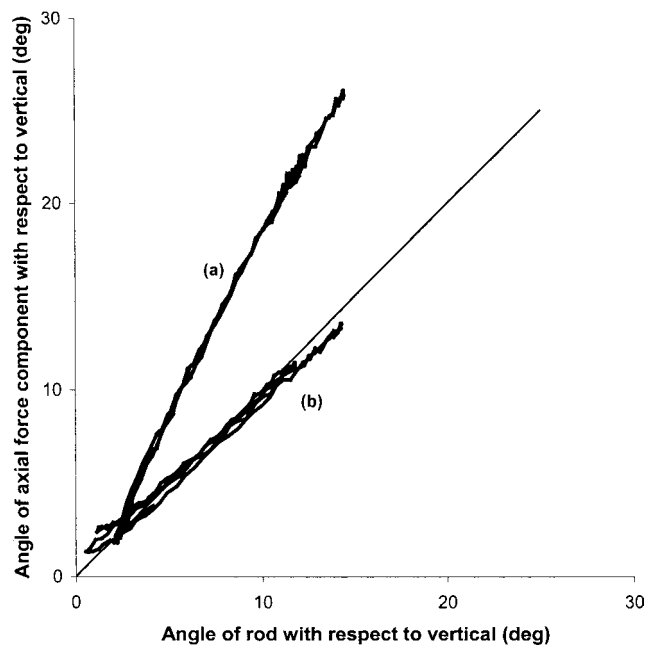


Fig. 7. The angle of the FP derived rod orientation (axial force) plotted vs. the angle of the testing rod orientation derived from the motion capture components, for two trials of test data processed with the analog scale factor for the F_y channel offset by a factor of two (the straight line indicates a one-to-one correspondence of the two angles). (a) The rod was kept close to the $y-z$ plane of the FP during the data collection, so that F_y shear forces were generated. Whenever there was an F_y shear component, the inclination of the FP derived rod orientation away from vertical was greater than the motion capture determined inclination of the testing rod. Thus, the magnitude of the rod orientation variable ($\Delta\theta$) also became progressively greater with greater inclination of the rod. (b) The rod was kept close to the $x-z$ plane of the FP during force application, so that minimal F_y shear forces were generated (see text for further details).

processed with the FP measurement origin not specified according to the convention (Fig. 8a), ΔCoP_x was -1.2 ± 11.6 mm (range of -21.0 to 17.8 mm) and ΔCoP_y was -2.7 ± 11 mm (range of -23.9 to 18.5 mm); with the FP measurement origin specified and interpreted according to the C3D file convention (Fig. 8b), analysis of the same data yielded values of 1.2 ± 1.5 mm (range of -2.1 to 4.9 mm) for ΔCoP_x and -1.1 ± 1.2 mm (range of -5.0 to 3.2 mm) for ΔCoP_y . The values for ΔCoP_z (which use the FP corner data to locate the working-surface of the FP) and $\Delta\theta$ were unaffected by the difference in specifying the FP origin location.

4. Discussion

The purpose of this paper is to describe a rapid and comprehensive system testing methodology for performing routine quality assessments in support of the CMA laboratory accreditation process. While appearing comprehensive in design, it is important to indicate that the proposed technique does not fully evaluate the FP free moment variable by loading it beyond a 0.0 N m load,

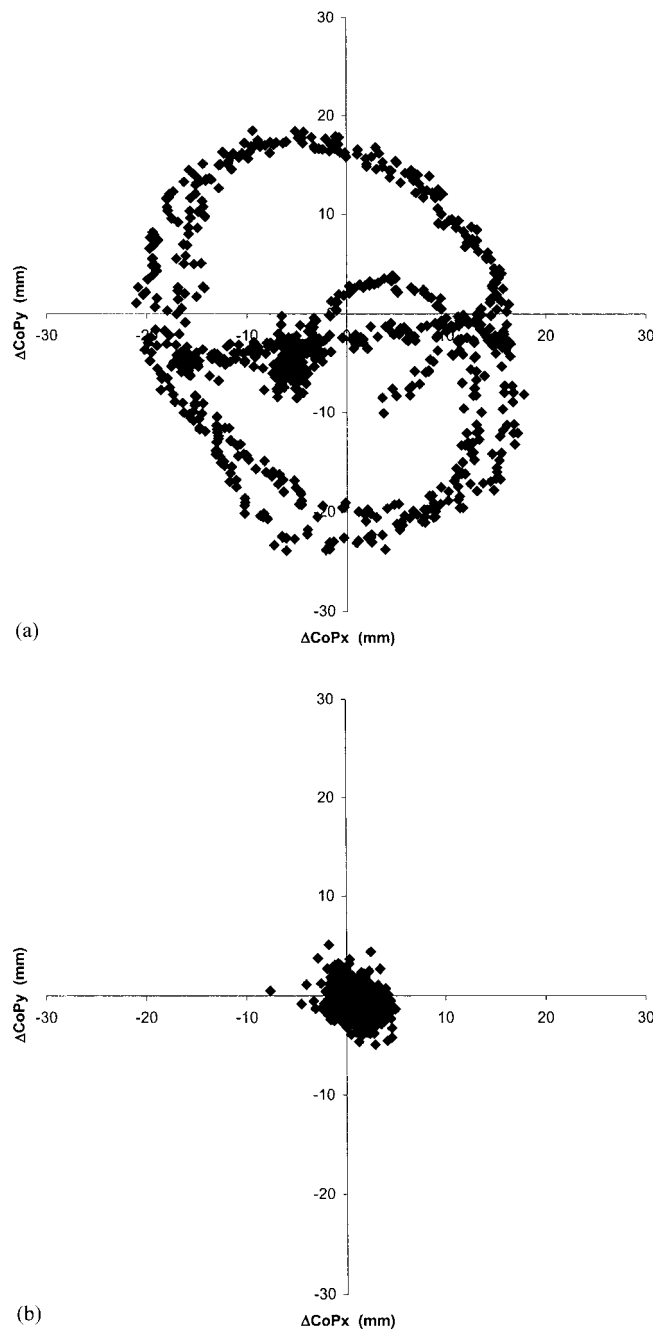


Fig. 8. ΔCoP_x and ΔCoP_y plotted using the same data for two specifications of the FP measurement origin location. (a) The FP origin location is specified as the negative of the convention, but is interpreted according to the convention. The test device was pivoted about a fixed point on the FP outlining an inverted conical pattern as forces were applied, producing a circular pattern of large errors in the FP-derived CoP locations. (b) The FP origin location is specified and interpreted according to the convention. The ΔCoP values show a random dispersion of much smaller magnitude.

nor does it readily reveal small errors in time synchronization. The primary focus of the method is to detect the presence of a broad range of errors, and to provide an indication of the specific source(s) of errors. This is a significant advancement over methods that primarily

focus on kinematic [18] or FP location factors [19]. The advancement stems from the ability to dynamically load and position the MLAT device rod throughout a broad range of orientations and planes with knowledge of the minimally confounding effects of inertial factors. Being comprehensive in nature, some errors could show up in similar ways in the four proposed test variables. However, a finding of ‘unacceptable’ results for any of the four variables from a single comprehensive test maybe further explored using more focused trials of the proposed testing technique to aid in determining the exact error source.

While the proposed test does not automatically reveal the specific source(s) of all errors, the ability to control rod movement and relocate the rod tip makes it is a useful tool to assist in the troubleshooting process. If an initial test yields ‘unacceptable’ results for any of the four variables, additional data collection trials can be performed. The additional tests may include movement of the testing rod in an arc in only one of the vertical planes (Fig. 7 illustrates how this can help to detect an error in the analog scale factor for one of the horizontal force components). Tests on each of the four quadrants of the FP surface may also prove helpful, depending on the specific nature of the data that caused concern.

An example of an actual application of this problem detection and troubleshooting ability occurred when it was observed that a patient’s CoP patterns, expressed in the foot coordinate system, appeared different depending upon which of two FPs the patient stepped on in a given trial. Repeated tests were made on both FPs in the laboratory, using a variety of different conditions and multiple locations on the FP surfaces. The data revealed that the magnitude of the CoP errors on one FP varied with the location of the applied force. Next, multiple tests were performed on each FP after switching the two cables that connected them to the amplifiers (to test for the possibility of a deteriorating cable), and again after switching the amplifiers used by each FP. Such a systematic application of the test allowed the laboratory staff to identify and replace a deteriorating FP in a manner that would not have been possible without the MLAT technique. The result is that considerable time was saved, compared with sending all of the equipment (or one piece at a time) to the manufacturer. If the test had been used earlier (as part of a regular quality check), the problem might have been detected prior to collecting the patient data that originally raised suspicion. This example and other previous experience has shown that the presence of errors can easily go undetected in regular laboratory use [3,9]; it is hoped that application of this testing technique (or a similar test) will help assure that such errors are detected and prevented from becoming a confounding factor in either a research or clinical application.

Results from the dynamics model evaluation indicate that the major assumption of the proposed test (the use of FP data static equilibrium equations to determine rod orientation when the rod is actually moving) is valid if loads of reasonable magnitude (greater is better) and movement cycles of reasonable duration (longer is better) are used. For example, performing one complete cycle of motion (e.g. forwards and backwards returning to an upright position over a maximum displacement range of ± 0.5 rad, approximately 29°) using the described test device in 3 s while applying a load equivalent to 15% of a 70 kg investigator will result in an acceleration induced error (β) in the rod orientation variable of less than 0.5° . It is important to note that these values may be improved further by optimizing the length and mass of the MLAT device rod—a process that was not considered in the context of this report.

Results of the dynamics model test indicate the theoretical best-case performance of the proposed test over a range of loads and movement frequencies. The dynamics model simulated the perfect motion capture system where the magnitude of $\Delta\theta$ was influenced exclusively by the missing inertial terms in the MLAT procedure. Based on the results, minimal performance criteria for a test procedure can be established so as not to exceed an inertial error tolerance. For example, a system test that repeatedly moves the described test device no faster than 3 s per cycle, through an arc of no more than 60° in each of the vertical planes, while loading the device with no less than 100 N force will result in inertial errors in the $\Delta\theta$ variable of less than 0.5° . Decreasing the rod size (length and/or mass) and decreasing the maximum allowed movement frequency of the test device will reduce the inertial error tolerance to insignificant levels for most CMA applications.

The significance of the magnitudes of the four MLAT variables obtained from experimental data must be interpreted in the context of a proposed clinical or research application and must be made within each laboratory in light of its specific applications and instrumentation capabilities. These variables were selected based on their relationship to fundamental measurements that can be independently derived from the motion capture and force plate components. This desired generic characteristic is explicitly intended for comparing basic measurement capabilities of the motion capture components in order to assure their proper configuration. Therefore, it is important to note that the MLAT variables do not contain estimates of all possible error sources contained within a specific movement analysis application—such as gait analysis.

The laboratory-based experimental conditions utilized in this study indicate values for the rod orientation ($\Delta\theta$) and the ΔCoP variables can reach sub-degree and mm levels using a six camera video-based CMA system configured for bilateral lower extremity gait analysis.

Results from the three primary FP tests indicate that the central tendency and variability measures associated with each MLAT variable provide important information. Certainly, the measurement resolution and configuration of the CMA laboratory systems will limit how small and variable one can reasonably expect the difference values to be. As the proposed test is used in more laboratories, and as additional studies are conducted to examine the sensitivity of the technique to different combinations of error sources, a body of knowledge will likely develop that can shed greater light on the question of significance and acceptance criteria.

Calculating the orientation of the MLAT device rod from FP data (Appendix A section I, vector quantity \mathbf{A}) allows that the value of $\Delta\theta$ should always be zero in the absence of measurement errors, noise and rod movement. This simplifies the presentation and interpretation of the test results. The desired value of zero for $\Delta\theta$ is independent of factors such as the orientation of the testing rod, or the magnitude of the applied force, or the weight of the testing rod. Currently, the $\Delta\theta$ variable utilizes estimates of rod orientation that are derived independently—an important conceptual point of this proposed test. Unlike related methods [3], the inertial terms are neglected in the calculations of $\Delta\theta$ because their inclusion would require estimates of the rod acceleration from motion system measurements. This would introduce test specific errors related to the target trajectory filtering and differentiation procedures that would confound the MLAT estimates of the basic motion capture component's capabilities. In addition, these processing related errors would not necessarily reflect the magnitude and nature of all error sources encountered during CMA studies.

The proposed test as implemented in this paper is specific to target-based motion capture systems. The principles of the approach, however, apply equally well to other methods of measuring body position and orientation. Regardless of the motion capture technology being used, the need remains to accurately measure and express external forces relative to body segments, in order to accurately apply inverse dynamics analysis. The testing device described here can be modified to accommodate other motion measurement sensors, thereby making the proposed test more universally applicable as a part of a laboratory evaluation and accreditation process.

Proper configuration and functioning of CMA laboratory measurement systems are essential to the accuracy of data on which clinical decisions and research conclusions are based. Use of the MLAT, or a similar technique that incorporates the same principles, can give a quick summary indication of system function. It is hoped that such a test will contribute to the evolving laboratory accreditation process, will assist in regular laboratory quality assurance testing, and may

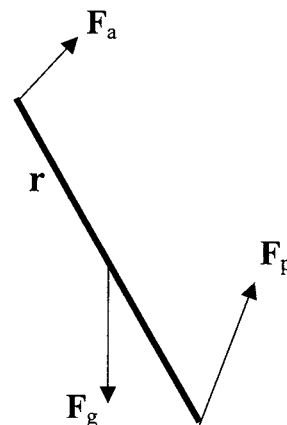
eventually become part of standard criteria for evaluating the quality of motion capture data.

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Appendix A: Calculation of the rod orientation variable and the equation for evaluating the static equilibrium assumption

Section I: Calculating the rod orientation variable under the assumed condition of static equilibrium



$$\sum \mathbf{F} = 0 = \mathbf{F}_p + \mathbf{F}_a + \mathbf{F}_g \quad (1)$$

$$\begin{aligned} \sum \mathbf{T}_p = 0 &= \mathbf{r} \times \mathbf{F}_a + \frac{\mathbf{r}}{2} \times \mathbf{F}_g \\ &= \mathbf{r} \times (-\mathbf{F}_p - \mathbf{F}_g) + \frac{\mathbf{r} \times \mathbf{F}_g}{2} \quad (2) \end{aligned}$$

$$\Rightarrow \mathbf{r} \left(-\mathbf{F}_p - \frac{1}{2} \mathbf{F}_g \right) = \mathbf{r} \times \mathbf{A} = 0 \quad (3)$$

Thus, \mathbf{r} and \mathbf{A} are parallel and the test device rod orientation (\mathbf{r}) is defined entirely by the vector quantity \mathbf{A} that is derived from FP measurements (\mathbf{F}_p) and the physical characteristics of the testing device ($\mathbf{F}_g/2$, i.e.

the weight of the rod and its center of mass location; in this case, half the rod length). The rod orientation variable ($\Delta\theta$) is determined from the dot product of the unit vector along \mathbf{A} and the unit vector aligned with the long axis of the rod (\mathbf{r}) as determined using the motion capture components.

Free-body diagram of testing device:

\mathbf{F}_p , ground reaction force; \mathbf{F}_g , gravitational force (weight); \mathbf{F}_a , applied force; \mathbf{r} , position vector between tips (p to a) of testing device rod.

Section II: Equation for evaluating the static equilibrium assumption.

Under 2D dynamic conditions, the following holds:

$$|\mathbf{r} \times \mathbf{A}| = \left(\frac{mr^2}{4} - I_{cg} \right) \theta \quad (4)$$

Rewriting the left-hand side of Eq. (4)

$$|\mathbf{r}||\mathbf{A}|\sin \beta = \left(\frac{mr^2}{4} - I_{cg} \right) \theta \quad (5)$$

Rearranging Eq. (5), the magnitude of the angular displacement (β) between vectors \mathbf{r} and \mathbf{A} due exclusively to the inertial terms can be isolated:

$$\beta = \sin^{-1} \left[\frac{(mr^2/4 - I_{cg})\theta}{|\mathbf{r}||\mathbf{A}|} \right] \quad (6)$$

where r is the length of the testing device rod, I_{cg} the moment of inertia of the test device rod about the center of mass location, m the mass of the testing device rod and θ is the angular acceleration of the testing device rod relative to an inertial reference frame

References

- [1] Leo T, Fioretti S, Maurizi M, Verdini F. A telematic system for the accreditation of clinical movement analysis laboratories. *Gait Posture* 2000;11(2):130–1.
- [2] Augsburger S, Hoffinger S, Graubert C. Evaluation of a 3-D motion analysis system. Proceedings of the 8th annual East Coast Clinical Gait Laboratory conference; 1993.p. 135–36.
- [3] Baker R. The ‘poker’ test: a spot check to confirm the accuracy of kinetic gait data. *Gait Posture* 1997;5(2):177–8.
- [4] Bhimji S, Deroy AR, Baskin ES, Hillstrom HJ. Static and dynamic accuracy of the VICON 370 3-D kinematic system. *Gait Posture* 2000;11(2):130.
- [5] Dabnichki P, Lauder M, Aritan S, Tsirakos D. Accuracy evaluation of an on-line kinematic system via dynamic tests. *J Med Eng Technol* 1997;21(2):53–66.
- [6] DeLuzio KJ, Wyss UP, Li J, Costigan PA. A procedure to validate three-dimensional motion assessment systems. *J Biomech* 1993;26(6):753–9.
- [7] Ehara Y, Fujimoto H, Miyazaki S, Mochimaru M, Tanaka S, Yamamoto S. Comparison of the performance of 3D camera systems II. *Gait Posture* 1997;5(3):251–5.
- [8] Haggard P, Wing AM. Assessing and reporting the accuracy of position measurements made with optical tracking systems. *J Motor Behav* 1990;22(2):315–21.
- [9] Masiello GH, Stanhope SJ, Vaughan CL, Payne PA. The first step towards standardization for three gait laboratories. *Gait Posture* 1994;2(1):54.
- [10] Miyazaki S. A simple and practical method for evaluating overall measurement error of joint moments obtained by a force plate and a position sensing device. *Frontiers Med Biol Eng* 1992;4(4):257–70.
- [11] Packer TL, Wyss UP, Costigan PA. Reliability of an optoelectric system to measure elbow kinematics. *Clin Biomech* 1993;8:315–21.
- [12] Richards JG. The measurement of human motion: a comparison of commercially available systems. In: Proceedings of the 5th international symposium on the 3-D analysis of human movement; 1998.p. 1–9.
- [13] Schmid OA, Wiinsche P, Trotnow K. Experiences with the dynamic accuracy of a new 3D calibration technique. In: Proceedings of the 6th international symposium on the 3D analysis of human movement; 2000. p. 17–20.
- [14] Scholz JP. Reliability and validity of the WATSMART™ three-dimensional optoelectric motion analysis system. *Phys Ther* 1989;69(8):679–89.
- [15] Stanhope SJ. On the magnitude of angular kinematic inaccuracies in gait analysis. In: Vossoughi J, editor. Proceedings of the 13th Southern Biomedical Engineering conference; 1994.p. 1031–1034.
- [16] Stanhope SJ. A procedure for evaluating gait analysis system performance. *Gait Posture* 1994;2(1):54.
- [17] Vander Linden DW, Carlson SJ, Hubbard RL. Reproducibility and accuracy of angle measurements obtained under static conditions with the Motion Analysis™ video system. *Phys Ther* 1992;72(4):300–5.
- [18] Delia Croce U, Cappelzozzo A. A spot check for estimating stereophotogrammetric errors. *Med Biol Eng Comput* 2000;38:260–6.
- [19] Rabuffetti M, Ferrarin M, Benvenuti F. Spot check of the calibrated force platform location. *Med Biol Eng Comput* 2001;39:638–43.
- [20] Dainis A, McGuire DA. AMASS: ADTECH Motion Analysis Software System. Gaithersburg, MD: ADTECH, 1995.