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In Situ Calibration and Motion Capture Transformation Optimization Improve Instrumented Treadmill Measurements

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We increased the accuracy of an instrumented treadmill's measurement of center of pressure and force data by calibrating in situ and optimizing the transformation between the motion capture and treadmill force plate coordinate systems. We calibrated the device in situ by applying known vertical and shear loads at known locations across the tread surface and calculating a 6 × 6 calibration matrix for the 6 output forces and moments. To optimize the transformation, we first estimated the transformation based on a locating jig and then measured center-of-pressure error across the treadmill force plate using the CalTester tool. We input these data into an optimization scheme to find the transformation between the motion capture and treadmill force plate coordinate systems that minimized the error in the center-of-pressure measurements derived from force plate and motion capture sources. When the calibration and transformation optimizations were made, the average measured error in the center of pressure was reduced to approximately 1 mm when the treadmill was stationary and to less than 3 mm when moving. Using bilateral gait data, we show the importance of calibrating these devices in situ and performing transformation optimizations.

Keywords: instrumented treadmill, center of pressure, calibration, gait

As instrumented treadmills that measure vertical and shear forces become more common (Lee & Hidler, 2008; Riley et al., 2007; Dierick et al., 2004; Belli et al., 2001; Kram et al., 1998), it is important to assess the accuracy of these measurement tools and determine how to optimally integrate them with motion capture technology. If used with motion capture systems, it is critical that these treadmills accurately measure the center of pressure (COP), since errors in the COP location of just 5 mm have been associated with 7% changes in maximum joint torque calculations (McCaw & DeVita, 1995). Whereas moving instrumented treadmills have demonstrated up to 10 mm (Kram et al., 1998) or more (Paolini et al., 2007) of COP error, techniques for reducing this error to those of fixed force plates have not been offered.

There are a number of reasons why calibration of instrumented treadmills and their integration with motion capture technology must be treated differently than that of traditional fixed force plates. First, if the force plate component is calibrated before the attachment of the treadmill, the plate may undergo microdeformations, resulting from the presence of the treadmill, which need to be accounted for after installation. In addition, the large footprint of these devices makes them susceptible to any variability in the laboratory floor surface on which they sit. Therefore, it is possible that these devices need to be calibrated in situ, not only to reduce cross talk, but also to accommodate any performance modifications introduced by their final assembly and installation in the laboratory.

Second, in contrast to traditional force plates, instrumented treadmills do not offer well-defined corners and edges that lend themselves to easy determination of force plate position and orientation using motion capture technologies. A method for initially estimating the location of the force plate coordinate system relative to the motion capture coordinate system, followed by an optimization process to reduce remaining errors in the transformation between these two coordinate systems is warranted. The accuracy of this transformation is critical due to the large size of treadmill force plates; since rotation by a small angle sweeps out a larger arc when located further from the origin of the rotation, small

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errors in the rotational component of the transformation will be amplified for COP measurements made far from the force plate measurement origin.

Rabuffetti et al. (2001) describe a technique for identifying error in this transformation, but not one for correcting it. While past researchers have not considered in situ calibration to account for errors introduced by the laboratory environment, efforts have been made to minimize cross talk. Cross talk between channels is often measured via application of a vertical load (Paolini et al., 2007; Dierick et al., 2004), which does not account for possible cross talk between shear forces. Belli et al. (2001) applied shear loads to assess cross talk with vertical channels, but did not evaluate cross talk between the shear channels.

A technique is presented for optimizing the COP data and subsequent calculation of kinetic data obtained from a split-belt, instrumented treadmill by performing an in situ calibration which includes all six of the treadmill's output channels, as well as minimizing error associated with calculating the transformation between the motion capture and treadmill force plate coordinate systems.

Methods

We worked with a split-belt treadmill instrumented with two side-by-side force plates (Model TM-06-B, Bertec Corp., Columbus, OH; Figure 1a), which each output three-dimensional forces (F_x, F_y, F_z) and moments (M_x,

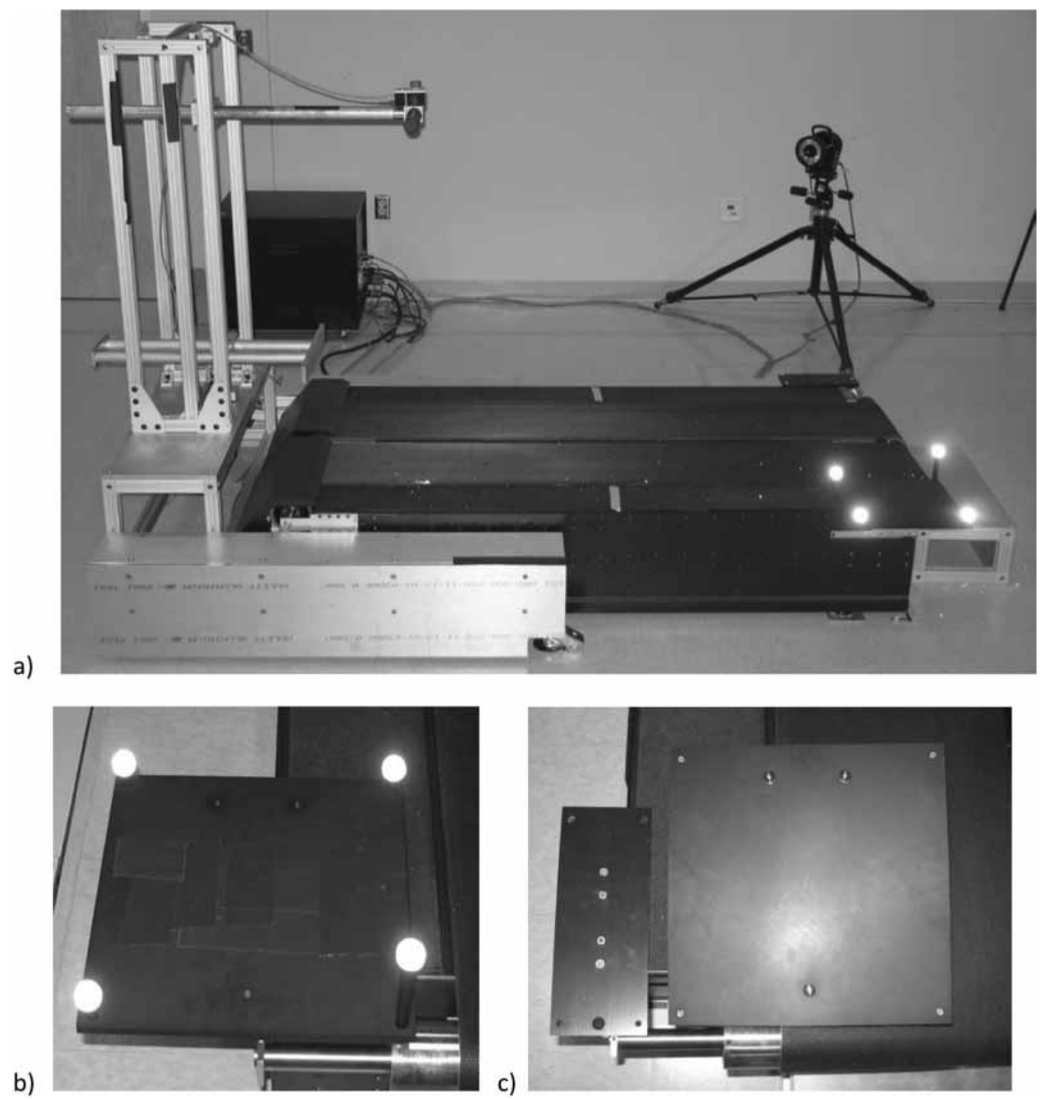

Figure 1 — a: The instrumented, split-belt treadmill with the locating jig registered to the left unit. Note the custom-designed handrails (in front of and overhanging the treadmill) that do not mechanically couple the left and right treadmills. b: The top surface of the locating jig, showing the four tracking targets, one of which is at a unique height. c: The bottom surface of the locating jig showing the three spheres that fit into hemispherical holes precision-machined into a base plate that was rigidly fixed to each treadmill.

M_y, M_z). To maximize the accuracy of the device in measuring the COP relative to the motion capture coordinate system, we calibrated the device in situ in a manner independent of the motion capture system and then optimized the transformation between the motion capture and treadmill force plate coordinate systems.

Even though the device was calibrated by the manufacturer before installation, we performed an in situ calibration that included all six channels of data output by each treadmill. A 400-N vertical load and a 225-N shear load were independently applied at known locations across the stationary treadmill surfaces and the resulting forces and moments were measured by the force plates. Vertical loads were applied in eight locations and medial/lateral (ML) and anterior/posterior (AP) shear loads were applied in four and three locations, respectively. Vertical loads were applied by placing a symmetric cylindrical load of 400 N on the treadmill, circular end down. Shear loads were applied via a very low friction pulley that attached a hanging load of 225 N to a symmetrical cylindrical load placed on the treadmill surface, the vertical load from which had been previously zeroed out. For both the vertical and shear loads, the locations of the applied loads relative to each force plate origin were determined using a digitizing arm (FARO Technologies Inc., Lake Mary, FL) to measure points along the circumference of the symmetrical cylindrical load and thus determine the location of its center. The manufacturer reports the accuracy of the digitizing arm to be 0.081 mm. These locations were then used to determine the applied moments. A 6 × 6 calibration matrix (**C**) was calculated as

$$C = \left[\left(pinv\left(M^T\right)\right)A^T\right]^T \tag{1}$$

where **M** and **A** are matrices containing the measured and applied loads, respectively, and *pinv* is the pseudoinverse. When calculating the 6 × 6 calibration matrix, **M** and **A** are 6 × 15 matrices. The 15 columns correspond to the locations where the loads were applied (8 vertical, 4 ML, and 3 AP) and the 6 rows contain the loads (F_x, F_y, F_z, M_x, M_y, and M_z). When applied to the 6 channels of treadmill data, the calibration matrix, **C**, reduced the error between the measured and applied forces and moments, including errors due to cross talk. A 3 × 3 calibration matrix was also calculated by only including 3 rows of data (F_z, M_x, and M_y) in the **M** and **A** matrices of Equation 1. This 3 × 3 matrix did not account for any errors in the shear loads (F_x and F_y), but was calculated as a potential alternative to the 6 × 6 matrix because it is much easier to generate, in that it does not require the application of a known shear load. Once calibrated, the treadmill was not moved.

Our assessment and correction of COP error were based on the MTD-2 tool (Motion Laboratory Systems, Baton Rouge, LA), a pointed rod fitted with five tracking targets, and associated CalTester software (C-Motion Inc., Germantown, MD) that quantifies COP error as the distance between the rod tip location determined by both the motion capture system and the treadmill force plate (Holden et al., 2003). The accuracy of this error value is a function of the accuracy of the MTD-2 tool dimensions. The individual components of the MTD-2 tool are each manufactured to a tolerance of 0.127 mm; in the unlikely event that the tolerances of each component of the device were maximally off in a cumulative manner, this would result in a worst-case maximum error in the known location of the rod tip relative to the motion capture targets of approximately 1.25 mm. CalTester also measures the orientation error between the measured orientation of the rod and the ground reaction force vector. Errors measured by CalTester are reduced both by improved accuracy of the treadmill force plate's measurement of the COP in the force plate coordinate system and by improved accuracy of the calculated transformation between the motion capture and treadmill force plate coordinate systems.

Traditionally, the transformation between the motion capture and force plate coordinate systems is calculated internally by motion capture software based on the location of the force plate corners, as determined by motion capture targets. However, small errors in the assumed known locations of the force plate corners relative to the targets can lead to error in the subsequent COP calculation. Since treadmill force plate corners are not readily accessible, we designed a custom locating jig fitted with four motion capture targets that reliably interfaced with the treadmill via three metal spheres affixed to its base (Figures 1b and c). We used the motion capture system to confirm that this design resulted in very repeatable registration of the locating jig.

Our goal was to find the locations of the jig targets relative to the force plate origin so that the jig could be used to accurately locate the force plate corners. To do this, we used initial assumed locations of the jig targets in the force plate coordinate system and the motion capture system's measurement of these target locations (P_{jig_MC}) to locate the force plate corners and calculate an initial transformation between the motion capture and force plate coordinate systems. We then used CalTester data to calculate and correct any error in the initial assumed locations of the jig targets.

Three trials of CalTester data were collected in each of the four quadrants of each treadmill force plate. The resulting COP values at the rod tip, as determined by the treadmill force plate, were calculated in the force plate coordinate system (P_{tip_FP}). The Caltester tip location was also determined by the motion capture system (P_{tip_MC}). These values were used to find an optimized transformation, consisting of a rotation R and a translation O, between the motion capture and force plate coordinate systems by minimizing the error expression

$$\sum_{n=1}^{12}\left[P_{tip\_FP} - (RP_{tip\_MC} + O)\right]^2 \tag{2}$$

using a least-squares method as described by Spoor and Veldpaus (1980), where n is the number of locations CalTester data were collected. This optimized transformation was then used to find the correct locations of the jig targets in the force plate coordinate system via

$$P_{jig\_FP}^{corrected} = R^{-1}(P_{jig\_MC} - O) \quad (3)$$

These corrected jig target locations could then be used in any subsequent data collection to correctly locate the force plate corners and calculate the transformation between the force plate and motion capture coordinate systems.

To evaluate our techniques, we collected five trials of CalTester data at the front, middle, and rear of each stationary treadmill. In addition, five CalTester trials were collected when the treadmill was moving at a speed of 0.2 m/s. Average static and moving trials lasted 12 and 6 s, respectively. The average vertical load applied during all CalTester trials was approximately 85 N. We also collected gait data from a shod, healthy, 77-kg subject walking on the treadmill at 1.3 m/s using a marker configuration as described by Holden et al. (1997). Informed consent was obtained for this IRB-approved study. For all trials, motion capture and force plate data were sampled at 120 and 1040 Hz, respectively, and filtered at 6 and 20 Hz (10 Hz for gait data), respectively. We compared the data processed with and without the transformation correction technique and corrected with the 3 × 3 and 6 × 6 calibration matrices.

Results

We measured an average of 5.5 and 2.4 mm of ML and AP COP error, respectively, in the uncorrected, stationary condition. The transformation optimization technique reduced the ML error to 1.0 mm and reduced the orientation error to 0.8° (Table 1). Applying the 3 × 3 calibration matrix resulted in improvement in the average AP COP error, reducing it to 1.7 mm (Table 2). Applying the 6 × 6 calibration matrix further reduced the average AP COP error to 1.2 mm and the orientation error to 0.6°. The average ML and AP COP errors in the fully corrected moving treadmill trials were 0.7 and 2.9 mm, respectively (Table 2).

Table 1 Average error (*SD*) in treadmill measurement of medial/lateral (ML) and anterior/posterior (AP) position (COP) and orientation of CalTester rod before any calibration or transformation optimization (left three data columns) and after just the transformation optimization (right three data columns) at three positions along the length of the stationary treadmill and collected when the treadmill was moving at a speed of 0.2 m/s. The average values for the three stationary positions along the treadmill are also given.

In Situ Calibration:	No Calibration			No Calibration		
Transformation:	Not Optimized			Optimized		
	ML-COP Error (mm)	AP-COP Error (mm)	Orientation Error (°)	ML-COP Error (mm)	AP-COP Error (mm)	Orientation Error (°)
Front left	6.0 (0.5)	4.7 (1.2)	1.5 (0.1)	0.4 (0.3)	2.5 (1.4)	0.9 (0.1)
Middle	5.4 (0.3)	1.3 (1.0)	1.3 (0.0)	0.8 (1.5)	1.5 (0.9)	0.7 (0.0)
Rear right	5.0 (0.2)	1.2 (1.1)	1.3 (0.0)	1.8 (0.2)	3.3 (1.6)	0.8 (0.0)
Average of three positions	5.5	2.4	1.4	1.0	2.4	0.8
0.2 m/s	4.3 (0.4)	4.2 (1.5)	1.2 (0.1)	0.3 (0.2)	5.7 (1.4)	0.9 (0.2)

Table 2 Average error (*SD*) in treadmill measurement of medial/lateral (ML) and anterior/posterior (AP) position (COP) and orientation of CalTester rod after transformation optimization and calibration with either a 3 × 3 (left three data columns) or 6 × 6 (right three data columns) calibration matrix at three positions along the length of the stationary treadmill and collected when the treadmill was moving at a speed of 0.2 m/s. The average values for the three stationary positions along the treadmill are also given.

In Situ Calibration:	3 × 3 Calibration Matrix			6 × 6 Calibration Matrix		
Transformation:	Optimized			Optimized		
	ML-COP Error (mm)	AP-COP Error (mm)	Orientation Error (°)	ML-COP Error (mm)	AP-COP Error (mm)	Orientation Error (°)
Front left	1.1 (0.6)	2.3 (1.4)	0.9 (0.1)	0.8 (0.4)	1.3 (0.8)	0.7 (0.1)
Middle	0.9 (0.3)	1.4 (1.1)	0.7 (0.0)	0.5 (0.4)	1.1 (0.3)	0.6 (0.1)
Rear right	1.4 (0.2)	1.5 (1.3)	0.8 (0.0)	2.0 (0.2)	1.1 (0.9)	0.6 (0.1)
Average of three positions	1.2	1.7	0.8	1.1	1.2	0.6
0.2 m/s	0.3 (0.3)	4.1 (1.6)	0.9 (0.2)	0.7 (0.4)	2.9 (1.2)	1.0 (0.2)

There was a meaningful change in the sagittal hip joint moment when a 3 × 3 versus a 6 × 6 calibration matrix was applied to the treadmill gait data (Figure 2). With the 3 × 3 calibration, a difference was observed between right and left hip moments for a subject who walked symmetrically over-ground. After the 6 × 6 calibration was applied, data from both the right and left treadmills shifted to be more bilaterally symmetrical. This shift was accompanied by a comparable shift in the AP ground reaction force (Figure 3).

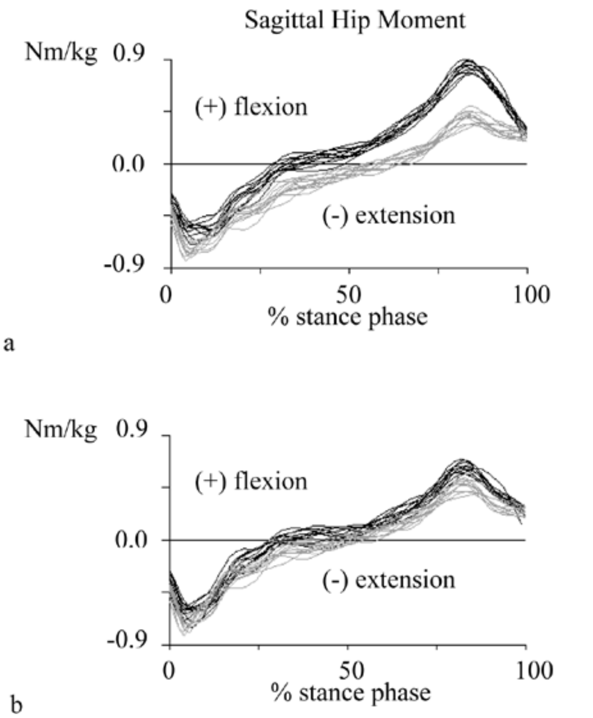

Figure 2 — Stance phase sagittal plane hip moment (N·m/kg) for right (gray) and left (black) legs calculated using the corrected transformation and a (a) 3 × 3 or (b) 6 × 6 calibration matrix.

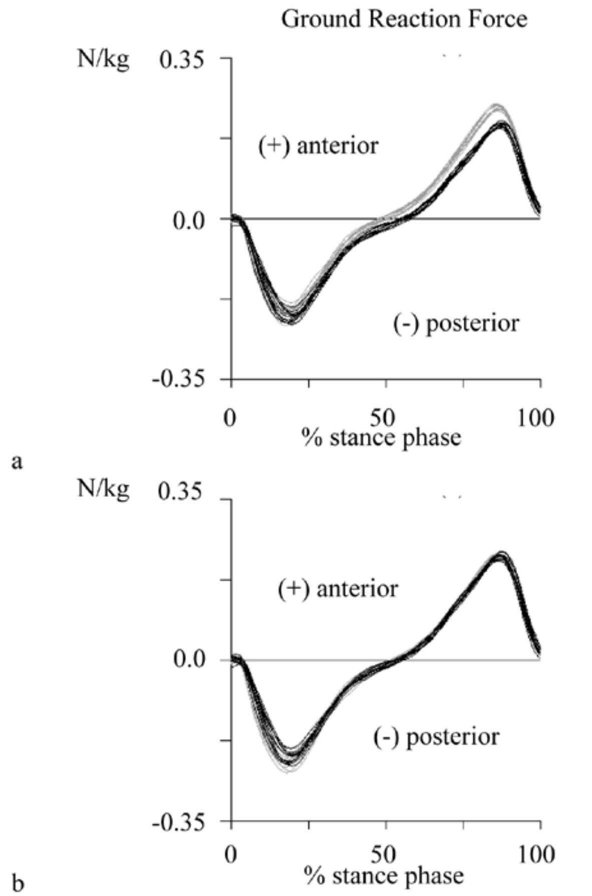

Figure 3 — Anterior/posterior ground reaction force (N/kg) for right (gray) and left (black) legs calculated using the corrected transformation and a (a) 3 × 3 or (b) 6 × 6 calibration matrix.

Discussion

Using the transformation optimization technique and calibrating all six data channels reduced COP measurement errors to values comparable to those measured for fixed force plates (Holden et al., 2003) and close to, if not below, the measurement ability of CalTester. While there was little difference between the average CalTester data error generated with the 3 × 3 and the 6 × 6 calibration matrices (Table 2), there was a significant difference for the gait data (Figures 2 and 3). This is likely due to the greater shear forces generated during gait compared with those generated during the CalTester trials. Unlike the 3 × 3 calibration matrix, the 6 × 6 calibration matrix included the F_x, F_y, and M_z channels, improving orientation error, measurement accuracy of the anterior ground reaction force, and subsequent calculation of the sagittal hip moment. Applying just the 3 × 3 matrix yielded errors large enough to result in data misinterpretation, highlighting the necessity to include all six data channels in the calibration.

The treadmill force plate was calibrated by the manufacturer before final assembly and installation. The dramatic improvement observed in the data after applying our own calibration demonstrates the importance of performing this calibration in situ. This observation, combined with our observation that small changes in the height of the treadmill's one adjustable-height leg influenced treadmill accuracy, indicates that the device is sensitive to its installation into the laboratory environment. We did not notice any degradation in the accuracy of the treadmill following more than 50 data collections over the course of 3 months, suggesting that the calibration did not have to be repeated in the short term to maintain accuracy. However, this may be because the laboratory floor was a 5-foot-thick slab of reinforced, harmonically damped concrete, providing a very stable laboratory environment.

The CalTester data collected while the treadmill was moving at 0.2 m/s suggest that COP error did not increase appreciably as a result of vibrational noise. While this speed is well below the walking speed of even impaired individuals, data collection was logistically challenging at faster speeds.

We reduced the COP measurement error of a moving instrumented treadmill to an average (maximum) of 0.7 mm (1.3 mm) in the ML and 2.9 mm (4.3 mm) in the AP directions. Past AP COP errors reported for moving instrumented treadmills have ranged from 2 mm (<10 mm) (Kram et al., 1998) to 4.4 mm (17 mm) (Paolini et al., 2007). Techniques that minimize this error are essential when combining instrumented treadmills and motion capture technologies. A procedure has been presented that can be used to improve the accuracy of instrumented treadmills after installation. We anticipate that the correction concepts presented here should be applicable to other treadmill models.

Acknowledgments

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