Medical Engineering and Physics 42 (2017) 99–104

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

Technical note

Dynamic assessment of center of pressure measurements from an instrumented AMTI treadmill with controlled precision

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ARTICLE INFO

Article history:
Received 27 January 2016
Revised 11 October 2016
Accepted 1 January 2017

Keywords:
Biomechanics
Kinetics
Force platforms
Validation
Accuracy

ABSTRACT

With the increasing use of instrumented force treadmills in biomechanical research, it is imperative that the validity of center of pressure (COP) measurements is established. The study aims were to compare an instrumented treadmill's static-belt COP accuracy to that of a floor-embedded platform, develop a novel method to quantify dynamic-belt COP accuracy with controlled precision and perform an initial investigation of how dynamic COP accuracy changes with weight and velocity. Static COP accuracy was assessed by applying a force while moving a rigid rod in a circular clockwise motion at nine positions of interest on the two treadmill and two ground-embedded force plates. Dynamic COP accuracy was assessed for weights (68.0, 102.1, and 136.1 kg), applied through a ball bearing of 2.54 cm circumference, with peak treadmill belt speeds of 0.5, 0.75, and 1.0 m/s. COP accuracy was assessed relative to motion capture marker trajectories. Statically, treadmill COP error was similar to that of the ground-embedded force plates and that reported for other treadmills. Dynamically, COP error appeared to vary systematically with weight and velocity and in the case of anteroposterior COP error, shear force, although testing with a larger number of weights and velocities is needed to fully define the relationship. This novel method can be used to assess any instrumented treadmill's dynamic COP accuracy with controlled precision.

1. Introduction

Instrumented force treadmills are designed for use in rehabilitation and biomechanical research [1]. Unlike ground-embedded force plates, instrumented force treadmills allow for continuous force data collection over extended time periods at steady speeds [2]. In addition, instrumented treadmills are not limited by foot placement demands for a single step in order to record valid force measurements. Therefore, subjects have less-constrained gait patterns [3,4]. Accordingly, instrumented treadmills are becoming increasingly popular for gait analysis in research and clinical settings [5,6]. With increasing use, it is imperative that measurement validity is established.

Accurate center of pressure (COP) measurements are crucial for calculating valid gait kinetics [7]. Load is typically applied over a large area or during human gait, meaning that the actual COP location is not precisely known and criterion motion analysis system estimations may, therefore, be inaccurate. Treadmill-specific factors can result in COP measurement errors in instrumented treadmills compared to ground-embedded force plates. These factors include 1) mounting distortions, 2) mechanical structure compliance and dynamics, and 3) vibrations from the motors or rollers [8-10]. Previous studies have performed COP validation tests involving one weight at a single treadmill belt velocity [11,12]. To our knowledge, there have been no previous investigations into how dynamic COP accuracy changes with weight and velocity.

Instrumented treadmills with a dual-belt design enable independent measurement of both feet. The study aims were to (1) compare the AMTI (AMTI Inc., Watertown, MA, USA) dual-belt instrumented treadmill's COP static accuracy to that of AMTI ground-embedded force plates with the same force plate design for a true ground-to-treadmill comparison, (2) quantify COP accuracy of the AMTI treadmill under dynamic conditions using a novel method to apply constant force over a known precise area for controlled dynamic COP accuracy evaluation and (3) perform an initial investigation into how COP accuracy varies with weight and velocity. We hypothesized that the AMTI treadmill-based COP measurements would not have significantly greater error than AMTI ground-embedded force plates, despite the treadmill-specific factors that could affect accuracy. We also hypothesized that, based

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http://dx.doi.org/10.1016/j.medengphy.2017.01.002
1350-4533/

on the signal-to-noise ratio, treadmill-based COP accuracy would increase with increasing load, but would decrease with increasing belt velocity.

2. Methods

Static COP accuracy tests were used to compare the AMTI instrumented treadmill's COP accuracy to that of AMTI ground-embedded force plates to ensure that treadmill-based COP measurements were not significantly different. Dynamic COP accuracy was then evaluated using our novel method described below.

2.1. Equipment and data collection

The commercially available, AMTI instrumented treadmill ($0.62 \times 0.62\,m^2$) with two inline force plates (Fig. 1) was evaluated in this study. Two gait lab AMTI ground-embedded force plates ($0.6 \times 0.4\,m^2$) were also assessed. Force plate data were collected at 1200 Hz for treadmill and gait lab force plates. Three-dimensional marker trajectories were recorded at 120 Hz using 8 and 10 camera systems (Motion Analysis Inc., Santa Rosa, CA, USA) for treadmill and gait lab force plates, respectively. Both the ground-embedded and treadmill force plates were calibrated by the manufacturer and a sensitivity matrix was provided to convert the voltages to forces and torques. The function of the force plates are checked quarterly by experienced kinesiologists (>15 years), using static weight tests to ensure a load accuracy within 1% and stick tests to verify a within 1 cm agreement between the force plates and the cameras. We additionally performed static vertical weight checks right before testing and observed <1% error for 68, 102, and 136 kg loads.

Motion capture data were recorded in order to establish reference values from which to determine accuracy. During conditions with a static surface, a rigid rod with four reflective markers and with one end attached to a rectangular surface about which it could rotate (Fig. 1) was used to apply force manually. Marker-based COP location was calculated by identifying the location where the vector from the midpoint of each pair of markers intersected with the surface. During dynamic tests with a moving surface, weights on a wooden board with three ball bearings (each with a circumference of 2.54 cm) attached were utilized (Fig. 1). Non-slip shelf liner was placed between both the weights and the board to maintain weight position on the board throughout testing. This setup was developed so that the motion-base estimate of COP would be calculated more precisely than with applying the weights directly or with human subjects. Two ball bearings were located at one board end with their locations identified by two reflective markers. The third ball bearing was located at the board's other end, identified by two markers whose mean location was used to calculate the reference COP location.

2.2. Experimental design

Static testing. The static tests were performed under three conditions: 1) treadmill motor on but no belt movement, 2) treadmill motor off to investigate whether motor vibrations induce significant errors, and 3) using two ground-embedded force plates. For each condition, nine positions on each force plate were examined (Fig. 1b). Marker and force plate data were collected during separate 5 s trials [9] for 36 and 18 trials on the treadmill and ground-embedded force plates, respectively. While the belt was static for each trial, an investigator (VL) applied a vertical force to the rod top while moving in a circular clockwise motion and therefore actual COP location varied throughout each trial (Fig. 2).

Dynamic testing. The board with weights was placed on the treadmill so that the ball bearing (identified by two markers) was positioned on one of five force plate positions (each at the same anteroposterior (AP) location but 10 cm apart in the mediolateral (ML) direction) with the other two ball bearings positioned so that they were both placed on the other force plate (Fig. 1e). For each trial, the treadmill belt surface was translated 0.45 m. One hundred and twenty trials were performed: for two weights (68.0 and 102.1 kg) using three triangular velocity profiles (with peak velocities of 0.5, 0.75, and 1.0 m/s) for each of the 5 position on each force plate (i.e. 10 positions total) twice (first with the belt moving backward and then forward). An additional 40 trials were performed with the 136.1 kg weight at 0.5 and 0.75 m/s (but not at 1.0 m/s due to the weight sliding on the board). Marker and force plate data were collected for 10 s trials (to ensure data collection for all belt movement) for 160 trials total.

2.3. Data analysis

All post-processing was performed offline using MATLAB (Version 7.11.0, Mathworks, Natick, MA, USA). Marker trajectories and force plate data were filtered using fourth order low-pass Butterworth filters with cut-off frequencies of 6 and 20 Hz [11], respectively. Force plate data were down-sampled to 120 Hz to match the marker data. Force and moment data (Fig. 3) were calculated from the treadmill force plate data according to the user manual. The COP data in the AP and ML directions were calculated [13]. The treadmill force plates' vertical force measurement accuracy under static conditions was estimated using 1 s of data before belt movement from each dynamic trial. To assess COP accuracy during the dynamic test, the middle 35 cm of belt translation were analyzed to exclude larger errors at belt movement initiation and termination (Fig. 3c). Root mean square errors (RMSEs) of force plate COP calculations relative to marker-based COP locations were estimated for all trials.

2.4. Statistical analysis

All statistical tests were performed using SPSS (IBM Corporation, Armonk, NY, USA).

Static testing. Analyses of covariances (ANCOVAs) were performed to identify significant differences in RMSE between plate conditions (treadmill on, treadmill off, ground-embedded) while accounting for rod location distance from the force plate center. Separate ANCOVAs were implemented for AP and ML errors. For a significant main effect of plate condition ($p < 0.05$), between condition comparisons were made using Sidak post-hoc adjustments.

Dynamic testing. The effect of mean vertical force plate forces (Fz), mean absolute shear forces (Fx), and peak velocity (v) on AP COP RMSE were evaluated using stepwise regression (enter $p < 0.05$, remove $p > 0.10$). The effects of Fz, mean absolute ML force (Fy), v, and marker-based mean ML location on ML COP RMSE were also evaluated using stepwise regression. The Fz and v interaction was included as a potential independent variable in both models, since it was hypothesized that v effects would be diminished by Fz (i.e. movement-related noise decreases with greater mass due to increased signal-to-noise ratio).

3. Results

Static testing. The mean Fz applied to the top of the rod was 139 N. Table 1 reports the mean (SD) RMSE of the force plate-based calculations compared to the marker-based calculations across all 54 trials. In the AP direction, there was no significant difference in mean RMSE between plate conditions ($p = 0.140$). In the ML direction, there was a significant effect on mean RMSE between plate conditions ($p = 0.004$). There were no significant effects with distance from the force plate center in the AP or ML

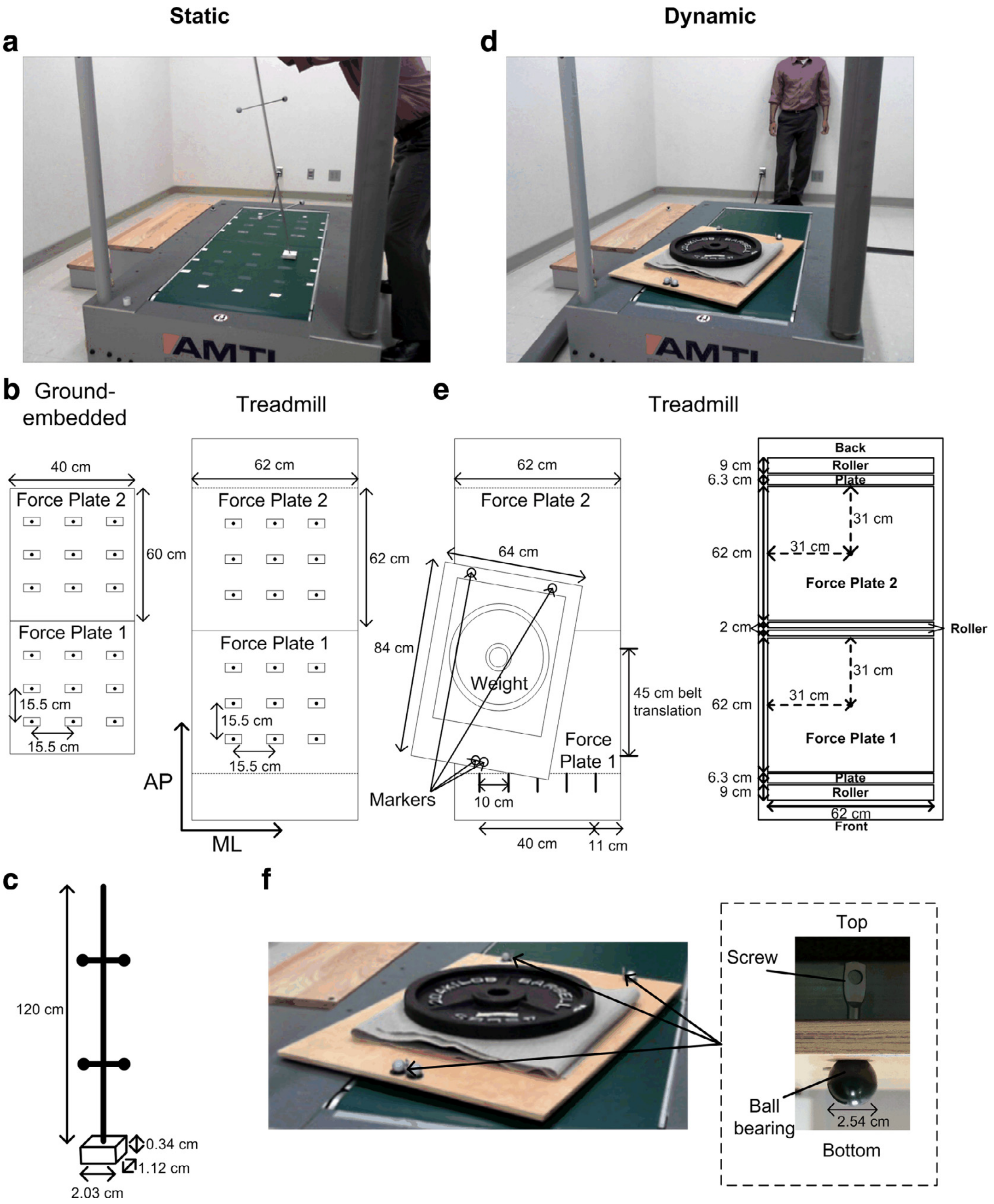

Fig. 1. Setup for the static testing (a) including top views of the 9 positions for each force plate (both ground-embedded and treadmill; b), the rigid rod (1.2 m, 0.8 kg; c), and for the dynamic testing (d) including top views of the board set-up with 5 starting positions at the same anteroposterior (AP) location but 10 cm apart in the mediolateral (ML) direction for each treadmill force plate (e). The overall dimensions of the treadmill are 1.82 m long, 1.1 m wide and 0.26 m high. The working surface of each treadmill belt is 0.74 m long, 0.66 m wide. The board was reinforced with metal bars to support the weights. Each ball bearing is attached to the bottom of the board with a screw (f).

Table 1
The mean (SD) root mean square error (RMSE) of the force plate-based COP locations relative to marker-based COP locations in the AP and ML directions for the treadmill plates with the motor off and on, and for the gait lab force plates during the static testing with the rod.

Direction	Treadmill (off)	Treadmill (on)	Gait lab
AP (mm)	12.3 (1.3)	12.4 (2.0)	13.6 (2.6)
ML (mm)*	11.1 (1.7)	13.5 (3.8)	14.8 (3.6)

*Significant ($p < 0.05$) difference between plate conditions.

directions ($p = 0.809$ and $p = 0.930$, respectively). Post-hoc analyses of estimated marginal means in the ML direction revealed that the treadmill-off condition had significantly less error than the floor condition ($p = 0.003$), but not the treadmill-on condition ($p = 0.088$). The treadmill-on condition did not have significantly different errors from the floor condition ($p = 0.543$).

Dynamic testing. The treadmill force plates measured the applied Fz from the weights before movement with RMSEs < 0.8% as the applied weight increased from 724.7 to 1392.5 N. The Fz applied to the force plate of interest ranged from 332 to 650 N. AP COP RMSE was from 6.4 to 28.3 mm and varied with v (mm/s; standardized $\beta = 0.816$; $p < 0.001$), Fx (N; standardized $\beta = 0.421$; $p < 0.001$), and a v × Fz interaction (mm/s•N; standardized $\beta = -0.231$; $p = 0.009$; Fig. 3d and f):

$$\mathrm{RMSE}_{AP} = 2.258 + 19.747(v) + 0.085(Fx) - 0.10(v \times Fz) \times (p < 0.001,\ R^2 = 0.312) \quad (1)$$

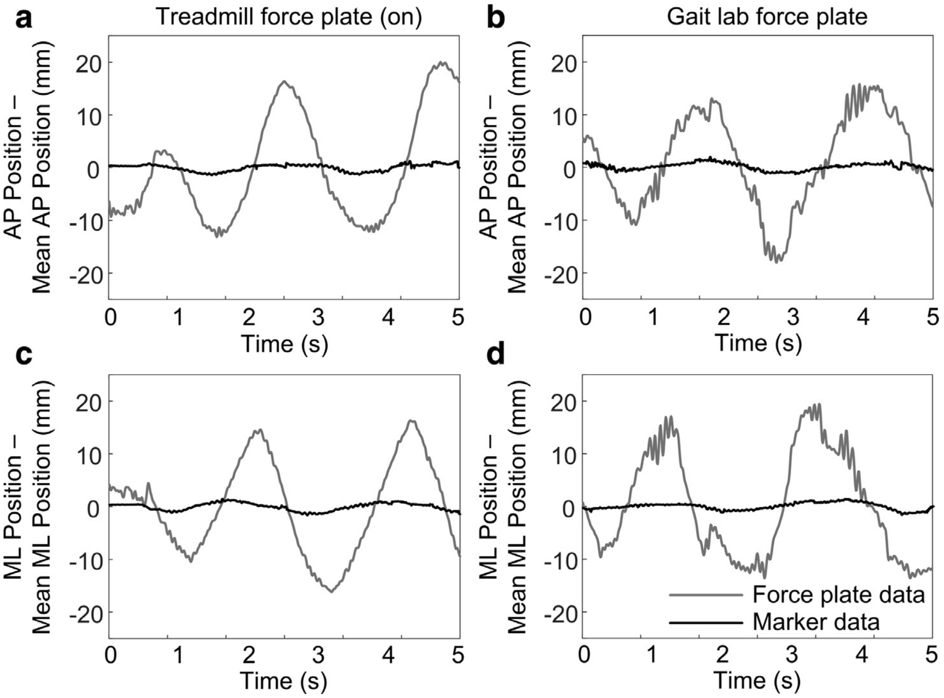

Fig. 2. Changes in COP calculations in the anteroposterior (AP) and mediolateral (ML) directions with time from force plate data and marker data using the rod for one sample static trial on a treadmill (motor on) force plate (a: unfiltered data, c: filtered data) and one sample static trial on a gait lab force plate (b: unfiltered data, d: filtered data).

ML RMSE was from 0.5 to 7.4 mm and varied with v (mm/s; standardized $\beta = 0.448$; $p = 0.001$) and Fz (N; standardized $\beta = -0.267$; $p = 0.039$; Fig. 3e):

$$\mathrm{RMSE_{ML}} = 193.682 + 7.854(\mathrm{v}) - 0.555 \times (\mathrm{Fz})(\mathrm{p} = 0.002, \mathrm{R}^2 = 0.224) \quad (2)$$

Mean ML location and Fy effects on COP error were not selected by stepwise regression.

4. Discussion

Due to the increasing use of instrumented treadmills for gait analysis, the study aims involved the comparison of COP static accuracy of AMTI treadmill and ground-embedded force plates, the development of a novel method of evaluating the COP measurement accuracy of an instrumented treadmill under dynamic conditions with controlled precision, and the initial investigation of variations in COP accuracy for a small number of different weights and velocities for the AMTI dual-belt instrumented treadmill. Even with the treadmill motor on, the static COP error was similar to that of the ground-embedded force plates. The dynamic COP error varied with changes in weight and velocity and in the case of AP COP error, shear force.

The COP mean RMSEs during static testing in this study were similar to a previous report of 10 mm in AP and ML directions involving rod tests with a single-belt treadmill [8]. However, another study reported lower AP and ML COP RMSEs of <5 mm [14]. The larger RMSE in the present study's treadmill COP measurements may be due to the application of smaller forces to the rod, as well as potential between-study differences in the rod's continuous circular movement. The present study's RMSE was less than half in the AP direction but slightly larger in the ML direction from what was reported for a custom-built split-belt treadmill using standard calibration [9]. The significantly lower RMSE for the treadmill-off condition and the similar RMSE for the treadmill-on condition compared to the gait lab suggests that the treadmill accuracy is comparable to if not better than the ground-embedded force plates. The treadmill force measurement error was smaller than those reported in previous treadmill studies [9,12,14].

Dynamically, both AP and ML RMSE were affected by weight, velocity, and in the case of AP error, shear force. The COP RMSEs for the 0.5 m/s trials are similar to those reported for a 44.5 kg load applied to the treadmill without controlled precision at 0.47 m/s [12]. Based on the present study's standardized beta coefficients, COP RMSE mostly increased due to increasing belt velocity. In support of this, a linear relationship between COP errors and joint moment uncertainties in addition to increasing joint moment uncertainty with increasing gait velocity has been reported [15]. Increases in AP COP error results in magnitude but not pattern changes in joint moments, with joint moment magnitudes and patterns having an even higher sensitivity in the ML direction [16]. If the relationship of error with weight and velocity observed in this study holds for human subjects, AP COP errors would be reduced for heavier subjects. However, the maximum Fz applied to a single force plate in the present study was only 650 N. In addition, only three speeds were investigated for two weights (or two speeds for three weights). Additional weights and speeds need to be tested before the relationship between COP error and weight and velocity can be fully determined. The force plate data filter cut-off frequency was lower compared to treadmill running studies (30 Hz; [17]). However, 20 Hz is typical for treadmill validation studies [11] and increasing the cut-off frequency to 40 Hz in the present study resulted in a COP location accuracy change of <0.1 mm suggesting that this treadmill is suitable for running research.

Static weights were used to maintain the validity of our measures. However, the relationship of COP error with force and velocity may differ when considering human subjects. On the other hand, the weights are inanimate and will not oscillate with speed variations. In addition, in this study the load was applied to the treadmill through an area <2.54 cm for precise control of the reference COP location. In future studies, COP measurements could

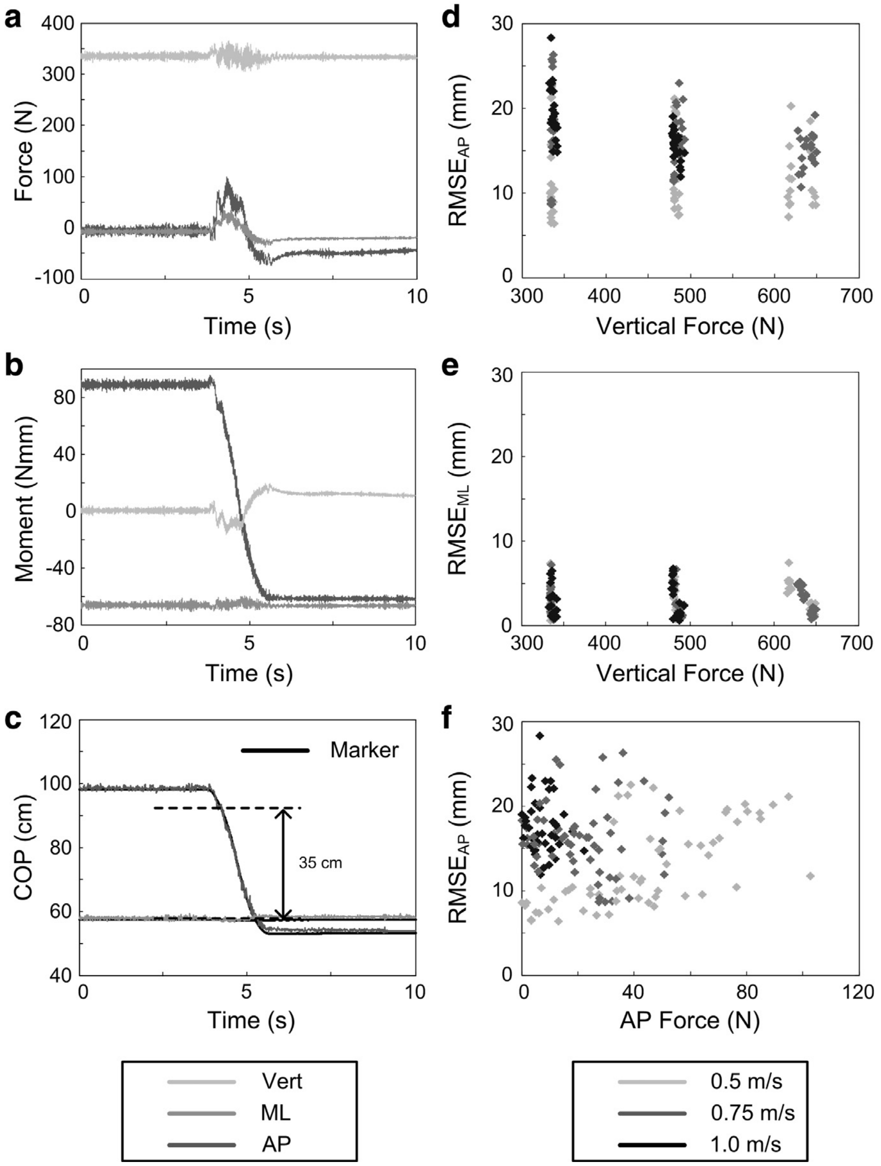

Fig. 3. Unfiltered forces (a) and moments (b) in the anteroposterior (AP), mediolateral (ML), and vertical (Vert) directions, and corresponding COP calculations (c) in the AP and ML directions for a sample dynamic trial (with a belt velocity of 0.5 m/s) for both force plate and marker data. The COP data were cut so that the middle 35 cm of belt translation (the region within the dashed black lines) in the AP direction were analyzed to minimize the errors that could be caused by the observed inertia at the initiation and halt of belt movements. Root-mean-square errors (RMSEs) in COP calculations for the dynamic board trials as velocity increases in the AP (d) and ML (e) directions versus vertical force and in the AP direction versus AP force (f).

be improved using better calibration methods [9]. It is important to note that the application of load over a smaller area results in higher pressure values. The resulting pressures should be verified with manufacturer specifications before testing to ensure that no damage occurs due to excessive pressure application. This is the first study to assess COP measurement validity using the AMTI dual-belt instrumented treadmill. The treadmill validation results show that the COP accuracy of the AMTI dual-belt treadmill is comparable to that of gait lab ground-embedded force plates and suggest that the dual-belt instrumented treadmill is acceptable for use in clinical and research settings.

As the force was applied manually and, therefore, inconsistently by an investigator during the static tests, it is not possible to determine whether differences were induced by the investigator or generated from the different motion systems. Ground-embedded force plates were not used as a reference for the dynamic test as the protocol would have been difficult to apply. The validity conclusions in this manuscript are limited to the AMTI dual-belt treadmill. However, the novel methods developed to evaluate dynamic COP accuracy with controlled precision may be used to evaluate the true COP accuracy of other instrumented treadmills. Furthermore, this manuscript is the first to perform an initial investigation of the possible effects of weight and velocity on COP accuracy in dynamic situations on a treadmill.

Conflict of interest

The authors report no conflict of interest.

Acknowledgments

Funding was provided by DOD DM090896 and NIH T32 HD07447. The authors would like to thank Kathie Bernhardt, Diana Hansen, and Denny Padgett for their help with gait lab and motion capture data collection. The information or content and conclusions do not necessarily represent the official position of, nor

should any official endorsement be inferred by the National Institutes of Health, the United States Navy, the Department of Defense, or the U.S. Government.

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