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Technical note

Optimal calibration of instrumented treadmills using an instrumented pole

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ABSTRACT

Calibration of instrumented treadmills is imperative for accurate measurement of ground reaction forces and center of pressure (COP). A protocol using an instrumented pole has been shown to considerably increase force and COP accuracy. This study examined how this protocol can be further optimized to maximize accuracy, by varying the measurement time and number of spots, using nonlinear approaches to calculate the calibration matrix and by correcting for potential inhomogeneity in the distribution of COP errors across the treadmill's surface. The accuracy increased with addition of spots and correction for the inhomogeneous distribution across the belt surface, decreased with reduction of measurement time, and did not improve by including nonlinear terms. Most of these methods improved the overall accuracy only to a limited extent, suggesting that the maximal accuracy is approached given the treadmill's inherent mechanical limitations. However, both correction for position dependence of the accuracy as well as its optimization within the walking area are found to be valuable additions to the standard calibration process.

1. Introduction

In gait analysis, normal and pathological gait patterns are examined on the basis of joint kinematics and kinetics. The latter includes net joint moments and powers, which are calculated through inverse dynamics using a linked segment model with mass distribution, kinematics, ground reaction forces (GRF) and moments, as well as hereof derived center of pressure (COP). Of all these data, errors in GRF and thus COP have been shown to be the main source of inaccuracies in lower body kinetics [1–4]. These errors are generally larger in instrumented treadmills compared with conventional force plates that are incorporated in the floor, because of their large and compliant structure [5]. Moreover, novel applications of these treadmills, such as feedback on frontal knee moments during gait [6] or system identification of the neuromuscular system [7], require highly accurate force measurements. Recently, a protocol has been presented to measure the performance of instrumented treadmills and assess their accuracy [5]. However, it is also imperative to improve their accuracy through optimal calibration procedures.

On site calibration procedures have been developed for conventional force plates that match recorded GRFs and COP against reference measurements. These reference values can be established in several ways; by using static weights [8], an instrumented pole [9–13], an (automated) platform testing rig with a loading rod [14–18], or a dynamic construction, such as a cylindrical container with a rotating mass [19], a 3D pendulum construction [20] or an artificial leg [21]. Most of these calibration methods require sophisticated set-ups around the force plate and are therefore impractical to use on a large treadmill, except for the weights and instrumented pole. Static weights have been used for calibration of instrumented treadmills, however, they are impractical for the calibration of horizontal forces. An instrumented pole facilitates the application of varying forces in different directions within a single measurement and has been shown to result in higher accuracy compared with weights [13].

For this type of calibration, an easy to perform protocol has been published by Collins and colleagues that describes how to capture data and calculate the calibration matrix [13]. The protocol consists of trials of 5s at 20 spots distributed over the treadmill belt. However, the chosen number of spots and measurement time are not substantiated, and accuracy might be further improved by

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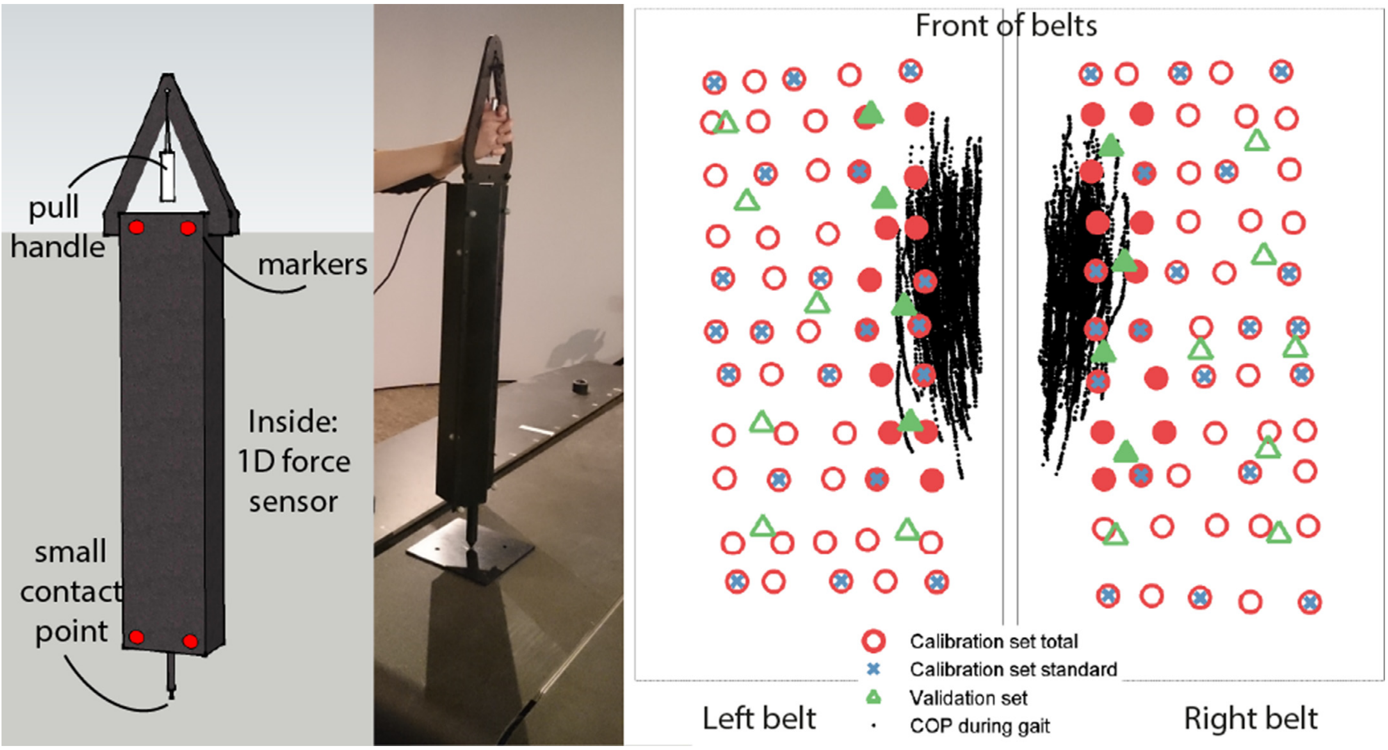

Fig. 1. The instrumented calibrator (left), setup of the measurement (middle) and the distribution of measurement spots on the treadmill (right). The latter includes the total calibration (red circles), standard calibration (blue cross) and validation (green triangles) measurements. In addition, the COP measured during a few minutes of treadmill walking is given in black stars. The filled circles and triangles are the selected measurements used for the calibration within the walking area. The relative large distance to the edge of the belt that is not calibrated is due to the size of the metal plate used to rest the tip of the calibrator upon. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

increasing them; or the same accuracy might be obtained from fewer measurements. In addition, correction for possible nonlinearity resulting, for instance, from asymmetrical distortion moments on the force sensors by bending of the plates might further increase the accuracy [8,22].

In this study we examined if this calibration protocol using an instrumented pole can be optimized by:

1. finding the optimal measurement duration and number of spots;
2. accounting for nonlinearity in the calibration matrix;
3. accounting for inhomogeneity in the distribution of errors across the belt surface.

In addition, the repeatability of the standard calibration procedure was determined.

2. Methods

2.1. Protocol

The principle of the calibration procedure was based on the protocol previously outlined by Collins et al. [13]. The force and COP measurements were calibrated by maximizing the match between treadmill output and reference data measured with an instrumented pole on a stationary treadmill. An instrumented calibrator (1.12 m, 5.3 kg) was used (Fig. 1), equipped with four optical markers and a 1 DOF axial load cell (S-type, Revere Transducers Europe) mounted within its frame (Motekforce Link, Netherlands). To limit forces that are not applied along the central axis, a compliant joint system was used on the inside of the calibrator to redistribute these forces to the central axis. A metal loading plate with a shallow hole was used to increase accuracy by applying a distributed load [23]. The tip of the calibrator was minimized with optimized friction to the metal plate and forces were exerted by pulling a handle attached to the calibrator with a rope. This instrumented calibrator gave comparable calibration results as a conventional instrumented pole (see Supplementary material). To determine the COP and the orientation of the calibrator, the lower tip was identified as a virtual marker by establishing its position relative to three of the technical markers using functional calibration, defining the tip as the position the calibrator was circled around on the treadmill belt in a calibration trial [24].

A dataset of 55 spots of 5s each was measured to construct different calibration matrices (Fig. 1). A selection of 20 spots uniformly spread over the area of each belt constituted the standard calibration dataset. Also, a validation dataset of 11 measurements per belt was collected to determine the accuracy of the calibration matrices. The following day, another standard calibration and validation dataset were collected. During the measurements, a force was applied through the calibrator by initially exerting as much vertical load as possible on the treadmill, followed by a slowly circular movement, applying as much load as possible in the horizontal directions.

The instrumented dual belt treadmill (50 × 200 cm/belt, R-Mill, Motekforce Link, Netherlands) had six force sensors under each belt with a full scale output of 1000 N in the horizontal and 10,000 N in the vertical direction [5]. To demonstrate the effect of the calibrations on gait data, force data were measured while a single subject (*F*, 28 year, 70 kg) walked on the treadmill at 3 km/h. Approval of the local ethics committee and written consent was provided.

2.2. Data analysis

Treadmill, load cell (both sampled at 1000 Hz), and motion (100 Hz) data were synchronized, down sampled to 100 Hz and

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