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Technical note

A comprehensive protocol to test instrumented treadmills

L.H. Sloot [a,b,*], H. Houdijk [b,c], J. Harlaar [a,b]

[a] VU University Medical Center, Department of Rehabilitation Medicine, PO Box 7057, 1007 MB Amsterdam, The Netherlands
[b] Research Institute MOVE, VU University Amsterdam, Van der Boechorststraat 7, 1081 BT Amsterdam, The Netherlands
[c] Heliomare Rehabilitation, Research and Development, Relweg 51, 1949 EC Wijk aan Zee, The Netherlands

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ABSTRACT

Instrumented treadmills are becoming more common in gait analysis. Due to their large and compliant structure, errors in force measurements are expected to be higher compared with conventional force plates. There is, however, no consistency in the literature on testing the performance of these treadmills. Therefore, we propose a standard protocol to assess and report error sources in instrumented treadmills. The first part of this protocol consists of assessment of the accuracy of forces and center of pressure (COP), including non-linearity, hysteresis and crosstalk. The second part consists of (novel) instrumented resonance testing and belt speed variability tests. The third part focuses on measurement variability over time, including drift, warming of the system and noise. The performance of two in-house instrumented treadmills with different dynamics was measured. Differences were found between the treadmills in COP accuracy (4.0 mm versus 6.5 mm), lowest eigen frequency (35 Hz versus 23 Hz) and noise level at 5 km/h (10 N versus 29 N). The loaded treadmills both showed a 3.3% belt speed variability at 5 km/h. Thus, the protocol was able to characterize strong and weak characteristics of the treadmills and allowed for a proper judgement on the validity of the instruments and their application in the domain of gait analysis. We propose to use this protocol when testing and reporting the performance of instrumented treadmills.

1. Introduction

Instrumented treadmills are increasingly used in gait analysis, because they facilitate the measurement of force data and consequently gait dynamics over long time series through their incorporated force sensors [1–4]. The downside is that they are more prone to errors in the recorded force data than conventional force plates, due to their larger and more compliant structure [5,6]. Errors in ground reaction forces (GRF) and the center of pressure (COP) calculated from these forces are repeatedly identified as one of the main contributors to errors in net joint moments [7–9]. Therefore, it is imperative to evaluate the accuracy of force data of instrumented treadmills.

Several causes of inaccurate force measurements have been suggested for ground-mounted force plates, including imperfect mounting of the force sensors [10], signal interference and electrical inductance [7], and imprecise calibration matrices that introduce errors transforming sensor signals to forces [6,11]. Instrumented treadmills are faced with additional error sources, such as higher non-linearity between exerted and measured forces due to bending of the compliant treadmill structure. In addition, they typically have lower eigen frequencies, which are frequencies at which the system resonates, amplifying specific frequency bands from the input signal and causing a time lag between the in- and output signal [6,12,13]. Due to the narrow gap between the plates, dual-belt treadmills with lengthwise force plates can be prone to crosstalk [14]. Horizontal forces can also be affected by friction if the belt is directly mounted over the sensors [5]. Finally, belt speed changes following initial foot contact and push off have been demonstrated to affect gait measurements [15]. Only a selection of these errors are usually reported for instrumented treadmills, with inconsistency in the chosen method and outcome variables, or without a clear description [5,6,12–14,16–21].

This study proposes a standard protocol to measure potential error sources in force measurement for instrumented treadmills, thereby also providing a guideline for technical quality assurance and systematic reporting of treadmill characteristics. The first part of the protocol tests measurement accuracy and force sensor properties. The second part focuses on testing of the system's resonance and belt speed variability. The third part examines measurement variability over time. The proposed tests were performed on two instrumented treadmills with different mechanical designs to demonstrate the feasibility of the protocol to identify and compare treadmill properties.

* Corresponding author at: VU University Medical Center, Department of Rehabilitation Medicine, PO Box 7057, 1007 MB Amsterdam, The Netherlands. Tel.: + 31 20 444 0756; fax: + 31 63 853 3128.
E-mail address: l.sloot@vumc.nl (L.H. Sloot).

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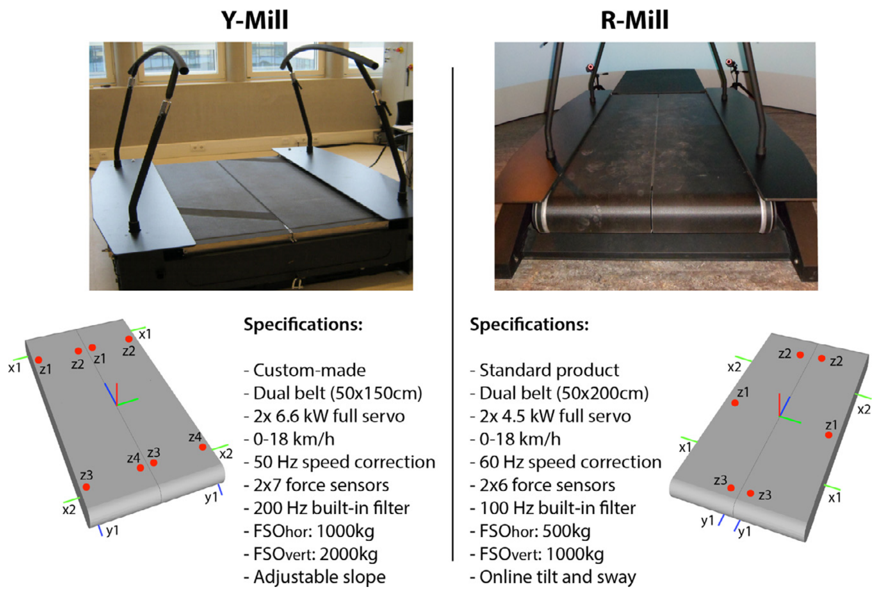

Fig. 1. The Y-Mill and R-Mill and their specifications. The configuration of the 14 force sensors of the Y-Mill and the 12 sensors of the R-Mill are schematically drawn.

2. Methods

The protocol incorporates a number of tests from the literature (see Table 3) and additional instrumented testing of the eigen frequencies, non-linearity and hysteresis. First, force and COP accuracy, non-linearity, hysteresis and crosstalk are measured on an idle belt. Second, the lowest eigen frequency and belt speed variability are determined. Third, the measurement variability over time is tested, including drift, warming of the system and noise. This protocol was applied to two dual-belt instrumented treadmills (Y-Mill and R-Mill; Forcelink B.V., the Netherlands): the Y-Mill was designed to be less compliant with more motor power and the R-Mill was able to translate and pitch (Fig. 1). The measurements were approved by the local ethics committee of the institution (FBW, VU University Amsterdam) and written consent was provided by the walking participant.

2.1. Accuracy

The accuracy of force and COP measurements was determined by comparing the treadmill output to reference data measured with a calibration stick. This instrumented stick (1 m, 1 kg) was equipped with three technical markers for motion tracking (Optotrak, NDI) as well as a 1DOF axial load cell and was used to manually apply varying forces in different directions on an idle belt [6]. Both tips of the stick were identified as virtual markers by establishing their relative position to the three technical markers using a pointing device [22]. These virtual markers were used to track the point of application (lower point of the stick) and the orientation of the stick (upper versus lower point) [22]. The orientation and point of application were used to represent the measured 1D force into 3D forces in the treadmill coordinate system [6]. A calibration matrix was constructed by minimizing the mean least-squares error between the instrumented stick and treadmill data following the PILS procedure [6], using a calibration dataset of twenty 5 s trials per belt (Appendix). Using this matrix, the electrical treadmill sensor output in Volts ($S_{TM(V)}$) were transformed to forces and moments in Newtons and Newtonmeters ($S_{TM(N)}$) by:

$$S_{TM(N)} = (S_{TM(V)} - \text{offset}_{(V)}) * C \tag{1}$$

with offset$_{(V)}$ the average sensor output of the unloaded and steady treadmill (in Volts) and C the calibration matrix relating the sensor outputs to forces and moments. The COP was calculated as follows:

$$COP_{ml} = \frac{F_{ml}COP_v - M_{ap}}{F_v} \quad COP_{ap} = \frac{F_{ap}COP_v + M_{ml}}{F_v} \tag{2}$$

with F the force, M the moment, ml the medio-lateral, ap the anterior-posterior direction and COP_v the vertical distance between the belt surface and the sensors. The measurements of the treadmill, load cell and motion data were synchronized, collected at or down-sampled to 100 Hz and low pass filtered with a 2nd-order Butterworth filter at 20 Hz to reduce noise effects. The accuracy of force and COP measurements was calculated as the root-mean-square error (RMSE) between the treadmill and reference data per force and COP direction. For this purpose, we gathered a validation dataset consisting of thirteen trials of 5 s per belt.

2.1.1. Non-linearity, hysteresis and crosstalk

The non-linearity and hysteresis were both evaluated using the instrumented stick. Instead of using weights imposing only vertical forces [13,16,17,20,21], linearity and hysteresis could also be determined in the horizontal planes and over the entire range of forces using the stick. The largest range of forces that appeared manually possible by the operator, both loading and unloading, was applied in each direction at the middle of each belt. Data were low-pass filtered at 20 Hz. A linear least-squares regression line was fitted through the loading data of the treadmill versus the loading data of the stick. Per force direction, non-linearity was defined as the maximum deviation (quantified by 3 standard deviations to ignore outliers) of the treadmill data from this regression line. Hysteresis was calculated as the maximum difference between the third order regression lines relating the treadmill's loading data to the reference loading data and relating the treadmill's unloading data to the reference unloading data. Non-linearity and hysteresis were also given as percentage of the full scale output (FSO, Fig. 1) [5,17,18,23]. Crosstalk was evaluated during a 10 s trial using a load of 25 kg (Y-Mill) and 30 kg (R-Mill), placed on the middle of each belt separately. Crosstalk between belts was defined as the ratio (in %) between the forces of the unloaded belt versus F_v of the loaded belt; and crosstalk within belts as the ratio between the measured F_{ml} or F_{ap} and the exerted F_v [17,18,23].