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Inertial compensation for belt acceleration in an instrumented treadmill

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ABSTRACT

Instrumented treadmills provide a convenient means for applying horizontal perturbations during gait or standing. However, varying the treadmill belt speed introduces inertial artifacts in the sagittal plane moment component of the ground reaction force. Here we present a compensation method based on a second-order dynamic model that predicts inertial pitch moment from belt acceleration. The method was tested experimentally on an unloaded treadmill at a slow belt speed with small random variations (1.20 ± 0.10 m/s) and at a faster belt speed with large random variations (2.00 ± 0.50 m/s). Inertial artifacts of up to 12 Nm (root-mean-square, RMS) and 30 Nm (peak) were observed. Coefficients of the model were calibrated on one trial and then used to predict and compensate the pitch moment of another trial with different random variations. Coefficients of determination (R^2) were 72.08% and 96.75% for the slow and fast conditions, respectively. After compensation, the root-mean-square (RMS) of the inertial artifact was reduced by 47.37% for the slow speed and 81.98% for fast speed, leaving only 1.5 Nm and 2.1 Nm of artifact uncorrected, respectively. It was concluded that the compensation technique reduced inertial errors substantially, thereby improving the accuracy in joint moment calculations on an instrumented treadmill with varying belt speed.

1. Introduction

Horizontal acceleration of the ground surface is commonly used in experiments to perturb posture and gait (Park et al., 2004; Chen et al., 2014). In order to determine joint moments during such tests, ground reaction forces must be measured, but this is problematic when the force plate is not rigidly attached to an inertial reference frame. In an accelerating force plate, inertial forces arise due to accelerating masses between the subject's foot and the force sensors. Compensation for these errors in a translating force plate is possible when mass properties of the plate are known and accelerations are measured (Pagnacco et al., 2000).

Instrumented treadmills are increasingly available as tools for gait analysis, and these provide a convenient means to apply horizontal surface acceleration during posture and gait (Owings et al., 2001; Sessoms et al., 2014). It is expected, however, that acceleration of the treadmill belt will induce a sagittal plane moment in the ground reaction force due to the inertia of the belt, rollers, and motor. This moment is an artifact which will directly translate into an error in the sagittal plane joint moments determined from inverse dynamic analysis. Similar errors may occur when belt speed is interactively controlled "self paced" by the subject in a virtual reality environment (Sloot et al., 2014). In this paper we will quantify the inertial artifacts caused by belt speed variations and present a method to compensate for these artifacts.

2. Methods

Input signals for control of belt velocity were created using MATLAB/Simulink (Version 2014a, Mathworks, Natick, MA) as shown in Fig. 1. A total of four 6-minute trials were generated, two with mean speed of 1.2 m/s and small perturbations, and two with a mean speed of 2.0 m/s and larger perturbations. A random acceleration signal was generated with discrete-time Gaussian white noise and variance in the acceleration was set to 25 m^2/s^4 (for the 1.2 m/s trials) and 2000 m^2/s^4 (for 2.0 m/s trials), respectively. The signal was clipped at the maximum belt acceleration of 15 m/s^2, integrated, and high-pass filtered (second-order, Butterworth) with a 0.2069 Hz passband edge frequency to eliminate any velocity drift. The mean velocity was added as a constant to the random signal and limited to a maximum speed of 3 m/s. Two trials were generated in this manner for each speed, using different random number seeds. The resulting belt velocity signals

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0021-9290/

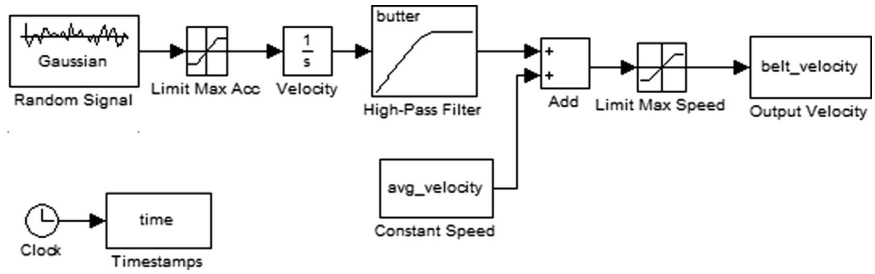

Fig. 1. MATLAB Simulink diagram for creating random belt velocities, in which a random acceleration signal is generated with Gaussian white noise. Belt velocity is obtained by integrating the signal and filtering with a high-pass Butterworth filter to reduce integration drift.

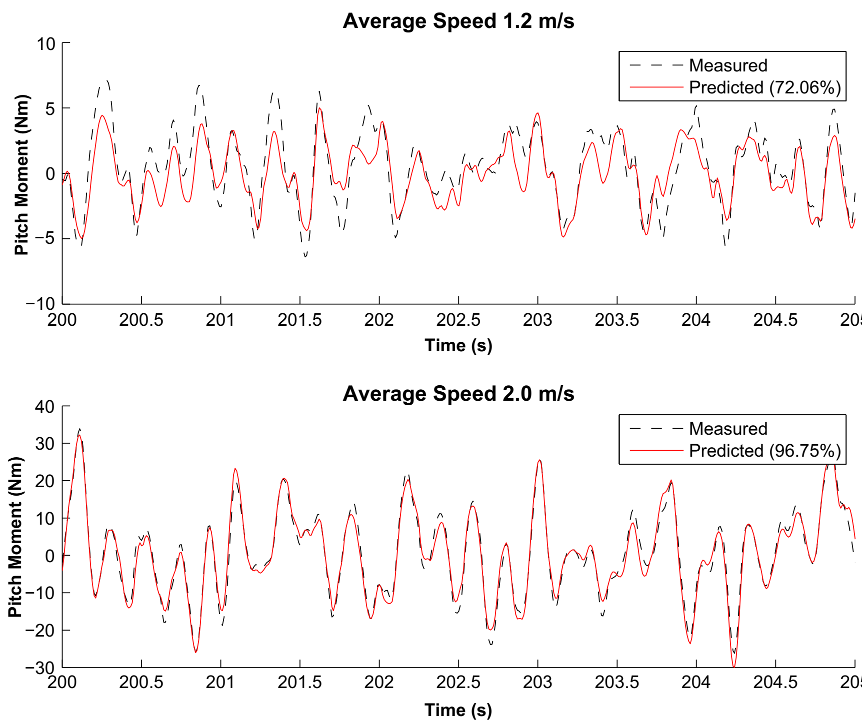

Fig. 2. Measured (black dotted) and predicted (red) pitch moment for the slow (top) and fast (bottom) speeds, with R^2 values of 72.08% and 96.75%, respectively. Only a small section of the 6-minute trial is shown. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this article.)

had a mean and standard deviation of 1.20 ± 0.10 m/s) and 2.00 ± 0.50 m/s, respectively.

Experiments were performed on a split-belt instrumented treadmill (VG005-A, Motek Medical, Amsterdam, The Netherlands). The belt speed signals were used to control the belt speed through software (D-Flow 3.16.2, Motek Medical). The D-Flow software was used to record ground reaction forces and moments and actual belt velocity during the four trials, without external loads applied to the treadmill surface. The sampling rate was 100 Hz.

The recorded pitch moment (sagittal plane moment) and belt speed were low-pass filtered (second-order, Butterworth) with a 6 Hz cutoff frequency to simulate how signals are typically processed for inverse dynamic analysis of gait (van den Bogert et al., 2013). Belt acceleration was derived from the low-pass filtered belt speed by a central difference formula.

A linear, second-order discrete-time model was used to predict the pitch moment M from belt acceleration a:

$$M_i = \theta_1 M_{i-1} + \theta_2 M_{i-2} + \theta_3 a_i + \theta_4 a_{i-1} + \theta_5 a_{i-2} \quad (1)$$

One trial at each speed was used to calibrate the model. The five model coefficients $\boldsymbol{\theta}$ were determined by minimizing the sum of the squared error between the predicted and measured pitch moment in the calibration trial. The minimization was performed in Matlab using the fmincon function.

The calibrated model was used to predict the pitch moment of the other trial at the same speed, and the predicted moment was subtracted from the recorded moment as would be done when compensating human test data for inertial artifacts. The root-mean-square (RMS) of the uncompensated and compensated pitch moment were computed. The coefficient of determination (R^2) verified the predictiveness of the simulation when compared to the measured values.

The analysis was repeated with low-pass filter cutoff frequencies up to 20 Hz to determine how well the inertial compensation would perform in other movements such as sports maneuvers, where the inverse dynamic analysis requires a higher cutoff frequency.

All software and data used are available (Hnat et al., 2014, http://dx.doi.org/10.5281/zenodo.10905).

3. Results

The pitch moment predicted by the model was in close agreement with the measured pitch moment, as illustrated in Fig. 2. The predicted