Inertial compensation for belt acceleration in an instrumented treadmill

Sandra K. Hnat*, Antonie J. van den Bogert

Department of Mechanical Engineering, Cleveland State University Cleveland, OH 44115, USA

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 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.

Keywords: biomechanics, instrumentation, gait, inertial artifacts, surface

*Corresponding author

Email address: `s.hnat@csuohio.edu` (Sandra K. Hnat)

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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 Figure 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 had a mean and standard deviation of 1.20 $\pm$ 0.10 m/s) and 2.00 $\pm$ 0.50 m/s, respectively.

Experiments were performed on a split-belt instrumented treadmill (VG005-A, Motek Medical, Amsterdam, 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:

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

One trial at each speed was used to calibrate the model. The five model coefficients θ 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 (Github Repository, 2014, DOI: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 Figure 2. The predicted moment was generated after calibrating the model using data from the other random trial at the same speed. R^2 values of 72.08% and 96.75% were obtained for the slow speed (1.2 m/s) and fast speed (2.0 m/s), respectively, and indicate that the model explains most of the pitch moment that is generated by belt speed variations.

Table 1 shows the RMS values of pitch moment before and after compensation. Substantial reductions in error were achieved, especially in the high speed condition.

Figure 3 shows the pitch moment before and after compensation for cut-off frequencies between 1 and 20 Hz. The relative error reduction is diminished at higher frequencies, but a substantial amount of compensation is still achieved.

4. Discussion

Accelerating the belt of an instrumented treadmill induces inertial artifacts in the sagittal plane ground reaction moment. To minimize these inertial errors, a compensation method was developed based on a second-order linear model. The method was tested in two experimental conditions: a slow belt speed with small variations (1.2 ± 0.10 m/s) and a fast belt speed with large variations (2.0 ± 0.50 m/s). At the 6 Hz bandwidth that is typically used in gait analysis, inertial artifacts were reduced by 47% and 82%, respectively, in these conditions. The effectiveness of the method declined somewhat at larger bandwidth (Figure 3), but a substantial fraction of the artifact could still be eliminated.

Sagittal plane moment between foot and ground is one of the inputs for inverse dynamic analysis of human motion. Inspection of the inverse dynamic equations reveals that any measurement error in this moment will result in an equal error in human joint moments. Peaks in the inertial artifacts during our tests were typically 6 Nm in the slow condition and 30 Nm in the fast condition (Fig. 2). Peak knee joint moments during human gait are about 40 Nm during slow walking (van den Bogert et al., 2013), so these inertial artifacts are large. We were able to reduce this error by about half. Our slow condition is representative of an experiment in which gait is perturbed just enough to cause subtle adaptive responses. In more extreme perturbations, such as sudden stopping or starting of the belt, the inertial artifacts would be larger, and as indicated by our fast tests, a much larger fraction of the artifact can be compensated in such conditions.

We calibrated the model on a trial containing similar belt variations to the trial that requires the compensation. We found, however, that the compensation on the slow trials worked almost equally well when the calibration was done on a fast trial. This suggests that the model accurately captured the dynamic properties of the system, and can be generalized to other movements without requiring recalibration. Other compensation methods using the mathematical relationships between motor, pulley, and belt inertias may also describe the dynamic properties of the system. However, these techniques require more complicated analyses and sufficient knowledge of the mechanical properties of the system. The system identification method presented here does not require such information.

At 6 Hz bandwidth, there was about 1-2 Nm of sagittal plane moment error that could not be explained or compensated by the model. Some of this may simply be the noise in the force plate system. Additionally, the model predictions were based on belt acceleration, which was estimated by numerical differentiation of belt speed data, potentially introducing error. It would be of interest to measure belt acceleration with better instrumentation, instead of using the belt speed information provided by the treadmill control system. Alternatively, the pseudorandom belt speed command signal could be used as input for the model. This would eliminate noise but requires the assumption that the belt speed control system can execute the commanded speed despite horizontal forces applied by a human subject. Finally, the linear second order model may not be able to accurately capture the internal dynamics of the system, especially at higher bandwidth. Unmodeled dynamics may include nonlinearities due to friction and internal vibration modes. Potential improvements to the model include nonlinear system identification approaches or an auto-regressive moving-average exogenous (ARMAX) model that more effectively identifies noise in the system.

With the emerging trend of using instrumented treadmills for gait and balance control, this method is simple and easy to implement in other instrumented treadmills, as long as they have the ability to control and measure belt velocity. The amount of inertial correction will vary depending on the properties of the treadmill and its instrumentation. Other balance perturbations, such as mediolateral translation or rotations of the walking surface, will require more sophisticated techniques to compensate for inertial effects in the moving force plate. For variations in belt speed, the compensation method presented here is capable of significantly reducing inertial artifacts, thereby allowing joint moments to be measured in experimental conditions where this was previously not possible.

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6. Conflict of Interest Statement

There are no conflicts of interest for any of the authors regarding the research reported in this manuscript.

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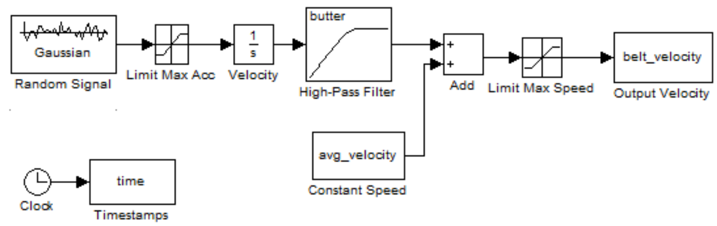

Figure 1: MATLAB Simulink diagram for creating random belt velocities, in which a random acceleration signal is generated with Gaussian white noise. Belt velocity is obtained by integrating the signal and filtering with a high-pass Butterworth filter to reduce integration drift

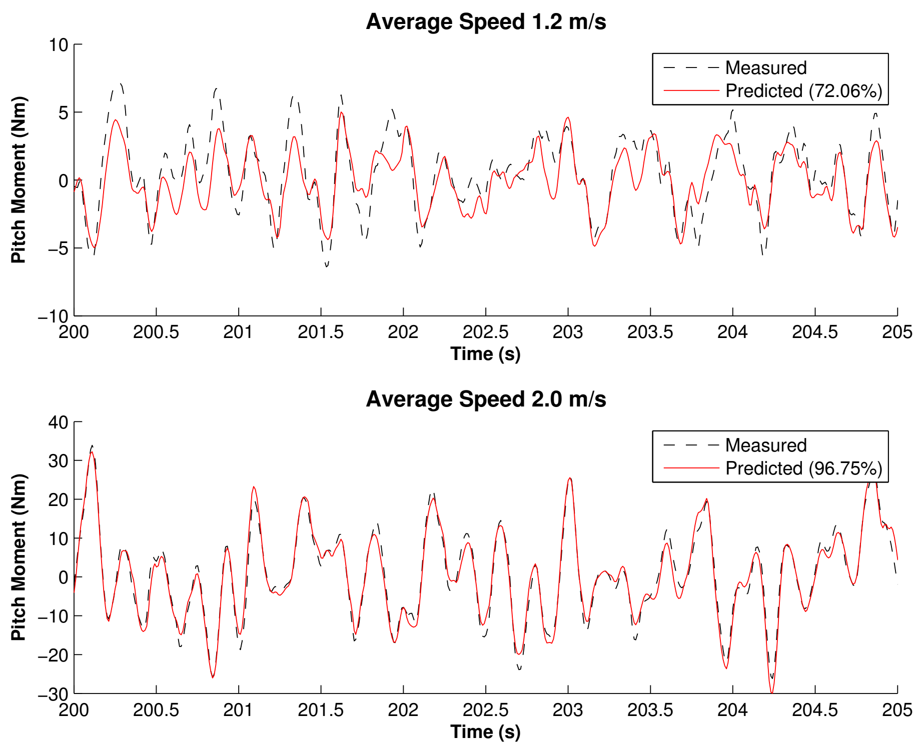

Figure 2: Measured (black dotted) and predicted (red) pitch moment for the slow (top) and fast (bottom) speeds, with R^2 values of 72.08% and 96.75%, respectively. Only a small section of the 6-minute trial is shown.

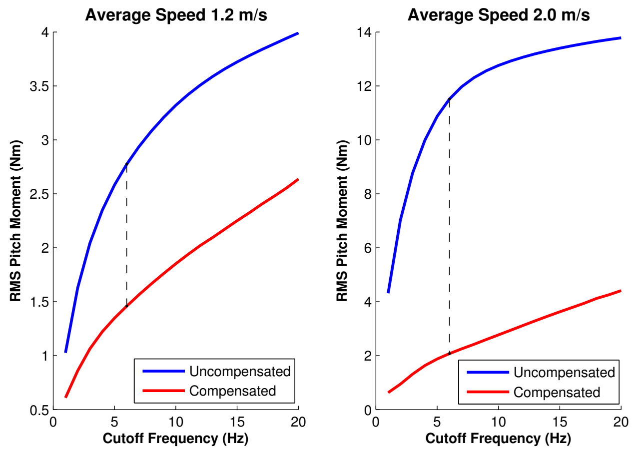

Figure 3: Root-mean-square (RMS) of the uncompensated (blue) and compensated (red) pitch moment as the cutoff frequency of the low-pass, second-order filter was increased from a range of 1-20 Hz. The dashed line indicates the results obtained at 6 Hz

Trial	RMS (Nm) Before Compensation	RMS (Nm) After Compensation	% Reduction
Low Speed (1.2 m/s)	2.77	1.46	47.37
High Speed (2.0 m/s)	11.51	2.07	81.98

Table 1: Root-mean-square (RMS) of the pitch moment before and after compensation. Compensation was performed by subtracting the predicted pitch moment from the measured value.