Journal of Biomechanics xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

Compensation for inertial and gravity effects in a moving force platform

Sandra K. Hnat [a,*], Ben J.H. van Basten [b], Antonie J. van den Bogert [a]

[a] Cleveland State University, Department of Mechanical Engineering, Cleveland, OH 44115, USA
[b] Motekforce Link, Hogehilweg 18–C, 1101 CD Amsterdam, The Netherlands

A R T I C L E I N F O

Article history:
Accepted 3 May 2018
Available online xxxx

Keywords:
Biomechanics
Instrumentation
Gait
Inertial artifacts
Surface perturbation

A B S T R A C T

Force plates for human movement analysis provide accurate measurements when mounted rigidly on an inertial reference frame. Large measurement errors occur, however, when the force plate is accelerated, or tilted relative to gravity. This prohibits the use of force plates in human perturbation studies with controlled surface movements, or in conditions where the foundation is moving or not sufficiently rigid. Here we present a linear model to predict the inertial and gravitational artifacts using accelerometer signals. The model is first calibrated with data collected from random movements of the unloaded system and then used to compensate for the errors in another trial. The method was tested experimentally on an instrumented force treadmill capable of dynamic mediolateral translation and sagittal pitch. The compensation was evaluated in five experimental conditions, including platform motions induced by actuators, by motor vibration, and by human ground reaction forces. In the test that included all sources of platform motion, the root-mean-square (RMS) errors were 39.0 N and 15.3 N m in force and moment, before compensation, and 1.6 N and 1.1 N m, after compensation. A sensitivity analysis was performed to determine the effect on estimating joint moments during human gait. Joint moment errors in hip, knee, and ankle were initially 53.80 N m, 32.69 N m, and 19.10 N m, and reduced to 1.67 N m, 1.37 N m, and 1.13 N m with our method. It was concluded that the compensation method can reduce the inertial and gravitational artifacts to an acceptable level for human gait analysis.

1. Introduction

Force plates and instrumented treadmills are commonly used to measure ground reaction forces (GRF) for clinical movement analysis, sports performance, or research on human movement. The combination of motion capture and force plate data allow for the calculation of joint moments through inverse dynamic analysis. Recently, instrumented treadmills have become equipped with actuators to translate and rotate the walking surface, for either virtual reality applications or for testing human response to perturbations. Acceleration of the force plate creates large inertial artifacts in the GRF measurement, because a large moving mass is located between the force of interest (foot/ground interface) and the load cells. Additionally, when the frame is tilted, its gravitational mass starts contributing to the horizontal GRF signals. The problem is especially severe in an instrumented treadmill, where the moving mass includes the treadmill frame, motor, and belts. These large errors in GRF data make it impossible to perform standard inverse dynamics in these conditions because the joint moment calculations are based on inaccurate force measurements. The same problem also occurs when the force plate foundation is not sufficiently rigid, or in a moving vehicle in order to study the biomechanics of driving.

Although the problem is noteworthy in human movement analysis, it exists in any load measurement system where the force of interest and the load cells are separated by a moving mass. This includes certain applications in high-speed material testing and in force-controlled robots (Hessling, 2009; Dixon, 1990). The work presented in this paper will be applicable in those fields as well.

In principle, the inertial and gravitational forces can be estimated and compensated using rigid body dynamics. This requires knowledge of the mass, inertia matrix, acceleration, angular acceleration, angular velocity, and orientation of the frame. This has been successfully done for one-dimensional linear motion such as in materials testing or a sliding force plate (Hessling, 2009; Dixon, 1990; Pagnacco et al., 2000; Yang and Pai, 2006). While it is straightforward to extend this approach into a six degree of freedom (DOF) load measurement, it becomes impractical due to the requirement to estimate full 3D motion relative to an inertial reference frame, and the use of nonlinear models (Berme and Guler,

* Corresponding author.
E-mail addresses: s.hnat@csuohio.edu (S.K. Hnat), ben.vanbasten@motekforcelink.com (B.J.H. van Basten), a.vandenbogert@csuohio.edu (A.J. van den Bogert).

https://doi.org/10.1016/j.jbiomech.2018.05.009
0021-9290/

2012a; Berme and Guler, 2012b; Hou et al., 2009; van den Bogert et al., 1996). Furthermore, mass and inertial properties of the frame must be known (Preuss and Fung, 2004). Some of the existing methods neglect the effect of rotation and are limited to compensating for errors due to vibrations within the building or floor (Boschetti et al., 2013).

In this paper, we introduce a simple linear, accelerometer-based compensation method for a fully general inertial and gravitational compensation of force plate data. The linear model is based on the principle that an accelerometer directly measures the inertial and gravitational force on its internal test mass. With a sufficient number of accelerometers, attached at different locations, the total inertial and gravitational artifact of all mass elements in the moving frame will be a linear combination of accelerometer signals (Zappa et al., 2001). The method will be presented and evaluated on an instrumented treadmill in various experimental conditions.

2. Methods

2.1. Compensation method

In a 6-DOF load measurement, three-dimensional force and moment are the variables of interest. The compensation model assumes that the effect of gravity and inertia on each of the six load signals, when expressed in the local reference frame of the sensor, is a static linear function of N accelerometer signals:

$$\begin{bmatrix} F_x \\ F_y \\ F_z \\ M_x \\ M_y \\ M_z \end{bmatrix} = C \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_N \\ 1 \end{bmatrix}, \tag{1}$$

where C is a $6 \times (N+1)$ matrix of model coefficients. Note that the model includes a constant term for each load variable (the last column of C) which will be used by the calibration to remove any static offsets that may be present in the load cell signals. It is not necessary to calibrate the accelerometers. Neither is it necessary to separate the accelerometer information into acceleration and gravitational effects. In fact, it is essential that such a separation is not performed because inertial artifacts arise from the combination of the two (van den Bogert et al., 1996). Raw accelerometer signals should be used.

The model must be calibrated by a system identification experiment, in which no external load is applied, and the load cells will only measure the artifacts. This is best done with random movements of the frame, to explore the entire space of potential artifacts. During this experiment, K samples of force and moment data are collected, along with accelerometer data. First, the data is arranged into matrices A (accelerometer signals) and F (force and moment data):

$$A = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1N} & 1 \\ \vdots & \vdots & \vdots & & \vdots \\ a_{K1} & a_{K2} & \cdots & a_{KN} & 1 \end{bmatrix} \tag{2}$$

$$F = \begin{bmatrix} F_{1x} & F_{1y} & F_{1z} & M_{1x} & M_{1y} & M_{1z} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ F_{Kx} & F_{Ky} & F_{Kz} & M_{Kx} & M_{Ky} & M_{Kz} \end{bmatrix} \tag{3}$$

and the model coefficients C are determined through a least-squares solution of the overdetermined system of linear equations:

$$AC^T = F \tag{4}$$

The calibration was coded in Matlab (version 2016a) as well as in C++. In Matlab, QR decomposition was used to obtain the least-squares solution, which is implemented as the "backslash" operator:

$$\mathtt{C} = (\mathtt{A}\backslash\mathtt{F})' \tag{5}$$

In C++, model coefficients were determined through linear regression using the Shark library (Igel et al., 2008). It was verified that the results were identical in both implementations.

2.2. Experimental validation

Experiments were performed on a split-belt instrumented treadmill capable of actuated mediolateral translation (sway) along the X-axis, and sagittal pitch in the YZ-plane (V-Gait, Motekforce Link, Amsterdam, Fig. 1). Each belt assembly, including motors, has a mass of about 150 kg which is located between the load cells and the walking surface. Two triaxial accelerometers (4030 2G range, Measurement Specialties) were mounted on the side of the treadmill (posterior-left and anterior-right), separated by 1.30 m in both the lateral and anterior/posterior directions (Euclidean distance of 1.83 m). Zappa (Zappa et al., 2001) proved that four non-coplanar accelerometers are sufficient to uniquely determine the acceleration at each point in a rigid body. Since there are only two actuated degrees of freedom (DOF, pitch and sway) in this application, only two accelerometers are required to detect the range of movements.

Sway and pitch signals were commanded to the treadmill using D-Flow 3.24 (Motekforce Link, Amsterdam). GRFs from the right belt, and accelerometer data, were directly acquired in the data acquisition unit of an optical motion capture system (Nexus 1.8.5, Vicon). All files were exported in C3D files for further offline analysis. Sampling rate was 1000 Hz. All signals were filtered with a 2nd order low-pass Butterworth filter with a cut-off frequency of 6 Hz, which is typically used for inverse dynamic analysis of walking (Winter, 1990; van den Bogert et al., 2013). After filtering, the first full second of data was removed to eliminate the filter startup effect.

The 6×7 model coefficient matrix C was calibrated using a 60-s unloaded trial in which the treadmill surface was randomly translated and rotated. Zero-mean Gaussian white noise signals were generated with a sampling time of 3.3 *ms* and RMS amplitudes of 0.707 m/s^2 and $127^\circ/s^2$ for sway and pitch, respectively, in MATLAB Simulink (Mathworks, Natick, MA, USA), as shown in Fig. 2. The signals were twice-integrated to obtain smooth treadmill displacements with realizable accelerations. Integration drift was eliminated by processing the input signals through high-pass filters (2nd order Butterworth) with a passband edge frequency of 0.21 Hz. Upper and lower limits were imposed on the signals, thereby restricting the translation and rotation movements to the maximum of ± 0.05 m displacement and $\pm 10^\circ$ pitch angle.

The calibrated model was evaluated in five tests where the platform was moved without load applied to the right force plate. The tests included platform motions induced by actuators, by motor vibration, and by human ground reaction force impacts. In Trial 1, the treadmill was subjected to 60 s of random pitch and sway movement generated by the same procedure as the calibration trial, but with a different random number seed. Trial 2 had the same random movement, but with the treadmill belts running at 1.3 m/s to evaluate the effect of motor vibration. Trial 3 again contains the same random movement as Trial 1 and 2, but with a subject walking on the left belt at 1.3 m/s. In Trial 4, the subject walked on the left belt with 1.3 m/s, without pitch or sway motion. In this trial, the subject walked on the front half of the treadmill to represent the worst case of walking-induced frame motion. In Trial 5, the treadmill was set in a static pitch angle of 9 degrees. As the

Please cite this article in press as: Hnat, S.K., et al. Compensation for inertial and gravity effects in a moving force platform. J. Biomech. (2018), https://doi.org/10.1016/j.jbiomech.2018.05.009