

Short Communication

ON THE FILTERING OF INTERSEGMENTAL LOADS DURING RUNNING

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Abstract

When performing inverse dynamics analysis, smoothing kinematic and force platform data at different cutoff frequencies creates an “impact” like artifact that is visible in the joint moments during impulsive activity. Here we illustrate a processing technique in which inverse dynamics analysis is performed on the raw kinematic and force platform data and the joint reaction forces and moments are subsequently smoothed based on the frequency content of the distal reaction force. The effectiveness of this technique is illustrated on forward dynamics simulation data with known intersegmental loads. We then apply the technique to an experimental data set of 10 subjects running at three prescribed speeds. We show that performing inverse dynamics on the raw data and subsequently smoothing the intersegmental loads results in minimal attenuation of the joint reaction force and avoids impact artifacts in the joint moments. Artifacts that occur using a traditional filtering technique are systematic, become more pronounced with speed, and are most noticeable at the hip joint.

Introduction

Intersegmental forces and moments can provide insight into the internal loading of joints and coordination of movements during impulsive activity such as landing and running. Owing to high-frequency noise, movement artifact, and the need to double differentiate position data for segmental acceleration, it is necessary to smooth biomechanical data to accurately characterize intersegmental loads from inverse dynamics analysis. Traditionally, kinematic data are filtered at a low cutoff frequency (e.g., 8 Hz) and force platform data are left raw or smoothed at a relatively high frequency (e.g., 50 Hz) because of discrepancies in signal-to-noise-ratio [1-4]. It has been demonstrated that this approach creates an “impact” like artifact that is visible in joint moments during impact activity [5-7]. This artifact may result from the attenuation of equilibrating segmental accelerations in the inverse dynamics calculations [6,7].

Joint moments free from artifacts can be resolved if kinematic and force platform data are smoothed at a relatively low, identical cutoff frequency (e.g., 20 Hz) [5]. This approach is not ideal when reaction forces are of interest because the impact portion of the reaction force, which has major frequencies between 10 and 30 Hz during running [8], is attenuated. The purpose of this study is to illustrate a filtering technique in which inverse dynamics is performed on the raw kinematic and force platform data, and the resulting moments and reaction forces are subsequently smoothed based on the frequency content of the reaction force (similar to White and Podraza [7]). This technique is first validated on forward dynamics simulation data with known intersegmental loads [6]. Joint moments and reaction forces are then calculated for a group of ten subjects running at three selected speeds.

Methods

Simulation

Running simulation data were obtained from the International Society of Biomechanics' data resource website (URL: <http://isbweb.org/data/invdyn/index.html>). These data were produced using a 2-D forward dynamics simulation, therefore the intersegmental loads are exactly known, and the associated kinematics are noise free [6]. To replicate a typical data collection system, the simulated kinematic and ground reaction force data were sampled at 160 and 1600 Hz, respectively. White noise (0.1 mm root mean square) was added to the kinematic data, which were then reinterpolated to 1600 Hz using a cubic-spline routine. A bottom-up, rigid-body inverse dynamics analysis was performed using two different filtering methods. In the first (pre_{filt}), ground reaction forces were smoothed at 100 Hz and kinematics were smoothed at a cutoff frequency corresponding to the mean 98th percentile frequency of all kinematic signals; inverse dynamics was then performed. In the second ($\text{post}_{\text{filt}}$), inverse dynamics was performed on the raw data and the resulting joint reaction forces and moments were smoothed at the 99th and 95th percentile frequency of the distal vertical reaction force, respectively. Therefore, forces and moments at the ankle were filtered according to the frequency content of the vertical ground reaction force, the knee according to the vertical ankle reaction force, etc. For both methods, cutoff percentiles were chosen from optimization, and corresponded to the cutoff frequencies that minimized the average root mean squared error (RMSE) for each joint between inverse dynamics results and known intersegmental loads. Cutoff percentiles were calculated from the cumulative sum of an integrated power spectral density curve and the optimization process was performed 10 times with newly generated noise. A 4th order, zero-lag Butterworth filter was used for both procedures.

Experimentation

The experimentation described below has been previously reported [9]. Briefly, ten males (age 24.9 ± 4.7 yrs; height 1.7 ± 0.1 m; mass 70.1 ± 8.9 kg) were recruited for this institutionally approved study after giving written informed consent. Subjects ran overground at 2.5, 3.5, and 4.5 m/s. Motion capture (Vicon MX, Vicon, Centennial, CO) and force platform (AMTI, Watertown, MA) data were collected concurrently at 160 and 1600 Hz, respectively. Ten trials were performed at each speed. Inverse dynamics was used to calculate net-internal joint moments and reaction forces of the lower-extremity. Both pre_{filt} and $post_{filt}$ procedures were applied using the methods described above.

Results

Simulation

The pre_{filt} method resulted in an impact-like artifact in the net-internal joint moments (Figure 1). RMSE progressively increased moving proximal towards the hip. The $post_{filt}$ method resulted in inverse dynamics that closely followed the known intersegmental loads; reaction forces were minimally attenuated and RMSEs were lower for the moments (Figure 1).

Experimentation

Similar results were observed for experimentally determined intersegmental loads. The pre_{filt} method resulted in an impact like artifact in the hip and knee moment, and reaction forces were not attenuated using the $post_{filt}$ (Figure 2). Artifacts using the pre_{filt} method became more pronounced with speed and these were visible in the group ensemble hip moment curves (Figure 3).

Discussion

The impact artifacts presented here were largest at the hip. These could influence statistical outcomes aimed at quantifying differences in peak instantaneous magnitudes.

Although these artifacts could be smoothed following inverse dynamics calculation, they are not randomly occurring events. They systematically increase with speed and are therefore highly related to the movement. Filtering these artifacts could potentially introduce systematic errors to the net internal joint moments.

When both joint reaction forces and moments are of interest, such is the case when analytical methods are used to estimate joint contact forces [10], van den Bogert and de Koning [6] recommended smoothing kinematic and kinetic data at identical cutoff frequencies, but performing inverse dynamics twice: once with a cutoff for optimal reaction forces, and again with a cutoff for optimal moments. This would likely produce similar results to the `post_fit` method. The benefit of the `post_fit` method is that optimal intersegmental loads can be calculated in a single inverse dynamics analysis, even if separate cutoff frequencies were chosen for each of three reaction forces and moments. For example, a lower cutoff percentile could be used for the hip reaction force to reduce the observed noise in Figure 2.

In summary, impact artifacts in joint moments are introduced when using traditional filtering techniques. These artifacts are most pronounced at faster speeds of running. Traditional filtering techniques would not be expected to introduce errors during less dynamic activities such as walking and stair climbing.

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Conflict of interest

The authors have no conflict of interest

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Figure Captions

Figure 1. Simulated inverse dynamics results (resultant magnitude of the reaction force and medial-lateral moment) and RMSE for the pre_{filt} and $post_{filt}$ methods. Known intersegmental loads are shown in grey and the pre_{filt} and $post_{filt}$ methods are shown in black. Positive moments correspond to extension.

Figure 2. Experimentally determined intersegmental loads for a subject running at 2.5, 3.5, and 4.5 m/s. The pre_{filt} method is shown in grey and the $post_{filt}$ method is shown in black. Positive forces are directed anterior, proximal, and lateral (dashed line = anterior-posterior; solid line = axial; dotted line = medial-lateral). Positive moments correspond to adduction, internal rotation, and extension (dashed line = anterior-posterior; dotted line = torsion; solid line = medial-lateral).

Figure 3. Group ensemble experimentally determined joint moments for three speeds of running (normalized to bodyweight, BW). The pre_{filt} method is shown in grey and the $post_{filt}$ method is shown in black. Positive moments correspond to adduction, internal rotation, and extension (dashed line = anterior-posterior; dotted line = torsion; solid line = medial-lateral).

Figures

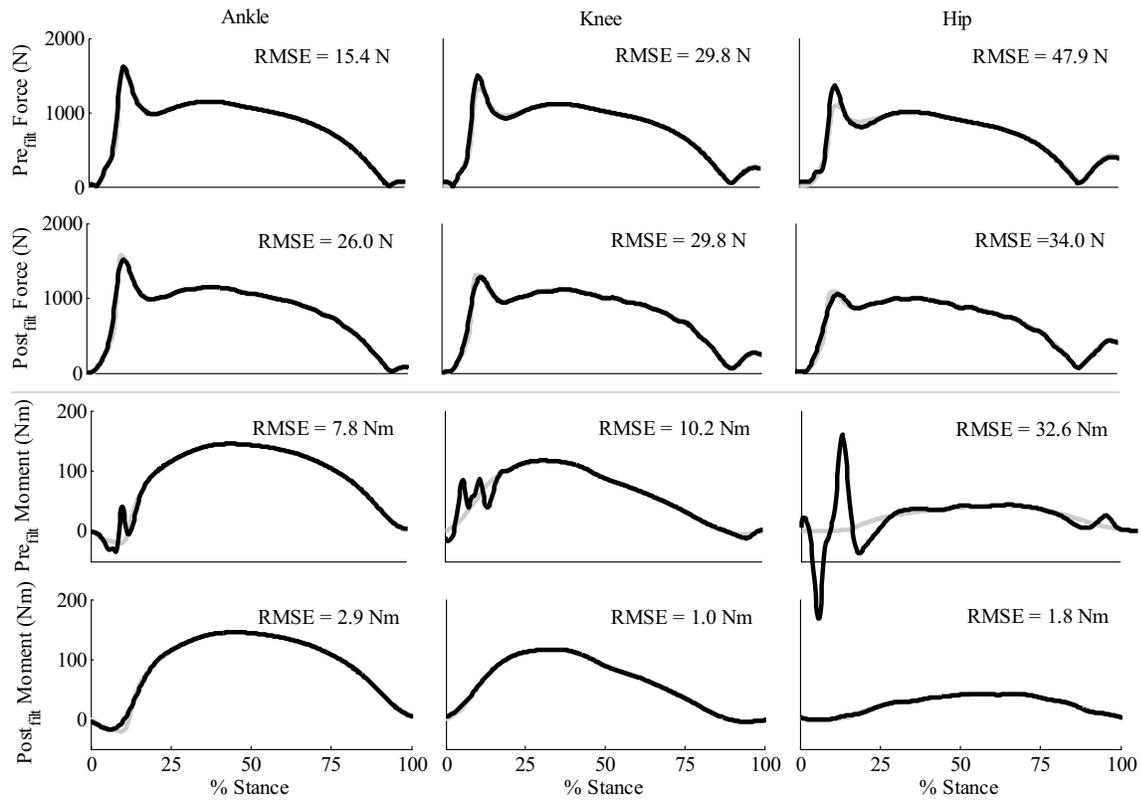


Figure 1.

Figure 2.

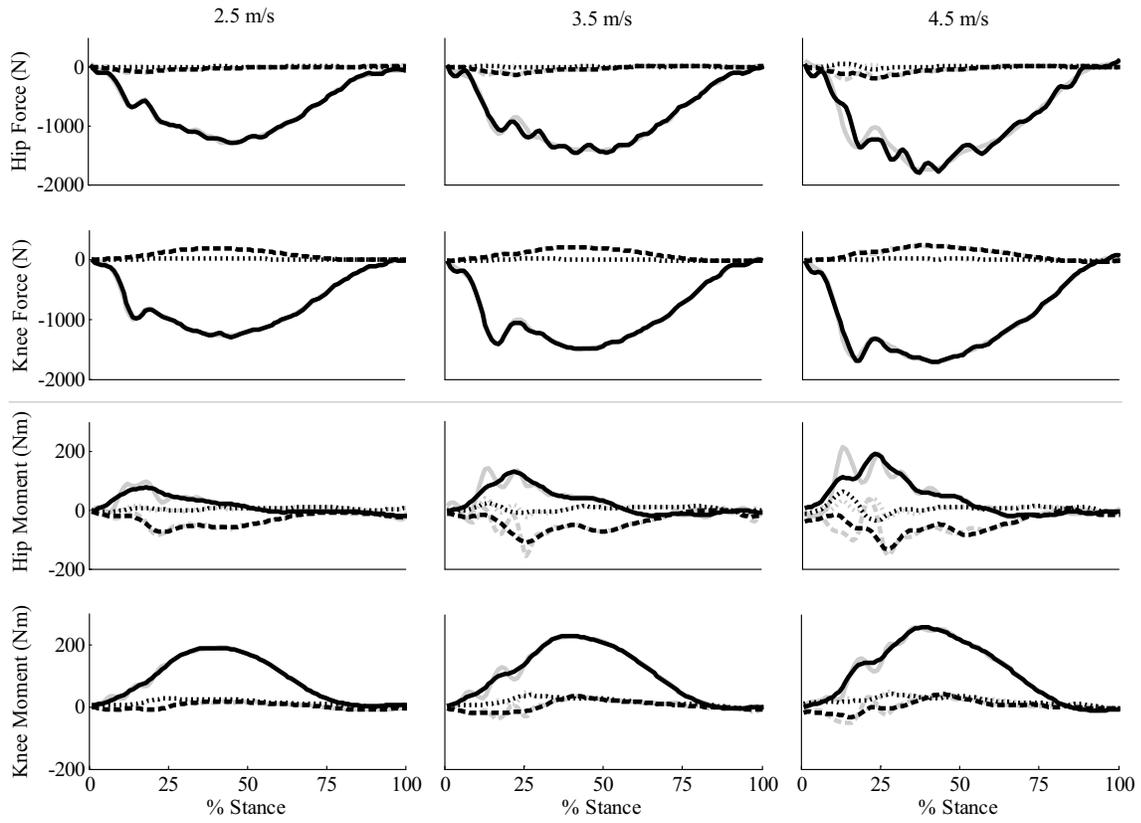


Figure 2.

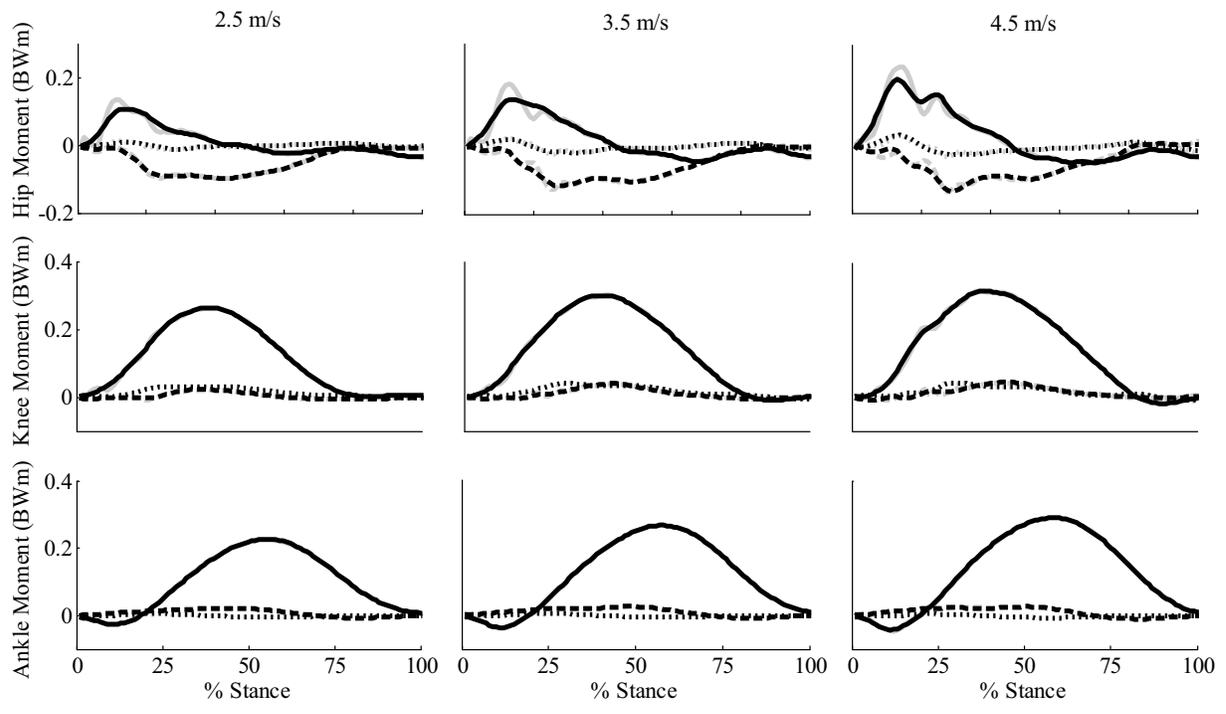


Figure 3.