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ON OPTIMAL FILTERING FOR INVERSE DYNAMICS ANALYSIS

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INTRODUCTION

Inverse dynamics analysis, the determination of intersegmental loads from movement data and ground reaction forces (GRF), is becoming a standard tool in gait analysis laboratories. It is well known that movement data must be low-pass filtered in order to prevent excessive noise in the second derivatives which occur in inertial terms in the equations of motion. However, low-pass filtering of kinematic data may remove high-frequency components of the actual movement, especially in impact movements such as running. The effects of such filter-induced errors are difficult to assess, since the true intersegmental forces and moments are never known. It is the purpose of this paper to evaluate the effect of low-pass filtering on calculation of intersegmental loading during running, and to develop recommendations for optimal filter parameters. Data from a simulated running movement, with known intersegmental loading, will be used for this purpose.

METHODS

A 2-D musculoskeletal model, consisting of four rigid segments (trunk, thigh, shank, and foot) and seven muscles was used to simulate the support phase of running. Details of this model are described elsewhere[2]. A parameter optimization was carried out to determine muscle stimulation patterns which resulted in a realistic vertical ground reaction force with the frequency content of running (Fig. 1). A second simulation was run backwards in time, starting at heel strike, to obtain movement data for the preceding swing phase.

Simulated ground reaction force, point of application, and coordinates of the joint centers were written to an output file at 5 ms intervals. White noise (0.5 mm RMS) was added to the kinematic data to simulate digitization errors. The data were then optionally filtered by a two-pass second order low-pass Butterworth filter. Four cut-off frequencies, for the three body segments and force plate data, could be selected independently. Filtered data were used as input for a standard 2-D inverse dynamics analysis[4], in which the same body segment parameters were used as in the simulation that generated the data.

In order to find the best combination of four filter cut-off frequences, optimizations were carried out to minimize the root-mean-square (RMS) difference between the inverse dynamics results and the known intersegmental loads. These optimizations were done separately for the intersegmental forces and the intersegmental moments and repeated ten times with newly generated white noise.

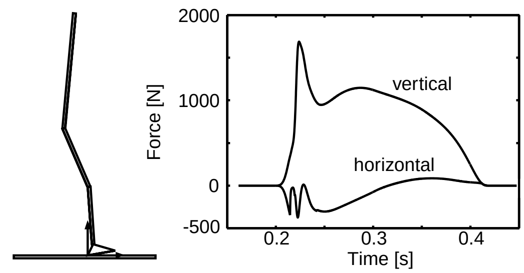

Fig. 1: Rigid-body model (from Gerritsen et al., 1995) shown at heel strike and simulated ground reaction forces.

RESULTS

Inverse dynamics results were identical to the known intersegmental loads, when presented with unfiltered noise-free data at a high sampling rate. When using the data with realistic sampling rate and noise, the results were sensitive to the filtering procedure. Fig. 2 shows the intersegmental loads obtained with a commonly used filtering procedure: a 15 Hz low pass filter for the kinematic data, and no filtering of force plate data. Large errors in the moments occur during the impact phase, especially at the proximal joints. Fig. 3 shows the intersegmental loads obtained by filtering all data (force and kinematics) with a 15 Hz low pass filter. This improved the hip and knee moments considerably, but removed the impact peak from the intersegmental forces, thereby increasing the error.

These results suggest that optimal filtering procedures should be found, depending on the variables of interest. Optimized combinations of cut-off frequencies for intersegmental forces and moments, and the resulting errors in all six loading variables, are presented in Table 1.

DISCUSSION

The large errors in joint moments, shown in Fig. 2, occur only during the impact phase and are therefore evidently not related to noise in the kinematic data.

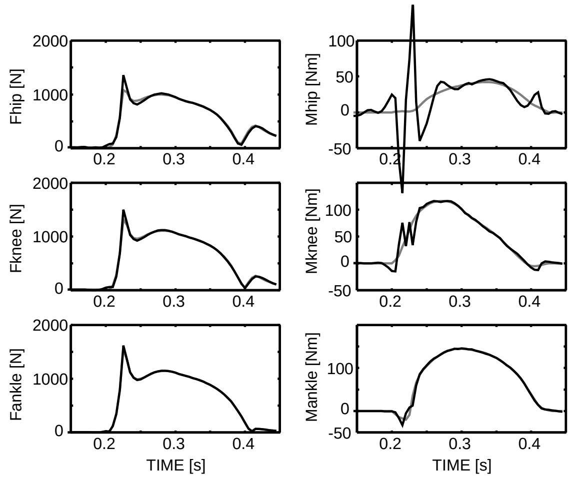

Fig. 2: Inverse dynamics results after using a 15 Hz low-pass filter for kinematics and no filter for ground reaction forces. Known intersegmental loads are shown in grey.

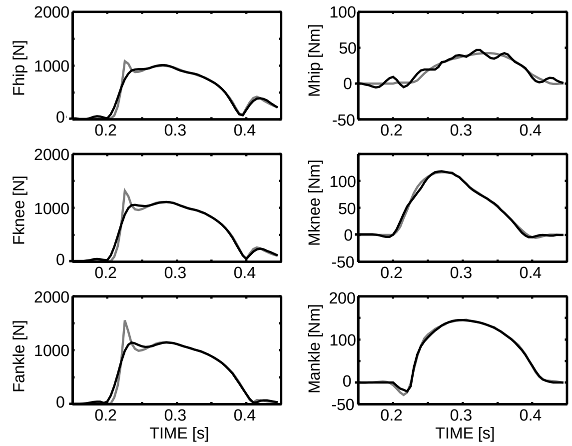

Fig. 3: Inverse dynamics results after using a 15 Hz low-pass filter for both kinematics and ground reaction forces. Known intersegmental loads are shown in grey.

Rather, these errors are caused by a combination of impact peaks in the horizontal GRF and our inability to calculate the high-frequency components of segment accelerations, which would 'absorb' external impact, with sufficient accuracy. Since low-pass filtering of kinematic data cannot be avoided, the proper method to avoid these artifacts is to filter the GRF with a similar cut-off frequency. This effectively removes inconsistencies between kinematics and forces.

Several studies on inverse dynamics of running have reported impact peaks in hip joint moments, which may be artifacts (as in Fig. 2) of the inverse dynamics analysis. Unfortunately, results are usually presented in a way that these peaks are not as obvious as in our simulated results. Either group averages were presented[3] or moments were low-pass filtered[1]. Both operations would reduce the amplitude of the artifact. However, since the artifact is *not* random noise but highly correlated to the movement, a systematic error will remain. We strongly recommend therefore to be critical of published joint moments, especially for the hip joint, in impact activities.

The results in Table 1 show that different filters must be applied to the raw data, depending on the purpose of the analysis. If intersegmental forces and moments are both required, as for example in a procedure to estimate joint contact forces, we recommend that the inverse dynamics should be done twice: once to obtain moments and once to obtain forces. One might even optimize the filtering procedure for each of the six intersegmental loading variables.

The cut-off frequencies listed in Table 1 are optimal for this specific data set: a typical running movement,

Table 1: Optimized cut-off frequencies and resulting RMS errors (average ± SD of 10 simulated sets of data).

filter parameters/ results	optimized for best forces	optimized for best moments
thigh cut-off [Hz}	18.0 ± 1.2	15.1 ± 1.0
shank cut-off [Hz}	24.9 ± 3.0	14.6 ± 1.6
foot cut-off [Hz]	25.7 ± 3.7	16.5 ± 2.0
force plate cut-off [Hz]	56.0 ± 2.5	15.1 ± 1.2
Fhip error [N]	27.2 ± 2.1	62.6 ± 4.5
Fknee error [N]	20.1 ± 1.7	77.2 ± 5.3
Fankle error [N]	18.8 ± 1.3	94.3 ± 6.3
Mhip error [Nm]	21.5 ± 2.5	4.1 ± 0.4
Mknee error [Nm]	5.9 ± 0.8	3.0 ± 0.5
Mankle error [Nm]	3.7 ± 0.3	3.1 ± 0.2

with kinematics sampled at 200 fps and 0.5 mm noise. Using the same set of simulated data, optimal cut-off frequencies for other frame rates and noise levels are easily obtained. The results of this study should not be directly applied to movements with a different frequency content.

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