THE EFFECT OF DIGITAL FILTERING PROCEDURES ON KNEE JOINT MOMENTS IN SPRINTING

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Inverse dynamics analyses are commonly used to obtain resultant joint moment data during sprinting. This study aimed to determine the effects of using different combinations of cut-off frequencies applied to the kinematic and kinetic input data on the determined knee joint moments. Input data from a sprinter during the first stance phase were recorded, and ten different combinations of cut-off frequency were applied. When the kinetic cut-off frequency exceeded the kinematic one, as is common, larger peaks and rapid fluctuations were evident in the knee joint moment soon after contact due to inconsistent frequency content between the input data. In contrast, when the cut-off frequencies were matched, the peaks and fluctuations were minimal, and it is suggested that they may be anomalies of data processing and not genuine aspects of sprint kinetics.

KEY WORDS: data smoothing, inverse dynamics, methods, modelling.

INTRODUCTION: When resultant joint moments (RJMs) are required to address a specific research question, an inverse dynamics analysis (IDA) is commonly undertaken. These analyses have been widely used to determine the RJMs during sprinting stance phases (e.g. Mann, 1981; Jacobs & van Ingen Schenau, 1992; Johnson & Buckley, 2001; Hunter et al., 2004; Bezodis et al., 2008), and rapid peaks and fluctuations in the knee RJM have commonly been observed soon after contact. An IDA requires kinematic (typically video), kinetic (typically ground reaction force; GRF) and segmental inertia input data, and thus the accuracy of each of these data sets is paramount for appropriate RJM data to be obtained. The kinematic input data have been shown to have a considerable influence on the determined RJM outputs (Challis & Kerwin, 1996). This is largely due to the unavoidable presence of noise as a result of digitising error and/or marker movement, and this noise in the raw displacement data is further amplified when deriving the linear and angular acceleration data required for an IDA. Smoothing of the kinematic input data is therefore of critical importance, and low-pass digital filters are commonly used to reduce the magnitude of this noise by applying a specific cut-off frequency to attenuate data above a certain frequency (Winter, 1990). In previous sprinting research, reported cut-off frequencies for kinematic data have ranged from 8 Hz (Hunter et al., 2004) to 20 Hz (Jacobs & van Ingen Schenau, 1992; Belli et al., 2002).

There is also noise present in the kinetic input data (i.e. GRFs), although this is not from the same sources as that in the kinematic data and will thus likely have a different frequency content. As high-frequency impact peaks are often observed in the GRF data during sprinting, these data are commonly filtered at a higher frequency in order to preserve these peaks – the previous sprinting joint kinetics studies which have reported their GRF filtering methods have typically used cut-off frequencies of 75 Hz (Jacobs & van Ingen Schenau, 1992; Johnson & Buckley, 2001; Hunter et al., 2004). However, Bisseling and Hof (2006) recently suggested that during impact-related activities, kinetic IDA input data should be filtered with similar cut-off frequencies to the kinematic input data in order to avoid the creation of artificial peaks in the computed RJMs. The aim of this study was therefore to determine how different combinations of cut-off frequencies applied to the kinematic and kinetic IDA input data affect the determined RJMs during a sprinting stance phase.

METHODS: One international-level male sprinter (age = 20 years, mass = 86.9 kg, height = 1.78 m, 100 m PB = 10.28 s) completed a series of 5 maximal effort sprints to 30 m. GRF

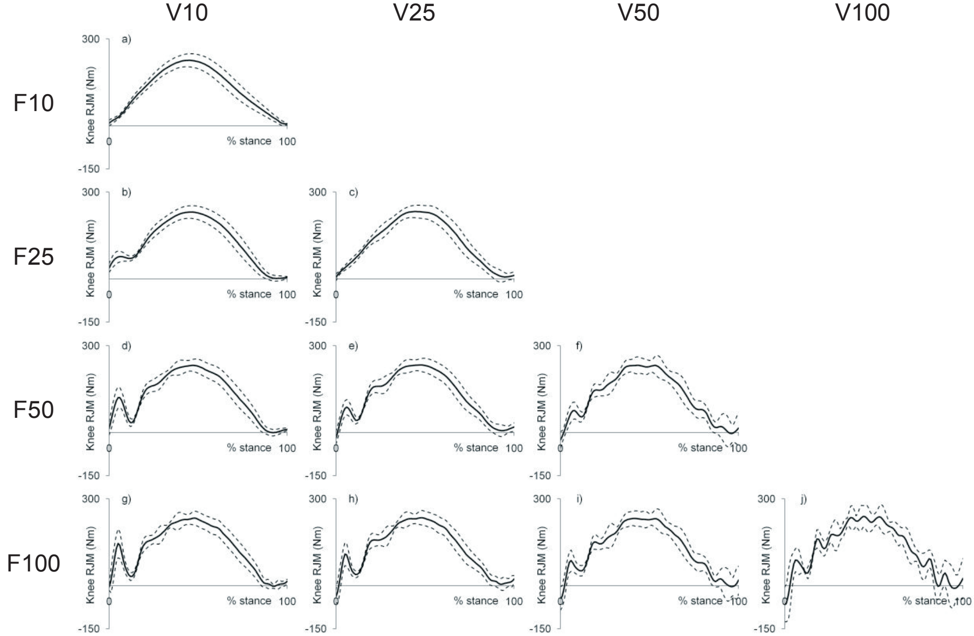
(Kistler, 9287BA) data were collected at 1000 Hz during the first stance phase following block exit. A high-speed camera (Redlake, Motion Pro HS-1) operating at 200 Hz and with a shutter speed of 1/1000 s was located 25 m away from the force platform, with its optical axis perpendicular to the running lane. Images were collected at a resolution of 1280 × 1024 pixels inside a 2.5 m field of view. These kinematic and kinetic data were synchronised to the nearest ms using a series of LEDs.
The raw video files were manually digitised (20 points: vertex, C7, shoulder, elbow, wrist, hip, knee, ankle and MTP joint centres, fingertips and distal halluces) from 10 frames prior to first stance touchdown until ten frames after toe-off. The raw GRF data were downsampled to 200 Hz to match the corresponding video frames during this time period. All kinematic and kinetic input data were passed through a 4th order Butterworth digital filter using four different cut-off frequencies (10, 25, 50 and 100 Hz). This yielded 10 combinations of video (V) and GRF (F) cut-off frequencies, which are subsequently referred to as e.g. V25F50, which would represent the results when filtering the video data at 25 Hz and the force data at 50 Hz. Each set of these filtered data were systematically combined with subject-specific inertia data (Yeadon, 1990) in an IDA to calculate the RJMs at the MTP, ankle, knee and hip joints of the stance leg. For each of the 10 combinations of cut-off frequencies used, the knee RJMs were time-normalised to 101 samples from touchdown to toe-off using an interpolating cubic spline, before mean ± *s* time-histories from all five trials were calculated.

RESULTS AND DISCUSSION: The results revealed a clear underlying general trend for a knee extensor RJM throughout stance which reached peak values just prior to mid-stance (Figure 1). When the video and force cut-off frequencies were matched (see bold values in Table 1 and diagonally from top left to bottom right of Figure 1) the peak extensor RJMs soon after contact were typically minimal, with less fluctuation evident. From the data with the least filtering (Figure 1j; V100F100) although the knee RJM was noisy due to a high magnitude of noise in the kinematic input data, the RJM peak soon after contact was not large (Table 1). However, using these kinetic data with kinematic data filtered at lower cut-off frequencies (Figures 1g-i) led to an increase in the peak extensor RJM during the first 5% of stance up to a mean value of 128 Nm (V10F100; Table 1). This trend was evident for all ‘un-matched’ combinations of cut-off frequency (as are commonly used in IDAs). For each kinematic cut-off frequency, as the kinetic cut-off frequency increased, so too did the peak extensor RJM in the first 5% of stance (Table 1). However, the different filtering combinations used only had a minimal effect on the peak RJM during the rest of stance (range = 226 - 239 Nm; Table 1).

Table 1: Mean peak extensor resultant joint moments (Nm) at the knee joint during the initial 5% and subsequent 95% of the first stance phase of a sprint.

	V10		V25		V50		V100	
	First 5%	Last 95%	First 5%	Last 95%	First 5%	Last 95%	First 5%	Last 95%
F10	**25**	**226**						
F25	73	231	**33**	**233**				
F50	109	232	73	233	**38**	**232**		
F100	128	234	89	235	57	232	**45**	**239**

Filtering the kinematic and kinetic data at different cut-off frequencies creates inconsistencies in the frequency content of the two data sets. The commonly adopted procedure of adopting a lower cut-off frequency for the kinematic data compared to the kinetic data clearly leads to large and relatively brief peaks in the extensor RJMs soon after contact, as previously observed in landings by Bisseling & Hof (2006). This is due to the removal of genuine high frequency segmental accelerations from the kinematic data which corresponded to the high frequency GRFs in the kinetic input data. Therefore, when calculating the internal joint forces (IJFs) based on Newton’s 2nd Law during the IDA, in order to make the sum of the forces acting on the most distal segment proportional to the relatively smooth acceleration of that segment, a large peak in the IJF countering the peak in the GRF is required. This spurious peak is then propagated up the leg as the calculations proceed to the more proximal joints and clearly affects the calculation of the RJM at the knee joint.



Figures 1a-j: The effect of different video and force cut-off frequencies on the calculated resultant joint moment (RJM) at the knee during the first stance phase of a sprint. Data represent the mean of 5 trials (solid) ± standard deviations (dashed).

Based on the current results, previously reported rapid fluctuations in knee RJM early in stance (e.g. Mann, 1981; Johnson & Buckley, 2001; Bezodis et al., 2008) could potentially be artefact introduced by applying a lower cut-off frequency to the kinematic input data than the kinetic input data. In these studies, which were conducted during mid-acceleration and maximum velocity phases of a sprint, this large change in the knee RJM after touchdown has also frequently been found to fluctuate between extensor and flexor dominance. Whilst the above authors have typically found these fluctuations to occur within 30 ms of contact, there has not been a physiological explanation of how or why such an action would occur. Although the true knee RJMs are unknown in the current analysis, it is likely that the observed periods of rapid change were spurious due to errors in the IJF calculation caused by mis-matched frequency content in the kinematic and kinetic input data.

It is acknowledged that kinetic data filtered with a low cut-off frequency are no longer fully representative of the true GRFs as the impact peaks are markedly attenuated. However, the same holds true for the kinematic data. Although much of the noise is removed and thus the kinematic signals are smoother when filtered at a low cut-off frequency, they too are not fully representative of the real signal as they also lack the true high-frequency components. Ideally, the data would not require filtering at all and the most genuine representation of the joint kinetics could be obtained. However, this is seldom the case, for whilst filtering at a very high frequency would mean that little or no true signal is removed, the typical levels of noise inherent to kinematic data limits this approach. A considerable degree of low-pass filtering must therefore be performed on these kinematic data in order to obtain acceleration time-histories that are not overly contaminated with noise. The magnitude of filtering required to achieve this during a sprinting stance phase depends on such factors as the system and set-up used to collect the kinematic data and the operator experience during any digitising procedures. However, the current results, combined with previous empirical (Bisseling & Hof,

2006) and theoretical (van den Bogert & de Koning, 1996) evidence, suggest that the kinetic data should be filtered at the same cut-off frequency as the kinematic data. This will likely yield the most realistic representation of the true RJMs (van den Bogert & de Koning, 1996), as the peak RJMs during mid-stance remain largely unaffected and likely artificial fluctuations soon after contact by 'un-matched' higher frequency kinetic input data are avoided.
An interesting finding which provided additional support for filtering the kinematic and kinetic input data using the same cut-off frequency was evident when comparing the data presented in Figures 1b and 1c. These combinations both used the same kinetic input data (filtered at 25 Hz) and thus, as mentioned above, contained considerable attenuation of the genuine GRF impact peaks. Whilst the V25F25 data produced no fluctuations in the RJM after contact (Figure 1c), reducing the kinematic cut-off frequency to 10 Hz (i.e. V10F25) reintroduced an initial peak in the extension RJM (Figure 1b). This confirmed that if the kinematic cut-off frequency was lower than the kinetic cut-off frequency, irrespective of the absolute values used, fluctuations in the extensor RJM appeared soon after contact.

CONCLUSION: This study revealed that in an IDA of the contact phase during sprinting, potentially artificial fluctuations in the RJMs occurred if the kinetic data were filtered using a higher cut-off frequency than the kinematic data. These peaks were created by removal of the high frequency content of the kinematic acceleration data associated with the high frequency GRFs soon after contact, requiring large and potentially spurious IJFs and thus RJMs to balance the IDA equations. It appears that applying identical cut-off frequencies to the kinematic and kinetic input data eliminates this issue, supporting previous methodological research (Bisseling & Hof, 2006; van den Bogert & de Koning, 1996) in an applied sprinting context. In order to obtain the most accurate RJM time histories during sprinting stance phases, the selected cut-off frequency should be as high as possible without making the RJMs uninterpretable due to excessive noise in the kinematic input data. It is therefore suggested that a single cut-off frequency for both the kinematic and kinetic input data could be identified through a residual analysis (Winter, 2005) of the kinematic data for the IDA. If separate GRF data are also required during the analysis of the sprinting stance, then these data could be treated separately using a more appropriate, higher cut-off frequency.

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