Original article:

Excessive fluctuations in knee joint moments during early stance in sprinting are caused by digital filtering procedures

Authors:

Neil E. Bezodis[a,b], Aki I.T. Salo[b], Grant Trewartha[b]

Affiliations:

[a]School of Sport, Health and Applied Science, St Mary's University College, Twickenham, UK, TW1 4SX.

[b]Sport, Health and Exercise Science, University of Bath, UK, BA2 7AY.

Corresponding author:

Neil E. Bezodis, PhD

email: bezodisn@smuc.ac.uk

Tel: +44 208 240 2325

Fax: +44 208 240 4212

Abstract:

Inverse dynamics analyses are commonly used to understand movement patterns in all forms of gait. The aim of this study was to determine the effect of digital filtering procedures on the knee joint moments calculated during sprinting as an example of the possible influence of data analysis processes on interpretation of movement patterns. Data were obtained from three highly trained sprinters who completed a series of 30 m sprints. Ten different combinations of cut-off frequency were applied to the two-dimensional kinematic and kinetic input data with the kinetic cut-off frequency set equal to or higher than the kinematic cut-off frequency. When using the commonly adopted practice of filtering the kinetic data with a higher cut-off frequency than the kinematic data, exaggerated fluctuations in the knee joint moment existed soon after contact. In extreme cases, the knee moved between flexor, extensor and flexor dominance in less than 33 ms and through ranges exceeding 500 Nm. During an inverse dynamics analysis of locomotion, mismatched cut-off frequencies will likely affect the calculated joint moments if the cut-off frequency applied to the kinematic data is less than the true frequency content, particularly during impact phases. In the example of sprinting, exaggerated fluctuations in the knee joint moment appear to be data processing artefact rather than genuine characteristics of the joint kinetics. When the cut-off frequencies, and thus the frequency content of all input data, are matched, the fluctuations after contact are minimal, and such a procedure is suggested for inverse dynamics analyses of gait.

1. Introduction

Resultant joint moments (RJMs) are commonly determined during analyses of human locomotion using an inverse dynamics analysis (IDA) to understand the underlying causes of movement. Such IDA approaches have been widely used in an attempt to understand the lower limb RJMs during discrete stance phases in the fastest form of gait, sprinting[1-7]. The role of the knee joint in sprinting has been of particular interest and debate, and the above studies have commonly reported excessive fluctuations of both high frequency and magnitude in the knee RJM during the early part of stance in steps ranging from the very first on the track up to maximum velocity. However, despite their existence, no clear explanation for the occurrence of these fluctuations has previously been offered.

In determining RJMs during gait, an IDA requires input from kinematic (typically video-based), kinetic (typically ground reaction force; GRF) and segmental inertia data. The accuracy of these input data is therefore clearly of importance in ensuring integrity of the output data. The kinematic input data have previously been shown to have the largest influence on the determined RJM outputs[8,9]. This is due to the unavoidable presence of noise in the displacement data as a result of digitising error or marker movement relative to the underlying joint centres, which is further amplified in the determination of the linear and angular acceleration data required for an IDA. The kinematic input data are therefore smoothed prior to inclusion in the IDA, with low-pass digital filters commonly used to attenuate data above a specific frequency[10]. The kinematic input data used in the aforementioned sprinting research studies were filtered using cut-off frequencies ranging from 8 to 24 Hz where stated. Kinetic input data also contain noise and are thus often also filtered for an IDA. In an attempt to preserve the commonly observed impact GRFs in sprinting, these kinetic input data are often filtered at a higher cut-off frequency than the

kinematic data. The above sprinting studies that stated their GRF cut-off frequency used either values of 75 Hz or the authors chose not to filter their kinetic input data at all.

It has been suggested that during activities with high impact forces, filtering the kinetic and kinematic input data using different cut-off frequencies could lead to the computation of artificial peaks in the determined RJMs[11-13]. It is thus possible that previously observed excessive fluctuations in the knee RJM during early stance in sprinting are influenced by the digital filtering procedures. The aim of this study was therefore to determine the effect of different cut-off frequency combinations applied to the kinematic and kinetic IDA input data on the determined knee joint RJMs, with a view to explaining the commonly observed fluctuations soon after impact in sprinting.

2. Methods

2.1. Research design and participants

Due to the methodological focus of this study, a within-participant analysis was adopted. This allowed the direct effects of the different filter combinations to be observed without potentially averaging out any fluctuations or effects due to between-participant differences. A multiple-single-participant approach (n = 3) was used to make the results more applicable to a wider population, including both sexes (participant A = male, 21 years, 82.6 kg, 1.81 m; participant B = male, 20 years, 86.9 kg, 1.78 m; participant C = female, 26 years, 60.5 kg, 1.76 m). All participants were highly trained sprinters (100 m personal best times: A = 10.14 s, B = 10.28 s, C (100 m hurdles) = 12.72 s) and provided written informed consent to participate in this study which had been approved by the Local Research Ethics Committee.

2.2. Equipment set-up

A start line was marked across one lane of an indoor running track so that the participants would land with their first ground contact on a 0.900 × 0.600 m force platform (9287BA, Kistler, Switzerland) sampling at 1000 Hz. The first stance phase was analysed because the magnitude and frequency of the ground reaction forces is lowest here[7], before increasing as a sprint progresses towards mid-acceleration[5] and then maximum velocity[6]. Any filtering artefact observed in the first stance phase would therefore likely still be evident, and potentially greater, during any of the subsequent steps of a maximal effort sprint. The force platform was covered with a fitted piece of synthetic track surface and was thus flush with the track. A high-speed digital video camera (Motion-Pro HS-1, Redlake, USA) sampling at 200 Hz was located 25 m away from the force platform, with its optical axis perpendicular to the direction of the running lane. Images were collected inside a 2.5 m field of view at a resolution of 1280 × 1024 pixels, and using a 1/1000 s shutter speed. The capture area was calibrated using four corner points of a rectangular frame (2.00 m horizontally × 1.60 m vertically). A series of LEDs were activated by the pressing of a custom trigger button and used to synchronise the video and force data to the nearest millisecond. This trigger also sent a signal to a sounder device to which the participants responded, representative of the auditory stimulus received in competition.

2.3. Data collection

Following a coach-directed warm up, each participant completed a series of five (A and B) or four (C) maximal effort sprints to 30 m. Each sprint commenced from starting blocks which were adjusted to the preference of each participant, who also wore their own spiked shoes. Each trial was initiated by an experienced starter who followed standard 'on your marks' and 'set' commands by pressing the custom trigger button to commence data

collection. Participants were allowed their normal recovery (approximately 8-10 minutes) after each trial to ensure subsequent performance was not affected by fatigue.

2.4. Data processing and analysis

The raw video files were imported into digitising software (Peak Motus® v. 8.5, Vicon, UK) and digitised with a resolution of measurement of just less than 1 mm. For each trial, five points (stance hip, knee, ankle and second metatarsal-phalangeal (MTP) joint centres, and distal hallux) were manually digitised from ten frames prior to touchdown until ten frames after toe-off. Projective scaling was then used to reconstruct raw displacement time-histories, and the raw force data were downsampled to 200 Hz to correspond to the kinematic data. These raw kinematic and kinetic data were then each passed through a 4th order zero-delay Butterworth digital filter[10] using four different cut-off frequencies (10, 25, 50 and 100 Hz). This yielded 10 combinations where the kinetic data cut-off frequency equalled or exceeded that of the kinematic input data, each of which is subsequently referred to in the format of VxFy where x and y represent the cut-off frequencies applied to the kinematic (video) and kinetic (force) data respectively (e.g. V25F100 represents video data filtered at 25 Hz and force data filtered at 100 Hz). Participant-specific segmental inertia data were calculated from 95 direct anthropometric measurements[14]. Each combination of kinematic and kinetic input data were then used with the inertia data in a standard two-dimensional IDA[10,15] to calculate the RJMs at the knee joint. A four-segment stance leg model which incorporated the MTP, ankle, knee and hip joints was used due to the importance of the MTP joint in sprinting[16]. The knee RJMs were time-normalised to 101 samples from touchdown to toe-off using an interpolating cubic spline, before mean ± standard deviation time-histories were calculated for each participant for each of the ten combinations of cut-off frequencies. Mean ± standard deviation peak impact (0-5% of

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stance) and active (20-100% of stance) RJMs from all individual trials for each participant were also determined for each of these combinations.

3. Results

The data from all combinations of cut-off frequencies clearly revealed an underlying trend for a knee extensor RJM which reached peak values just prior to mid stance (Figure 1). The ten different cut-off frequency combinations altered this mean peak active RJM by up to 49, 45 and 29 Nm for participants A, B and C, (up to 48%, 22% and 29% of the peak active RJMs), respectively. When the kinematic and kinetic input data cut-off frequencies were matched (from top left to bottom right of Figure 1; bold values in Table 1) there were only minor fluctuations away from the underlying rising extensor dominance in the RJM during early stance, and the frequency and magnitude of these fluctuations did not appear to exceed any of the fluctuations seen throughout the remainder of the stance phase. However, when the kinetic input data cut-off frequency was higher than that of the kinematic data, the magnitude of the peak impact moment during the first 5% of stance increased, and the increased magnitude of these impact moments was more marked as the kinetic cut-off frequency increased for any given kinematic cut-off frequency. Using participant A as an example, when the cut-off frequencies were matched, there were minimal or no extensor peaks in the RJM evident during the first 5% of stance (Figure 1 and Table 1), yet when the kinetic cut-off frequency increased above that of the kinematic input data, impact extensor moments were clearly apparent and reached a mean value of 446 Nm in the V10F100 condition. Although participant A showed the largest increases in impact moments as the kinetic cut-off frequency increased, the above impact moment trends were apparent for all three participants. When filtering the kinematic data at 10 Hz, as the kinetic input data cut-off frequency was altered from 10 Hz to 100 Hz the mean

peak impact RJM increased from 38 Nm to 139 Nm (266% increase) for participant B and from 23 Nm to 207 Nm (800% increase) for participant C). Furthermore, participants A and C both demonstrated fluctuations between extensor, flexor and returning to extensor dominance during the first 15% of stance when the cut-off frequencies were not matched. The most extreme example of this was in the V10F100 condition, where the knee RJM of participant A fluctuated from +376 Nm (extensor peak) to -206 Nm (flexor peak) and back to +90 Nm (extensor peak) in less than 33 ms. Participant B showed the same fluctuating pattern although the RJM never became flexor dominant.

4. Discussion

This study assessed the effects of different kinematic and kinetic cut-off frequencies on the determined knee RJM time-histories during gait, placed in the context of the first stance phase of a maximal effort sprint. It was found that the different filter combinations had a small effect on the peak active moment during mid-stance. The increases in the peak active RJM as the cut-off frequency magnitudes increased were due to the increasingly noisy nature of the entire RJM time-history since less of the noise in the kinematic input data was removed. However, the choice of cut-off frequency combinations had a considerable effect on the magnitude of the peak knee extensor RJM during the first 5% of stance. When the kinetic cut-off frequency matched that of the kinematic input data, these impact moments were either virtually non-existent (participant A) or small (participants B and C). However, as the kinetic cut-off frequency increased above that of the kinematic input data – as has typically been the case in sprinting IDA studies – the impact RJM increased up to magnitudes of 446, 139 and 207 Nm for participants A, B and C, respectively (in the V10F100 condition). For participants A and C, these values were more than double the peak active moment observed during mid-stance in the same condition.

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These impact RJMs were markedly greater than those observed when cut-off frequencies were matched (participant A seldom exhibited an extensor moment during the first 5% of stance, whilst participants B and C exhibited mean impact RJMs smaller than 53 Nm during the four matched cut-off frequency conditions).

These results can be explained by considering the calculations used in an IDA. As the frequency of the impact peak during running is related to the acceleration of the lower limb[17,18], filtering the kinematic input data at a lower cut-off frequency than the kinetic input data creates inconsistencies in the frequency content of these two data sets. The genuine high frequency segmental accelerations which corresponded to the high frequency GRFs in the kinetic data are removed from the kinematic input data. This means that when determining the internal joint forces in the most distal joint (using Newton's 2nd Law; ΣF = ma), a large peak in the calculated internal joint force is required to counter the inputted high frequency peak in the GRF data and thus make the sum of the forces proportional to the inputted (smoothed) acceleration of this distal segment. This spurious peak is then propagated up the leg as the calculations proceed to the more proximal joints and clearly affects the calculated knee RJM. Based on these results, the excessive fluctuations in knee RJM that have been previously reported during early stance in various phases of a sprint[1-7] are likely to be an exaggerated artefact introduced by filtering the kinematic input data at a considerably lower cut-off frequency than the kinetic input data.

Data for the current study were collected from the first stance phase of a sprint where, based on previous evidence[7], the magnitude of any peak GRFs soon after impact appear to be typically lower than steps during mid-acceleration[5] or maximum velocity[6]. Given that these peak impact GRFs appear to increase as a sprint progresses, and that the

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participant who experienced the largest impact GRFs in the current study (i.e. participant A; Figure 2) also experienced the largest increases in knee RJM as the IDA input data were filtered at increasingly mismatched cut-off frequencies, it can be expected that the effects of this filtering mismatch will be even more pronounced during later phases of a sprint. However, based on the aforementioned explanations for these exaggerated RJMs, it is also possible that these effects would exist to some extent during impacts in any form of gait. If the kinetic data are filtered at a higher cut-off frequency than the kinematic data, and the cut-off frequency applied to the kinematic data is lower than the highest frequencies found in the true kinematic signal, then excessive fluctuations in the RJM will be produced around impact.

Interestingly, for both participant A and participant C (who also exhibited relatively high impact GRF magnitudes; Figure 2), the knee RJMs calculated with mismatched cut-off frequencies often fluctuated rapidly between extensor, flexor and then extensor dominance within less than 33 ms after touchdown (Figure 1). However, although such rapid and excessive fluctuations in knee RJM have been readily reported, no clear physiological explanations have previously been offered for these fluctuations and we believe that they are more likely due to the data analysis procedures employed. Although the novel inclusion of the MTP joint in this study was different from previous IDAs in sprinting, the choice to include or exclude the MTP joint has no independent effect on any fluctuations soon after impact[16].

Whilst previous studies have identified similar phenomena in landings and cutting manoeuvres[12,13], these have only been investigated using one or two widely mismatched cut-off frequencies. The data presented in the current study extend these findings to the

analysis of gait, whilst further highlighting that even relatively small mismatches between the cut-off frequencies applied to the kinetic and kinematic data affect the calculated RJM at the knee joint, and that these effects are not necessarily dependent on the absolute values of the cut-off frequencies that are chosen. A clear example of this is evident when the kinetic input data were filtered with a cut-off frequency of 25 Hz; a relatively severe degree of filtering which largely attenuated the GRF impact peak. When the kinematic data were also filtered at 25 Hz (i.e. V25F25; Figure 1c), fluctuations in the RJM after impact were minimal. However, when the kinematic cut-off frequency was reduced to 10 Hz (i.e. V10F25, Figure 1b), despite the kinetic input data being identical to those used in the V25F25 example and thus lacking much of the true impact GRF peak, fluctuations in the knee RJM after impact again became apparent.

In summary, this study revealed that excessive fluctuations in the knee RJM during a ground contact phase are evident when the kinematic and kinetic input data to an IDA are filtered with mismatched cut-off frequencies. These occur due to the removal of genuine high frequency accelerations in the kinematic data which relate to the high frequency impact GRFs, thus meaning that spurious joint forces are introduced to the IDA to balance the equations of motion. The frequency of the GRFs is clearly the most important factor, and even when the ground reaction force impact peaks are relatively small in magnitude, as was the case for one of the participants in the current study, a mismatch in the cut-off frequencies used leads to exaggerated fluctuations in the knee RJM soon after impact. Applying identical cut-off frequencies to the kinematic and kinetic input data prevents the generation of these fluctuations. The ideal cut-off frequency is dependent on the quality of the kinematic input data and should be determined from these data, ideally being as high as possible without making the RJMs uninterpretable due to excessive noise. It is essential

that cut-off frequencies applied to kinematic and kinetic data are clearly stated, and care must be taken to ensure that processing undertaken in commercial software programmes at any stage of an IDA is fully understood and transparent. If variables are required from the GRF data in addition to those used as kinetic inputs for the IDA, it is recommended that these GRF data are filtered separately with a higher cut-off frequency to prevent unwanted attenuation.

Highlights

- Different inverse dynamics cut-off frequency combinations were investigated
- Mismatched cut-off frequencies create inconsistencies within the input data
- In sprinting, excessive knee moment fluctuations are due to mismatched filtering
- Matching kinematic and kinetic cut-off frequencies prevents calculation artefacts
- Filtering procedures must be clearly detailed in inverse dynamics analyses of gait

Conflict of interest statement

There are no conflicts of interest for any of the authors with regard to this work.

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Tables

Table 1. Peak impact and active extensor resultant joint moments (Nm) at the knee joint during the first stance phase of a sprint for all three participants (intra-participant mean ± standard deviation).

		V10		V25		V50		V100	
		Impact	Active	Impact	Active	Impact	Active	Impact	Active
Participant A	F10	**13 ± 35**	**54 ± 23**						
	F25	148 ± 36	66 ± 21	**n/a**	**67 ± 21**				
	F50	306 ± 60	76 ± 19	109 ± 43	78 ± 17	**n/a**	**90 ± 19**		
	F100	446 ± 114	89 ± 15	246 ± 98	89± 14	102 ± 88	99 ± 17	**13 ± 105**	**103 ± 22**
Participant B	F10	**38 ± 20**	**163 ± 20**						
	F25	73 ± 24	169 ± 19	**31 ± 9**	**173 ± 19**				
	F50	118 ± 42	172 ± 20	76 ± 29	176 ± 21	**43 ± 29**	**188 ± 14**		
	F100	139 ± 54	176 ± 21	97 ± 41	181 ± 20	65 ± 39	190 ± 12	**53 ± 64**	**208 ± 22**
Participant C	F10	**23 ± 3**	**72 ± 13**						
	F25	86 ± 8	73 ± 13	**4 ± 10**	**75 ± 14**				
	F50	164 ± 17	77 ± 13	84 ± 11	79 ± 15	**26 ± 22**	**86 ± 15**		
	F100	207 ± 20	81 ± 12	123 ± 15	83 ± 14	61 ± 23	89 ± 14	**52 ± 33**	**101 ± 14**

Note: V and F represent the kinematic (video) and kinetic (force) data, respectively, with the subsequent numbers representing the cut-off frequencies applied to the data (e.g. V25 represents kinematic (video) data filtered at 25 Hz).
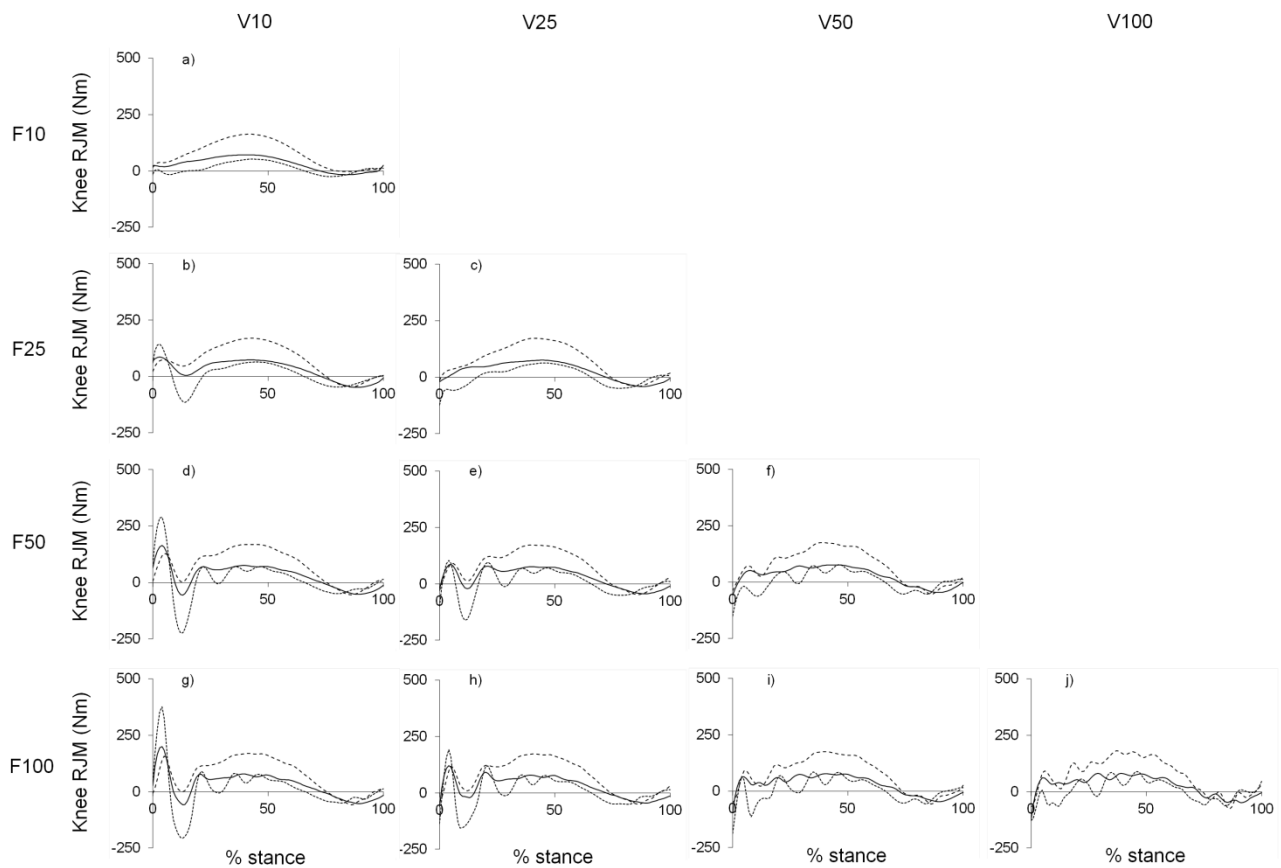
Figures 1a-j. Mean resultant knee joint moment time-histories for each of the three participants for all ten cut-off frequency combinations (participant A = dotted line, participant B = dashed line, participant C = solid line). Standard deviations are omitted for clarity purposes but are presented for selected discrete values in Table 1.
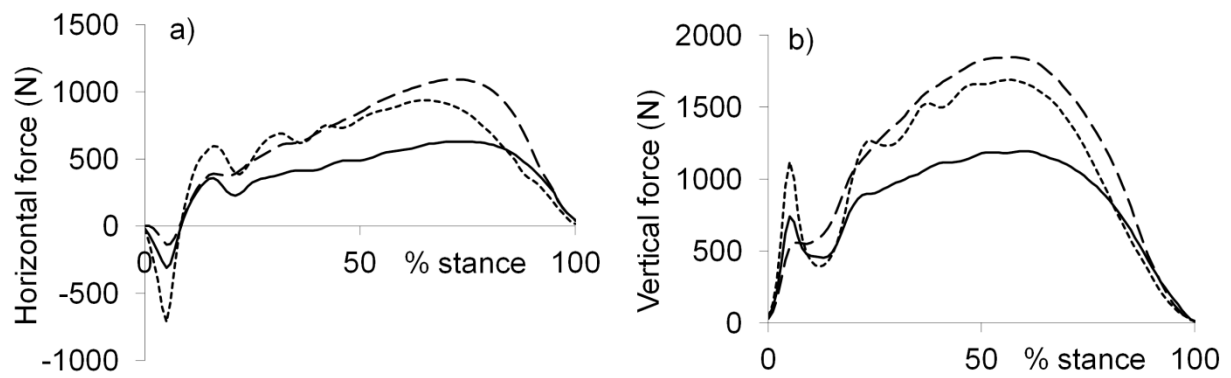
Figure 2. Mean raw a) horizontal and b) vertical ground reaction force time-histories for each of the three participants (participant A = dotted line, participant B = dashed line, participant C = solid line).