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Measurement procedures affect the interpretation of Metatarsophalangeal joint function during accelerated sprinting

MPJ function during sprinting

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Abstract

The metatarsophalangeal joint (MPJ) is a significant absorber of energy in sprinting. This study examined the influence of MPJ axis choice and filter cut-off frequency on kinetic variables describing MPJ function during accelerated sprinting. Eight trained sprinters performed maximal sprints along a runway. Three-dimensional high-speed (1000 Hz) kinematic and kinetic data were collected at the 20m point. Three axis definitions for the five MPJs were compared. MPJ moments, powers and energies were calculated using different filter cut-off frequencies. The more anatomically appropriate dual axis resulted in less energy absorbed at the MPJ compared to the oblique axis which also absorbed less energy compared to the perpendicular axis. Furthermore, a low cut-off frequency (8 Hz) substantially underestimated MPJ kinematics, kinetics and the energy absorbed at the joint and lowered the estimate of energy production during push-off. It is concluded that a better understanding of MPJ function during sprinting would be obtained by using an oblique or anatomically appropriate representation of the joint together with appropriate kinematic data sampling and filtering so that high frequency movement characteristics are retained.

Introduction

When calculating joint kinetics using inverse dynamics analysis inaccuracies may occur due to joint modelling simplifications, resulting in incorrect moment arms. For particularly rapid movements, higher frequency signals can be removed by the filtering process and original signal content can become distorted (Bisseling and Hof, 2006). Both of the above issues can influence the assessment of the joint moment. This paper addressed those two factors in relation to the calculation of joint kinetics of the metatarsophalangeal joint (MPJ) during sprinting. Stefanyshyn and Nigg (1997) highlighted the importance of MPJ motion to sprinting and found the MPJ to be a large dissipater of energy during the stance phase. This investigation explores whether inverse dynamics calculations based on previous simplifications of the MPJ joint axes and the filtering of the kinematic data can misrepresent the joint kinetic information during sprinting. Such information can be important for determining the propulsive function of the foot and the design of both sports and therapeutic footwear.

Stefanyshyn and Nigg (1997, 1998, 2000) considered the five metatarsophalangeal joints of the foot as a single joint rotating about an axis perpendicular to the sagittal plane and originating from the lateral fifth metatarsal head (MTH). This two dimensional (2D) approach simplifies the motion analysis of the MPJ and does not reflect the changing or oblique nature of the MPJ axis. The moment arms necessary for joint kinetic calculations will be influenced by the definition of the joint axis used by investigators. Assuming a perpendicular axis instead of an oblique axis will influence joint moments, powers and energies and therefore an understanding of the function and role of the MPJ during sprinting. Bosjen-Moller and Lamoreux (1979) highlighted that the MPJ has two axes about which push-off with the toes can be performed: an axis through the heads of the first and second metatarsals (MTH1 and MTH2) and an axis through heads of MTH2 and MTH5. They

considered that push-off performed about the axis of MTH1-2 to be more efficient at faster motions. De Cock et al. (2005) reported pressure profiles during barefoot jogging and during the last 55% of stance the forefoot started to push-off firstly over the lateral metatarsals followed by a more central push-off over the second metatarsal and finally over the hallux. For sprinting, a similar lateral to medial transition has been confirmed (Smith & Lake, 2010), with the centre of pressure more anterior to the metatarsal heads, adding support that a dual axis definition of the MPJ more closely represents what occurs in practice.

Kinetic calculations will be influenced by the filtering of the segmental displacement data (Bisseling & Hof, 2006). Studies that have documented foot motion in sprinting have commonly used kinematic sampling rates of 100-200 Hz and consequently filtered the displacement data with a cut-off frequency of 8-20 Hz (Stefanyshyn & Nigg, 1997, 1998; Krell & Stefanyshyn, 2006). These measurement procedures are typical of those found for slower activities such as walking and jogging; however it is unclear whether they can adequately capture the rapid motion of the foot during ground impact in high-speed activities such as sprinting. If high frequency components of the motion are present, then filtering the data with a low cut-off frequency distorts the original displacement curves and, subsequently, the movement transients (joint angular velocities and accelerations) would be greatly underestimated. There are clear indications that the signal being discarded by the low cut-off frequency, (such as peak angular displacement) is of interest. Consequently, high filter cut-off frequencies must be used otherwise calculations of joint kinetics during fast movement transients may be inaccurate (Bisseling & Hof, 2006).

The aim of this study was to investigate the influence of MPJ definition and typical measurement procedures on MPJ kinematics and kinetics. It was hypothesised that both the

more anatomically appropriate joint axis definition and more accurate motion transients would cause a substantial change in joint kinetics and hence the interpretation of MPJ function during sprinting.

Methods

The study comprised of two separate phases of testing, using eight participants in total. The first phase of testing (n=4) allowed the comparison of two different MPJ lines: an oblique axis to the sagittal plane defined by a straight line through MTH1 and MTH5, and an axis perpendicular to the sagittal plane based solely upon MTH5, replicating the 2D analysis used by Stefanyshyn and Nigg (1997) (see Figure 1). In addition, the effect of cut-off frequency (F_c) was investigated as it is known that this influences data for high speed actions like sprinting. The second phase of testing (n=4) extended the representation of the MPJ axis further by using a dual axis definition with one axis between MTH1 and MTH2 and a second axis between MTH2 and MTH5 (as suggested by Bosjen-Moller & Lamoreux, 1979).

In phase one, three female sprinters / hurdlers (aged 22.3 ± 3.7 years, height 166 ± 11.3 cm, mass 62.7 ± 4.6 kg and 100m best 12.4 ± 0.4 s) and one male decathlete (aged 27.7 years, height 180 cm, mass 82 kg and 100 m best 11.2 s) participated. In phase two, two female sprinters / combined eventers (aged 23.1 ± 6.1 years, height 170 ± 12.7 cm, mass 62 ± 5.6 kg, 100 m best 12.4 ± 0.4 s) and two male combined eventers (aged 20.5 ± 0.3 years, height 188.5 ± 0.7 cm, mass 80 ± 5.7 kg and 100 m best 11.4 ± 0.0 s) participated. Informed written consent was obtained from all participants in accordance with the University's Ethics Committee.

Four sprinting trials were collected on each sprinter, wearing their own sprint spikes. The sprints were performed on a 55 m indoor runway with an indoor synthetic track surface. They were instructed and encouraged to run maximally and a single left foot ground contact in the middle of a force platform (Kistler model 9287B) at 20 m was used for analysis. A customized starting mark was used to aid the athlete in striking the force plate without the need to alter their stride pattern prior to force plate contact. Timing gates were located 2.5 m either side of the force platform, therefore recording sprint times over 5 m as the athletes crossed the force platform. The athletes were still accelerating at this point. Kinematic data were collected using a 6 camera system (Pro-Reflex MCU 1000, Qualisys Inc., Sweden) sampling at 1000 Hz. Force data were also sampled at 1000 Hz. In order to avoid using correction algorithms, foot contacts towards the edges of the force plate were discounted due to the higher centre of pressure (CoP) inaccuracies around load cell locations (Kistler, 1993).

Data was processed using Visual3D (C-Motion, Inc). A three-segment foot model was used for the kinematic analysis with the forefoot segment defined similarly to Oleson et al. (2005). Eleven mm diameter reflective markers were placed on the medial and lateral malleoli (removed before the sprint trials), the posterior, medial and lateral heel, 1st and 5th metatarsal bases (used with MTH1 and MTH5 to define the midfoot) and the markers on the MTH1, MTH5 and on the head of the second toe at the distal end of the toe box defined the forefoot. Markers were placed on the sprint shoe on the side of the MTH joints. An additional MTH2 marker was placed on the sprint shoe, superior to the underlying landmark, however this was used as a tracking marker only. The focus of this study was to investigate only MPJ kinematics and kinetics, the other segments were not used in the investigation. As in Stefanyshyn & Nigg (1997), the inertial effect of the phalanges was considered to be negligible. The five metatarsophalangeal joints were considered as a single joint rotating

about an axis oblique to the sagittal plane defined by MTH1 and MTH5 markers (see Figure 1). The MPJ angle was defined as the angle between the forefoot and midfoot segments in relation to a standing calibration for a reference measurement. To compare the three dimensional modelling approach (oblique axis from MTH1 to MTH5) to the 2D approach used by Stefanyshyn and Nigg (1997, 1998, 2000), for the joint moment arm, the MPJ was also modelled using an axis perpendicular to the sagittal plane based upon MTH5 marker.

In the dual axis representation of the MPJ, during the second phase of testing, a virtual marker was used for MTH2, defined using a pointer in the standing trial and the MPJ was modelled using an axis between MTH1 and MTH2 and an axis between MTH2 and MTH5. Furthermore, in this second phase, holes were cut in the standard sprint shoes and MTH1, MTH2 and MTH5 markers were placed on the skin. The marker set and locations were identical to the first phase of testing, except for the use of the virtual marker for MTH2. CoP data from the force platform was used to define which of the two joint axes was being used (MTH1-2 or 2-5), When the medio-lateral coordinate of the CoP surpassed the medial-lateral coordinates of the MTH2, the joint axis was switched from MTH2-5 to MTH1-2, therefore if in-toeing or out-toeing of the foot on the force platform occurred this would not affect the choice of joint axes used.

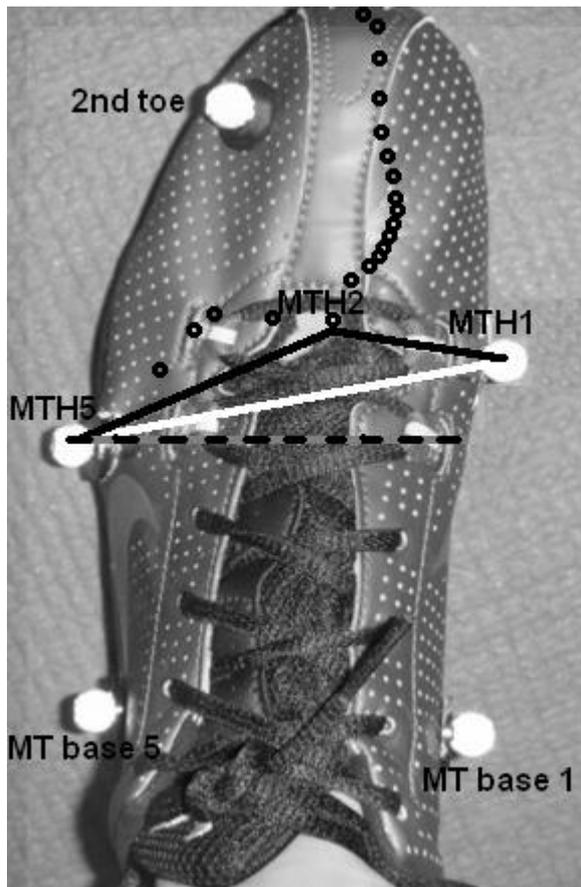


Figure 1. Image of the left foot demonstrating marker location and axes of the MPJ. The black line represents the dual axis representation through MTH1-2 and MTH2-5. The white line represents the oblique axis through MTH1-5 and the dashed line represents the 2D perpendicular axis based on MTH5. Typical centre of pressure position during the stance phase of sprinting is also demonstrated.

Joint positional and force data were smoothed using a fourth-order low pass Butterworth filter with a cut-off frequency (F_c) of 100 Hz. This F_c was chosen following visual inspection of the kinematic curves and from the calculation of the joint moments, powers and energies using a filter bank with F_c s of 50, 60, 70 and 100 Hz. A spectral analysis (FFT) was performed on one typical trial using 256 points, a spectral resolution of 3.96 Hz. This analysis of typical MPJ angular motion data revealed that signal power above 30 Hz and upto approximately 100 Hz was evident (Figure 2). Furthermore, high speed video observations demonstrated oscillations of the whole foot on landing, suggesting high frequency components of the signal (corresponding to frequencies between 70 and 100 Hz when

different F_c s were tested) were not due to movement artefact. Bisseling and Hof (2006) also highlighted the importance of using the same cut off frequency for both kinematic and kinetic data when investigating high speed movements / impacts.

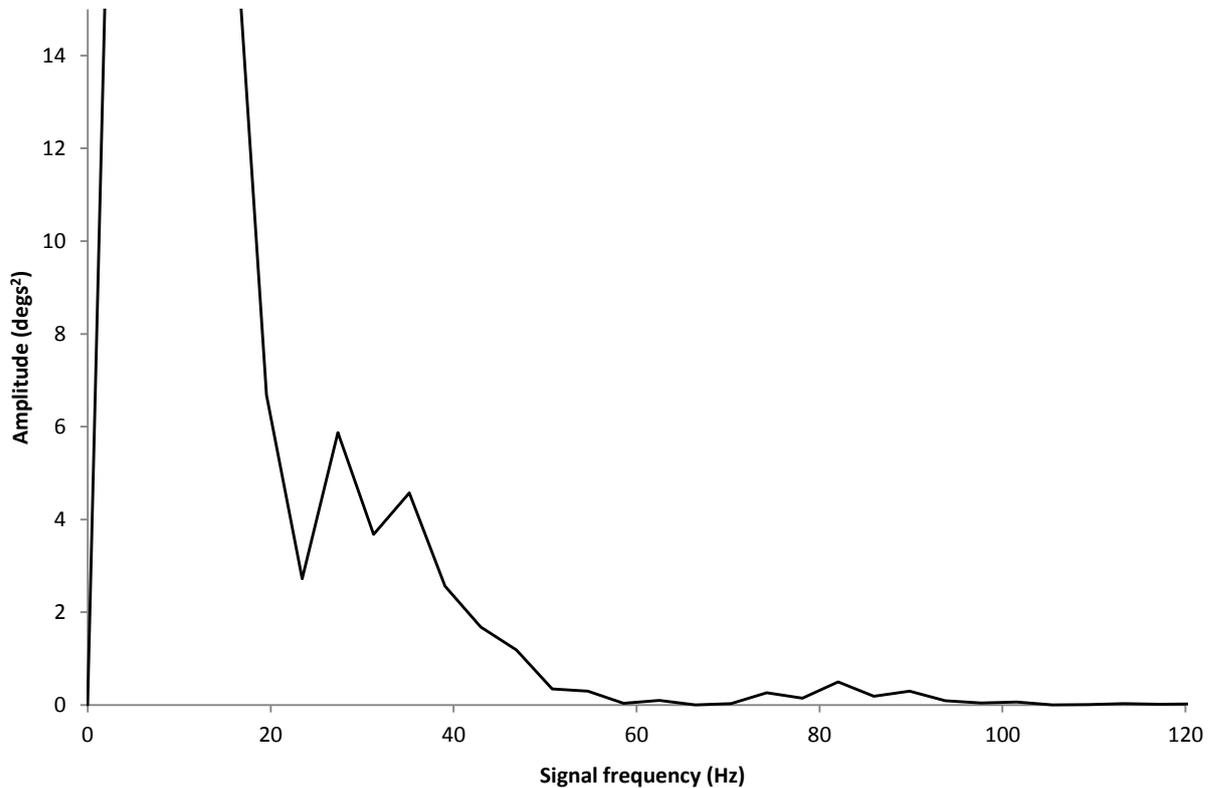


Figure 2. Spectral analysis of the MPJ angle for a typical shod trial.

To compare to typical processing procedures used by others, the positional data was also filtered using $F_c = 8$ Hz as this was used by Stefanyshyn and Nigg, (1997). In pilot work, data was also resampled to 200 Hz then filtered at $F_c = 8$ Hz, however, besides the number of data points, there was little difference in the resultant calculated joint moment curves from data sampled at 1000 Hz and filtered at $F_c = 8$ Hz, as it was the low cut off frequency that dramatically affected the shape of the calculated joint moments. The $F_c = 100$ Hz was retained for filtering force platform data.

To minimise errors in the CoP data and following visual inspection, CoP thresholds of 100 N and 50 N were used at the start and end of ground contact respectively. Beyond these thresholds the CoP was distorted and in a position outside of the forefoot, due to low loading on the force platform. The coordinates of the centre of force are typically inaccurate for small forces at the beginning and end of stance (Nigg, 2007). Joint moments, powers and energies were calculated according to Winter (1983). The two dimensional analysis assumed the resultant forces and moments at the MPJ were zero until the GRF acted distal to the joint and that the inertial effect of the phalanges was negligible (Stefanyshyn & Nigg, 1997). MPJ plantarflexor moments (defined as positive) therefore resulted from the ground reaction forces acting distally to the MPJ line, with the horizontal (X) moment arm calculated as the perpendicular distance from the x and y CoP coordinates to the MPJ line, a straight line through the x and y coordinates of MTH1 and MTH5 for the oblique axis definition, and two straight lines through the x and y coordinates of MTH1, MTH2 and MTH5 for the dual axis definition. Where data was normally distributed, paired samples t-tests were performed to compare mean differences in MPJ kinematic and kinetic variables between different MPJ representations and processing approaches. 7 out of 40 conditions analysed were not normally distributed, therefore Wilcoxon non-parametric tests were performed. For both the level of significance was set at $\alpha = 0.05$.

Results

The mean sprinting speeds in testing phase 1 were 7.2 ± 0.3 m/s for the three female sprinters and 8.5 ± 0.1 m/s for the male. In phase 2 mean speeds were 7.2 ± 0.1 m/s for the two

females and 8.6 ± 0.1 m/s for the two males. These sprinting speeds were similar to those recorded by Stefanyshyn and Nigg (1997) at 15 m which ranged from 7.1 to 8.4 m/s.

The motion of the MPJ during ground contact was as follows. Initial foot contact is executed with the forefoot. Immediately after touchdown the heel is lowered towards the floor and the MPJ plantarflexes typically during the first 40 ms of stance (plantarflexion phase). From 40 ms to 110 ms the heel rapidly rises and the MPJ dorsiflexes (dorsiflexion phase). Finally, the MPJ plantarflexes during the last 10 ms of stance (push off phase) as the foot pushes off, however plantarflexion continues after take-off. Mean MPJ resultant kinetics for the $F_c = 100$ Hz condition are given in Table 1. For all four subjects power was produced shortly after touchdown, during the landing phase (190.6 ± 66.1 W) and during the final push-off phase (111.8 ± 45.9 W). However, overall the MPJ was an energy absorber (-22.9 ± 8.3 J) and little energy was generated during the push-off phase (0.4 ± 0.4 J) for all sprinters.

The perpendicular axis definition resulted in greater values (approximately between 2 and 4 times higher) for all joint kinetic variables. An example is illustrated in Figure 3. The higher moment and power for the perpendicular axis was due to an increased moment arm of the ground reaction force about the MPJ. For the four subjects, resultant joint moments were higher by on average 47.7 N·m (± 21.2 N·m) and energy absorption was higher by on average 12.4 J (± 8.0 J) for the perpendicular compared to the oblique joint axis (both filtered at 8 Hz). All joint kinetic data presented in Table 1 were significantly greater when using a perpendicular axis definition, in comparison to an oblique axis definition, with the exception of energy generated during push-off, which was minimal.

Table I. Mean ($\pm s$) MPJ moment, power and energy for four participants (Phase 1). Comparison of $F_c = 100$ Hz and $F_c = 8$ Hz using the oblique and 2D perpendicular axis definitions as described in the text. MPJ plantarflexion, dorsiflexion and push-off phases are defined in Figure 3.

Joint axis F_c	Oblique MTH1-5 100 Hz	Oblique MTH1-5 8 Hz	2D MTH5 100 Hz	2D MTH5 8 Hz
Peak MPJ plantar flexor moment (N · m)	58.2 (\pm 11.1)	58.9 (\pm 11.4)	110.7 (\pm 18.7)*	106.7 (\pm 21.5)*
Peak Positive Power (W) generated during MPJ plantarflexion	190.6 (\pm 66.1)	59.0 (\pm 28.2)	629.6(\pm 301.0)*	182.7(\pm 143.0)*
Peak Negative Power (W) generated during MPJ dorsiflexion	-758.3 (\pm 295.1)	-348.3 (\pm 177.2)	-1391.0 (\pm 808.9)*	-638.9 (\pm 364.3)*
Total Energy generated (J) during MPJ plantarflexion	2.6 (\pm 1.4)	1.0 (\pm 0.8)	9.0 (\pm 6.1)*	5.0 (\pm 4.7)*
Total Energy absorbed (J) during MPJ dorsiflexion	-22.9 (\pm 8.3)	-14.0 (\pm 6.8)	-43.0 (\pm 20.2)*	-26.4 (\pm 14.7)*
Total energy generated (J) during push-off	0.4 (\pm 0.4)	0.0 (\pm 0.1)	0.5 (\pm 0.5)	0.0 (\pm 0.1)

*denotes a significant difference ($P < 0.05$) between the 2D axis definition, in comparison to the oblique axis definition using the same F_c .

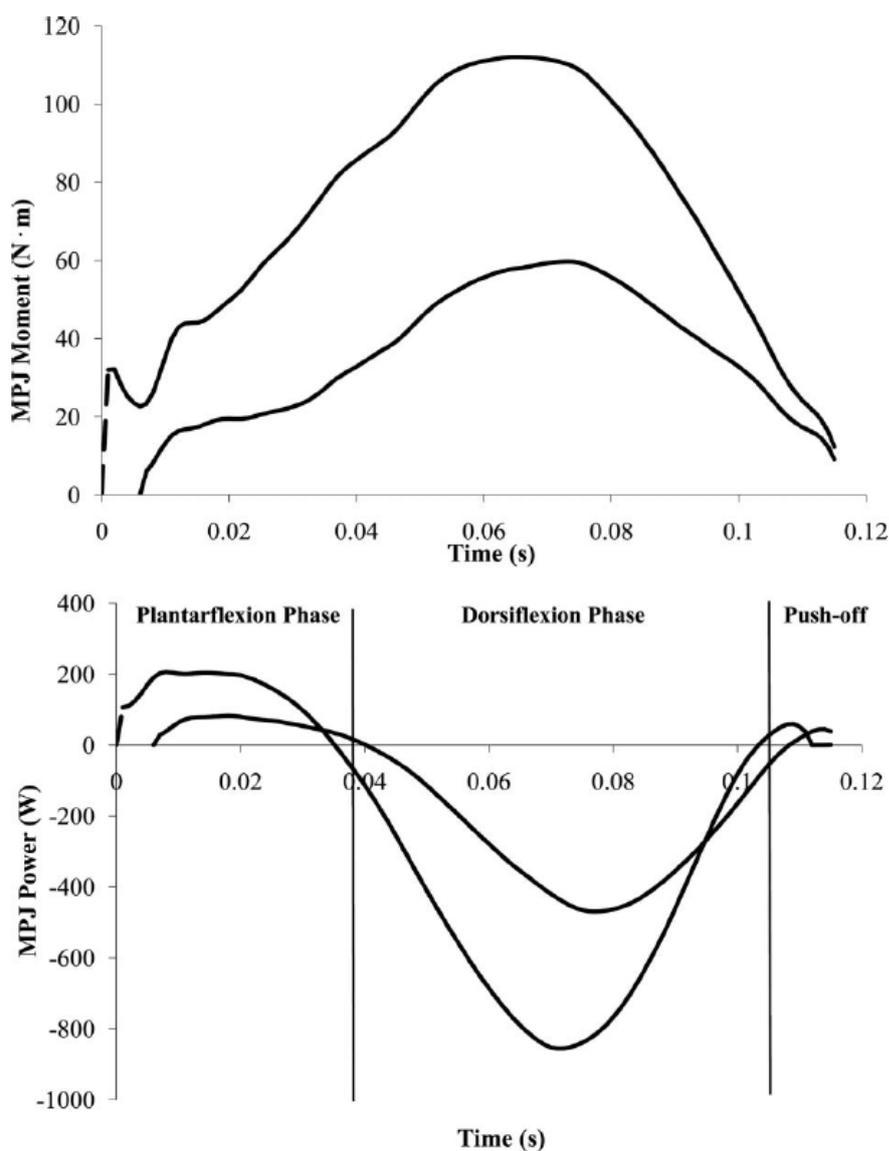


Figure 3. MPJ moment (upper graph) and power (lower graph) using two definitions of the MPJ axis for one typical trial. Solid curve represents the oblique axis; the dashed line represents the 2D axis. Positional data filtered at $F_c = 8$ Hz.

The MPJ kinetics were also calculated for a dual axis for four subjects in the second phase of testing. Three subjects only used axis MTH1-2 as the centre of pressure was medial of the MTH2 marker during stance as the first few frames were removed due to the threshold for accuracy of the CoP. Overall, the mean joint moment, energy absorbed and energy generated, both during MPJ plantarflexion and push-off were significantly higher relative to the oblique axis than the dual axis (Table 2). This was due to the larger moment arm for the oblique axis during push off.

Table II. Mean ($\pm s$) MPJ moment and energy for second set of participants ($n = 4$). Comparison of oblique joint axis to dual MPJ axis, data filtered using $F_c = 100$ Hz.

	Oblique axis joint definition MTH1-5	Dual axis joint definition MTH 1-2 and MTH 2-5
Peak MPJ plantar flexor moment (N · m)	65.3 (\pm 12.1)	47.3 (\pm 7.4)*
Total Energy generated (J) during MPJ plantarflexion	1.3 (\pm 1.9)	0.5 (\pm 0.9)*
Total Energy absorbed (J) during MPJ dorsiflexion	-30.2 (\pm 7.7)	-22.7 (\pm 5.2)*
Total energy generated (J) during push-off	1.3 (\pm 0.2)	1.0 (\pm 0.2)*

*denotes a significant difference ($P < 0.05$) between the dual and oblique axis definitions.

Table III. The effect of cut-off frequency on MPJ kinematics ($n = 4$).

Joint axis Kinematics F_c	Oblique MTH1-5 100 Hz	Oblique MTH1-5 8 Hz
MPJ Range of motion	36.3 (\pm 5.1)	21.5 (\pm 3.8)*
MPJ peak doriflexion velocity (rad s ⁻¹)	-1144.9 (\pm -707.7)	-438.6 (\pm 183.6)*

*denotes a significant difference ($P < 0.05$) between the $F_c = 100$ Hz and $F_c = 8$ Hz.

With regard to cut-off frequency, $F_c = 8$ Hz (Table 3) significantly underestimated both MPJ angular range of motion and angular velocity compared to $F_c = 100$ Hz. MPJ angular range of motion throughout stance was underestimated by approximately 15 degrees. Figure 4 clearly demonstrates the extent and rate of the MPJ dorsiflexion underestimation using $F_c = 8$ Hz. The $F_c = 100$ Hz data shows dorsiflexion of the MP joint at impact, followed by rapid plantarflexion with damping oscillation which was not present with the $F_c = 8$ Hz. Rapid MPJ motion and power production just after touchdown, were not present with the $F_c = 8$ Hz (Figure 3). Overall, energy absorption at the MPJ was underestimated by approximately 40% when smoothing at 8 Hz compared to 100 Hz (Table 1). A small amount of energy generated during push-off was only revealed when high frequency angular motion was included in the analysis (using the higher filter cut-off frequency).

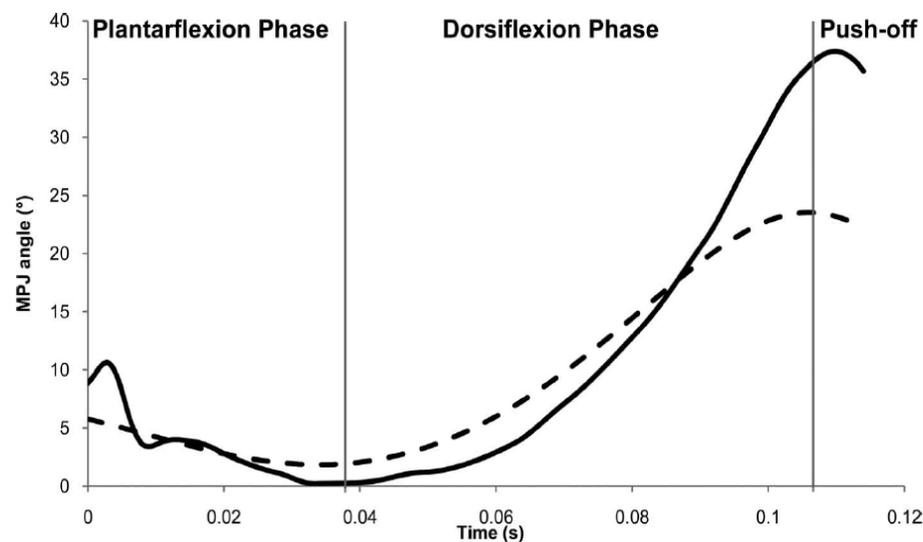


Figure 4. MPJ angle for one typical sprint trial, positional data filtered at two different cut-off frequencies: $F_c = 100$ Hz (black line) and $F_c = 8$ Hz (dashed line).

Discussion

This study has highlighted that the procedures for processing MPJ data affect the resulting joint kinetics for the foot during a high-speed activity like sprinting. Results demonstrate that using a 2D perpendicular (to the sagittal plane) joint axis, based only on a single lateral marker, MPJ kinetics were substantially overestimated compared to other axes definitions. As the MPJ axis definition progressed towards one which was more anatomically appropriate (oblique then dual axis approaches) the kinetic variables further decreased due to smaller moment arms about the joint. This suggests that previous researchers have oversimplified the modelling of the MPJ. Furthermore, typical sampling and filtering procedures underestimate MPJ motion and suppress high frequency transients. This study has demonstrated methodological considerations that warrant attention by researchers when investigating the function of the foot during high speed activities.

Pressure results from Smith and Lake (2010) demonstrated that after approximately 20% stance during sprinting, the lateral side of the forefoot became almost unloaded and the pressure was centred on the medial side of the foot, where push-off onto the toes also occurred. This was also true for the subjects in this study. This suggests that defining the orientation of the MPJ line using solely a lateral marker on MTH5 is too simple a model, as the function of the lateral foot is different to that of the medial foot during sprinting.

The primary aim of the study was to demonstrate the effect of different joint axis definitions on resultant MPJ kinetics. Modelling the joint using a perpendicular axis increased the distance from the MPJ axis to the centre of pressure and overestimated joint kinetics. Peak MPJ moment increased by approximately 86% compared to the oblique joint axis which

resulted in a shorter moment arm. The extent of the difference did depend on the anatomy; however the resultant moments and kinetics were substantially increased when using a perpendicular axis based on the lateral marker, not an oblique axis as suggested in this study. If a 2D perpendicular analysis based upon a single marker is to be used, it is recommended that a marker on MTH2 may provide more accurate moment arms than a marker on the MTH5.

Bosjen-Moller (1978) stated that the MPJ has a transverse axis through MTH1–2 and an oblique axis through MTH2-5. Comparing the resultant joint kinetics from the oblique axis to the dual axis, the peak joint moment and total energy absorbed during stance both differed on average by 38%. Overall, the moment arm had a great effect on the resultant MPJ kinetics and this was dependant on the joint axis definition. Although, with current technology, there is no way of calculating completely accurate joint moment arms, the perpendicular 2D approach severely overestimated the MPJ moment and the oblique axis also resulted in higher values than the dual axis.

High cut-off frequencies for processing both position data and ground reaction force data result in better assessment of joint moments during fast transients like the impact phase (Bisseling & Hof, 2006). It has been demonstrated that using a low cut-off frequency not only distorts vital data after landing but also severely underestimates the rate of peak dorsiflexion of the joint, evident in the severe underestimation of the MPJ power. Smith and Lake (2007) found significant signal power in MPJ motion data above 30 Hz. Power production during push-off was only evident when high frequency movement characteristics were retained which is particularly important as generating power has potential performance implications. However, despite the inclusion of high frequency components improving estimates of MPJ

energetics, the MPJ mainly acted as an energy dissipater throughout stance. This agrees with the notion of the need to reduce energy loss in order to improve running / sprinting performance (Nigg & Segesser, 1992; Stefanyshyn & Nigg, 2000).

In conclusion, this study has demonstrated that MPJ kinetics are sensitive to errors in both the modelling of the MPJ line and the processing of the kinematic and ground reaction force data. As previous modelling definitions overestimate joint moments and powers and current processing approaches exclude high frequency components and underestimate peak powers absorbed in stance and produced during push-off, these errors are counteractive in the kinetic calculations. However, the underestimation due to the exclusion of high frequency components did not fully compensate for the overestimation due to axis definition, highlighting the importance of the modelling approach on the resultant kinetics. In order to have confidence in moment arm lengths and joint moments, the researcher should be aware that appropriate joint axis definitions should be used, with at least representing the MPJ axis as an oblique axis from MTH1 to MTH5.

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