Title:

Lower limb joint kinetics during the first stance phase in athletics sprinting: three elite athlete case-studies

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Abstract:

This study analysed the first stance phase joint kinetics of three elite sprinters to improve the understanding of technique and investigate how individual differences in technique could influence the resulting levels of performance. Force (1000 Hz) and video (200 Hz) data were collected and resultant moments, power and work at the stance leg metatarsal-phalangeal, ankle, knee and hip joints were calculated. The metatarsal-phalangeal and ankle joints both exhibited resultant plantarflexor moments throughout stance. Whilst the ankle joint generated up to four times more energy than it absorbed, the metatarsal-phalangeal joint was primarily an energy absorber. Knee extensor resultant moments and power were produced throughout the majority of stance, and the best performing sprinter generated double and four-times the amount of knee joint energy compared to the other two sprinters. The hip joint extended throughout stance. Positive hip extensor energy was generated during early stance before energy was absorbed at the hip as the resultant moment became flexor dominant towards toe-off. The generation of energy at the ankle appears to be of greater importance than in later phases of a sprint, whilst knee joint energy generation may be vital for early acceleration and is potentially facilitated by favourable kinematics at touchdown.

Introduction

Athletes must accelerate from a stationary starting position in all athletics sprint events. It has been demonstrated that exerting as much power as possible from the very start of a sprint, thus reducing the amount of time spent at sub-maximal velocities early in the race, is the most favourable strategy for improved overall sprint performance (de Koning, de Groot, & van Ingen Schenau, 1992; van Ingen Schenau, de Koning, & de Groot, 1994; van Ingen Schenau, Jacobs, & de Koning, 1991). The start of a sprint is therefore a critically important element of overall performance, and having left the blocks the first stance phase on the track is the ground contact where the greatest increase in velocity of any stance phase in a sprint is achieved (Salo, Keränen, & Viitasalo, 2005). Due to the importance of this first stance phase, several previous studies have detailed the external kinetic and associated linear kinematic centre of mass (CM) data from the first stance phase of a sprint (e.g. Mero, 1988; Mero, Luhtanen, & Komi, 1983; Salo et al., 2005; Slawinski et al., 2010). Results have shown that higher-performing sprinters produce greater rates of external force development, resulting in larger net propulsive impulses and thus higher velocities and greater displacements of the CM than their less well-trained counterparts during the first stance phase. However, despite the relatively widespread evidence detailing these CM translations, there is only a limited understanding of the techniques used to achieve them.

To investigate sprint technique in specific detail, stance phase joint kinetics have previously been reported from groups of sprinters at different distances, from the second step to the maximum velocity phase (e.g. Bezodis, Kerwin, & Salo, 2008; Brüggemann, Arampatzis, Emrich, & Potthast, 2008; Burkett, McNamee, & Potthast, 2011; Hunter, Marshall, & McNair, 2004; Jacobs & van Ingen Schenau, 1992; Johnson & Buckley, 2001; Mann, 1981; Mann & Sprague, 1980). The first stance phase joint kinetics of a single sprinter were recently described by Charalambous, Irwin, Bezodis and Kerwin (2012) who observed phases of ankle joint dorsiflexion then plantarflexion and a resultant ankle joint moment which was plantarflexor dominant throughout stance. The kinetics of the metatarsal-phalangeal (MTP)

joint were not investigated but may be of interest due to previous evidence of MTP involvement in sprinting (Bezodis, Salo, & Trewartha, 2012; Smith, Lake, Lees, & Worsfold, 2012; Stefanyshyn & Nigg, 1997). Charalambous et al. (2012) also observed hip extension throughout stance with the resultant joint moment becoming flexor-dominant towards the end of stance. Whilst these general ankle and hip mechanical patterns are similar to previous studies from later phases of a sprint, the knee joint results presented by Charalambous et al. (2012) did not show the flexion during early stance that has been previously observed in some sprinters at 16 m (Johnson & Buckley, 2001) and all of those studied at 45 m (Bezodis et al., 2008). However, with the technique of only a single internationally-competitive sprinter studied during the first stance phase, it remains unclear whether the above joint kinetics represent a general pattern for elite sprinters. Furthermore, joint kinetics previously reported from later phases of a sprint show some variation within the groups of sprinters studied (e.g. Bezodis et al., 2008; Johnson & Buckley, 2001), suggesting that between-sprinter differences exist. Although these differences in technique may be relatively minor, they are important to consider in the context of elite sprinting due to the fact that even slight improvements in performance could give an athlete a competitive edge and affect finishing position within a race. The aim of this study was therefore two-fold; firstly, to analyse and understand the common joint kinetics of three elite sprinters during the first stance phase of a sprint, and secondly, to identify differences in the joint kinetics between these elite sprinters and therefore gain a better understanding of the differences in their performance during this important phase of the start.

Methods

Three internationally-competitive sprinters (A: male, 21 years, 82.6 kg, 1.81 m, 100 m personal best (PB) of 10.14 s; B: 20 years, 86.9 kg, 1.78 m, 100 m PB of 10.28 s; C: female, 26 years, 60.5 kg, 1.76 m, 100 m hurdle PB of 12.72 s) provided written informed consent to participate in this study which had received local research ethics committee approval. All of the sprinters had reached the final of European or World Indoor Championships less than

two years prior to this study. The cohort contained sprinters of both sexes to provide wider potential applications as performance can be considered as a physical characteristic rather than a sex-dependent issue. Each sprinter completed a series of five (A and B) or four (C) maximal effort 30 m sprints from their chosen starting block settings on an indoor track. These sprints were completed as a normal part of their training just prior to the competition phase of the indoor season. All sprints were initiated by an experienced starter who provided standard starting commands before pressing a trigger button which provided an auditory stimulus for the sprinters to start. After each trial, sprinters were allowed their normal recovery (about 8-10 minutes) in order to facilitate performance without the effects of fatigue.

The blocks were located so that the first stance phase after block exit would occur near the centre of a force platform (9287BA, Kistler, Switzerland) operating at 1000 Hz and covered with a standard artificial track surface to be flush with the remainder of the track. A high-speed video camera (Motion-Pro HS-1, Redlake, USA) operating at 200 Hz was located perpendicular to the direction of the running lane, 0.95 m in front of the start line and 25 m from the lane centre. An area of 2.00 m horizontally × 1.60 m vertically was calibrated using a rectangular calibration frame positioned inside a field of view 2.50 m wide. The camera collected images at a resolution of 1280 × 1024 pixels with a 1/1000 s shutter speed. A second high-speed video camera (Motion-Pro HS-1, Redlake, USA) was set exactly as above aside from being 0.25 m ahead the start line. This camera was only used for determining CM velocity at the onset of the first stance phase. The video and force data were synchronised to the nearest millisecond with the aforementioned trigger button which sent signals to the force platform and a series of 20 LEDs illuminating at 1 ms intervals in the view of the camera.

Touchdown and toe-off were identified from the raw force data using a threshold of 2 standard deviations above the zero load force platform data. Twenty specific anatomical points (vertex and C7, bilateral shoulder, elbow, wrist, hip, knee, ankle and second MTP joint

centres, fingertips and distal toes) were then manually digitised (Peak Motus® v. 8.5, Vicon, UK) from 10 frames prior to touchdown until 10 frames after toe-off. All subsequent data analysis was undertaken using custom-developed scripts in Matlab™ (v. 7.4.0, The MathWorks™, USA). Where the hand left the field of view during the last few of the 10 frames after toe-off in some of the trials, these trajectories were padded via reflection prior to filtering in order to reduce the effects of any endpoint error (Smith, 1989). The raw co-ordinates were scaled (using projective scaling based on the four corner points of the calibration frame) and the resulting joint centre displacement data were digitally filtered using a fourth-order Butterworth digital filter with a cut-off frequency of 24 Hz (selected as the mean value from residual analyses of all stance leg joint centre trajectories from all trials). These filtered displacement data were then combined with individual specific segmental inertia data calculated from 95 direct anthropometric measurements (Yeadon, 1990) taken on each sprinter by an experienced researcher to create a 16 segment model (head, trunk, upper arms, lower arms, hands, thighs, shanks, rearfeet, forefeet). To account for the mass of the spiked shoes, 0.20 kg was added to the mass of each foot (e.g. Hunter et al., 2004). The division of spike mass between the two foot segments was determined directly from the ratio of forefoot:rearfoot length, assuming an equal division of mass across the length of the spike. The whole body CM displacement time-history was consequently calculated from the segmental data using a summation of segmental moments approach. Where required, the linear and angular displacement time-histories were subjected to second central difference calculations (Miller & Nelson, 1973) in order to derive their corresponding velocity and acceleration time-histories. Extension at the hip and knee joints, and plantarflexion at the ankle and MTP joints, were defined as positive.

Two approaches to filtering the force data were adopted (Bezodis, Salo, & Trewartha, 2013). A cut-off frequency of 150 Hz was used when determining discrete force values and average horizontal external power. This power value was used as the measure of first stance phase performance due to the aforementioned importance of the production of maximal external

power from the very start of a sprint for optimum overall sprint performance (de Koning et al. 1992; van Ingen Schenau et al. 1991; 1994). Average horizontal external power incorporates both the change in velocity and the time taken for these changes into a single objective measure and is quantified based on the rate of change in kinetic energy of the CM in a horizontal direction (Bezodis, Salo, & Trewartha, 2010). The initial velocity used in this calculation was determined from the second high-speed camera using the procedures described by Bezodis et al. (2010). Quantifying average horizontal external power during just the first stance phase therefore provides a performance measure that is directly relevant to the analysed technique. For the kinetic inputs to the inverse dynamics analysis, the force platform data were downsampled to the sampling rate of the kinematic data (200 Hz), and filtered with a cut-off frequency of 24 Hz to prevent the generation of artefacts soon after impact (Bezodis et al., 2013; Bisseling & Hof, 2006; Kristianslund, Krosshaug, & van den Bogert, 2012). Using these filtered kinematic and kinetic data in combination with the individual-specific segmental inertia data, a 2D inverse dynamics analysis was undertaken (Elftman, 1939; Winter, 2005). Resultant joint moments were calculated about the stance leg MTP, ankle, knee and hip joints. Joint powers were then calculated as the product of the resultant joint moment and joint angular velocity, and phases of positive and negative power at each joint were identified. To quantify energy absorption and generation, joint work was calculated as the time-integral (trapezium rule) of each major positive and negative phase of the joint power time-histories (see Figures 1 to 4 for illustrations of these power phases). To facilitate comparisons between the sprinters, data were normalised to dimensionless numbers according to the convention of Hof (1996), with the power normalisation adjusted as outlined by Bezodis et al. (2010). Specifically, angular velocity data were divided by (gravity / leg length)$^{1/2}$, force data were divided by weight, moment and work data were divided by (weight × leg length), and power data were divided by (body mass × gravity$^{3/2}$ × leg length$^{1/2}$). Individual mean time-histories were presented to address the first part of the aim and understand common joint kinetic patterns. To address the second aim of this study and quantitatively identify any between-sprinter differences, confidence intervals (95%) for

discrete joint kinetic variables were calculated using the appropriate critical values of t at the two-tailed level for each of the three sprinters (Thomas & Nelson, 2001). Due to these confidence intervals representing the likely range of the true value, between-sprinter differences were identified where confidence limits did not overlap.

Results

Sprinter B exhibited the highest normalised average horizontal external power (a measure of first stance phase performance) of 1.030 ± 0.038 (mean $\pm$ 95% confidence interval; sprinter A = 0.833 ± 0.070, sprinter C = 0.790 ± 0.035; Table 1). All three sprinters exhibited a braking phase of no more than 0.017 s during which sprinter B exhibited the lowest braking forces. This was followed by a propulsive phase which always lasted for at least 90% of stance, and during which sprinter B exhibited the greatest propulsive forces (Table 1).

****Table 1 near here****

The joint angle, angular velocity, resultant moments and powers at each of the four leg joints during stance are presented in Figures 1 to 4. Both the MTP and ankle joints exhibited resultant plantarflexor moments throughout stance (Figures 1c and 2c). The ankle showed a clear pattern of dorsiflexion then plantarflexion (Figures 2a and 2b), and thus phases of energy absorption (A1) then generation (A2; Figure 2d) with sprinter B generating more energy than sprinters A and C during phase A2 (Table 1). At the MTP joint, there were fluctuations in joint power during the first half of stance, then a phase of energy absorption as the joint dorsiflexed from around mid-stance (M1) before a phase of energy generation as the joint plantarflexed towards toe-off (M2; Figure 1d). The knee and hip joints extended from touchdown throughout the majority of stance (Figures 3a and 4a) and in several trials began to flex just before toe-off. Sprinters A and C exhibited a consistent knee flexor resultant moment at touchdown and thus an initial phase of energy absorption (K1). Knee joint moments became extensor dominant and energy was thus generated (K2) until late

stance where energy was absorbed (K3; Figures 3c and 3d). Sprinter B exhibited resultant knee extensor moments and energy generation from touchdown and generated 363% and 188% of the normalised energy at the knee joint that sprinters A and C produced during phase K2, respectively (Table 1). At the hip joint, large resultant extensor moments were evident at touchdown before these gradually reduced and became flexor dominant later in stance (Figure 4c). The hip joint therefore generated energy during early stance (H1) and absorbed it during late stance (H2; Figure 4d).

****Figures 1-4 near here****

Discussion

The results of this study demonstrated a common joint kinetic pattern during the first stance phase of a maximal effort sprint in three elite sprinters. The similarities in joint kinetics between these three sprinters and with the single internationally-competitive sprinter previously analysed by Charalambous et al. (2012) yield confidence in the application of these data to understanding elite athletes' first stance phase performance. Additionally, some differences were identified between the three sprinters in the current study, and these can be explored to understand how they may relate to the performance differences in this first stance phase.

The existence of a resultant plantarflexor MTP moment throughout stance (Figure 1c) concurs with previously recorded MTP joint moments in sprinting (Smith et al., 2012; Stefanyshyn & Nigg, 1997). These moments, and in particular the energy absorbed by the MTP joint during mid-late stance (phase M1), reiterate the importance of considering the MTP joint in kinetic analyses of sprinting as highlighted by Bezodis et al. (2012). When comparing sprinters, Sprinter B generated a higher normalised MTP plantarflexor moment than sprinters A and C (Table 1). This may be an important factor in his higher level of sprint performance as it has been suggested by Goldmann and Brüggemann (2012) and

Goldmann, Sanno, Willwacher, Heinrich and Brüggemann (2013) that toe flexor muscles are important contributors to movements where an individual is in a forward leaning position (as is the case during early acceleration) and strength training of these muscles can improve performance in tasks which require a forward lean (i.e. horizontal jumping; Goldmann et al., 2013). It is also possible that a greater contribution from the biarticular toe flexor muscles (flexor digitorum longus and flexor hallucis longus) could consequently have allowed Sprinter B to generate greater positive plantarflexor energy at the ankle joint than sprinters A and C (Table 1). These muscles also help to reduce ankle dorsiflexion during running (Mann & Hagy, 1979), and previous research has shown that stiffening the shoe around the MTP joint can significantly increase the resultant plantarflexor ankle joint moment (Roy & Stefanyshyn, 2006). It must be acknowledged that the specific components of the resultant plantarflexor MTP joint moments cannot be identified using the current inverse dynamics analysis. Whilst greater resultant plantarflexor MTP joint moments could be due to the toe flexor muscles, they may also be due to passive biological structures (e.g. plantar fascia) or a non-biological component such as the stiffness of the spiked shoes (Stefanyshyn & Fusco, 2004; Toon, Vinet, Pain, & Caine, 2011; Willwacher, König, Potthast, & Brüggemann, in press).

Whilst the ankle joint kinetics were broadly similar to other phases of a sprint in terms of a resultant plantarflexor moment being evident throughout stance and phases of energy absorption followed by generation (Figures 2c and 2d), closer consideration of the joint work data highlights some important differences. Energy was generated at the ankle from around mid-stance onwards (phase A2), and sprinters A, B and C generated more energy at the ankle than they absorbed (phase A1) by a factor of 3.4, 3.3 and 4.0, respectively (Table 1 and Figure 2d). Johnson and Buckley (2001) previously presented ankle joint power time-histories from the 16 m mark which showed energy absorption of similar magnitude to the subsequent energy generation (i.e. a factor of 1.0), whilst at maximum velocity Bezodis et al. (2008) found the amount of energy absorbed exceeded that generated (whole group mean factor = 0.6). It therefore appears that the net energy generated at the ankle joint gradually

decreases from a large positive value to a negative value as a sprint progresses. Combined with the fact that sprinter B generated more ankle joint energy in phase A2 than sprinters A and C, an ability to generate ankle joint energy therefore appears to be an important aspect of early acceleration technique.

In comparison to the knee joint at maximum velocity (Bezodis et al., 2008) large magnitudes of extensor resultant moment and positive power were evident at the knee joint throughout the majority of stance (Figures 3c and 3d). This highlights the relative importance of the knee joint during early acceleration, similar to Charalambous et al. (2012). In the maximum velocity phase, the knee extensors are initially used to terminate the negative vertical velocity of the CM at touchdown before playing a role in generating positive vertical and horizontal velocity for the remainder of stance (Mann, 1981). As there is a lower initial negative vertical velocity to be reversed during the start of a sprint, the knee is therefore able to have an increased role in the generation of positive power, and thus acceleration of a sprinter. Consequently, it is of interest that some of the most evident between-sprinter differences were observed at the knee. The greater energy generated at the knee joint by sprinter B (363% and 188% of that generated by sprinters A and C during phase K2, respectively; Table 1) was a result of both the earlier rise and the higher peak in the resultant knee joint moment (joint extension velocities were more similar between sprinters than resultant moments; Figure 3b). In accordance with the geometrical constraints identified by van Ingen Schenau, Bobbert and Rozendal (1987), the knee joint has considerable potential to contribute to forwards horizontal translation of the CM at the start of a sprint, and is thus a likely factor in the generation of higher levels of external power by sprinter B. The ability of sprinter B to generate knee extensor resultant moments from the onset of stance may also have been assisted by his touchdown kinematics, as he exhibited a lower horizontal toe velocity at touchdown compared to sprinters A and C (Table 1). This has previously been associated with reduced braking force magnitude (Jacobs & van Ingen Schenau, 1992; Mann & Herman, 1985; Putnam & Kozey, 1989) and thus the touchdown kinematics of

sprinter B helped to reduce the magnitude of the braking forces he experienced (Table 1) and assisted the generation of energy at the knee joint during stance. Experimental training interventions or computer simulations of the first stance phase may be useful to investigate the extent to which manipulating touchdown kinematics can influence knee joint kinetics and ultimately performance during early acceleration.

The resultant hip joint extensor moments observed at touchdown for all athletes in this study, and which peaked soon after touchdown (Figure 4c), are consistent with the later phases of a sprint (Bezodis et al., 2008; Johnson & Buckley, 2001). These large hip extensor resultant moments at touchdown imply that an extensor resultant moment was present at the hip prior to touchdown. This suggests the existence of a similar strategy to that used in later phases of a sprint, whereby the hip extensor moment reduces the forward momentum of the swing leg prior to touchdown, decreasing the toe touchdown velocity and thus the braking forces experienced (Jacobs & van Ingen Schenau, 1992; Mann & Herman, 1985; Putnam & Kozey, 1989). The resultant hip moment became flexor dominant before toe-off to absorb energy, thus reducing hip extension and helping to terminate ground contact. Sprinter B performed greater negative work at the hip joint during this phase (H2) compared to sprinters A and C which suggests that this strategy which has previously been highlighted as important in maximum velocity sprinting (Mann, 1981; Mann & Sprague, 1980) could also play an important role in early acceleration.

It was decided to limit the current analysis to sprinters who had competed in a major international final within the last two years, and this study thus analysed the techniques of three world-class sprinters. Whilst a larger cohort of sprinters would be desirable, there exist low numbers of potential elite participants due to the inherent nature of being elite. Combining sub-elite sprinters in to the current study could have weakened the understanding that could be obtained. Data were collected outside of competition to enable the collection of ground reaction force data, but were collected as close to the competition

season as possible when the performance levels of the sprinters were intended to peak. This limited the number of trials and measurements that could be collected, and whilst additional data such as joint moment-velocity relationships or muscle architecture and tendon moment arms (e.g. Baxter, Novack, van Werkhoven, Pennell, & Piazza, 2012; Karamanidis et al., 2011; Lee & Piazza, 2009) could further the understanding of some of the inter-individual differences observed, the current data clearly show some consistent joint kinetic patterns and thus offer a valuable insight in to the techniques exhibited by sprinters who were competing at the highest level at the time of this study.

Conclusion

This study identified a clear joint kinetic pattern associated with the four main stance leg joints during the first stance phase of a sprint. The MTP joint was a net absorber of energy, whereas at the ankle joint net energy generation was evident and considerably greater in comparison with previously published data from later phases of a sprint. The hip joint was more similar to other phases of a sprint as it extended throughout stance. It initially generated energy before energy was absorbed as the resultant joint moment became flexor after mid-stance, similar to the maximum velocity phase of sprinting. Finally, the knee joint was a clear net energy generator. The ability to generate a large resultant knee extensor moment appeared to be a key difference between the highest performing sprinter and the other sprinters in this study. An earlier rise and a greater peak in this resultant knee extensor moment may have been facilitated by the kinematics of this sprinter at touchdown, due to a reduced forwards velocity of the foot which led to lower braking forces. Enhancing knee extensor power therefore has the potential to improve early acceleration performance, either through technical adjustments around touchdown or through strengthening the relevant musculature.

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Table 1. Ground reaction force and joint kinetic discrete variables for each of the three sprinters (mean and 95% confidence limits).

	A	B	C
Average horizontal external power	0.833 (0.764 – 0.903)[B]	1.030 (0.992 – 1.068)[A,C]	0.790 (0.755 – 0.825)[B]
Peak braking force	0.903 (0.625 – 1.180)[B]	0.172 (0.056 – 0.288)[A,C]	0.525 (0.346 – 0.705)[B]
Duration of braking phase (s)	0.016 (0.016 – 0.017)	0.016 (0.015 – 0.017)	0.015 (0.014 – 0.017)
Peak propulsive force	1.158 (1.078 – 1.237)[B]	1.284 (1.260 – 1.307)[A,C]	1.064 (1.035 – 1.092)[B]
Duration of propulsive phase (s)	0.176 (0.166 – 0.187)	0.175 (0.172 – 0.179)[C]	0.161 (0.152 – 0.170)[B]
Vertical impact peak	1.494 (1.356 – 1.633)[B]	0.709 (0.599 – 0.820)[A,C]	1.501 (1.402 – 1.599)[B]
Vertical active peak	2.094 (1.938 – 2.250)	2.178 (2.154 – 2.202)[C]	2.021 (1.917 – 2.126)[B]
Peak MTP plantar flexor moment	0.138 (0.130 – 0.146)[B]	0.177 (0.165 – 0.190)[A,C]	0.120 (0.103 – 0.138)[B]
Peak ankle plantar flexor moment	0.452 (0.421 – 0.483)[C]	0.451 (0.443 – 0.460)[C]	0.378 (0.353 – 0.404)[A,B]
Peak knee extensor moment	0.087 (0.053 – 0.121)[B]	0.216 (0.187 – 0.245)[A,C]	0.138 (0.098 – 0.178)[B]
Peak hip extensor moment	0.359 (0.279 – 0.439)	0.354 (0.295 – 0.414)[C]	0.273 (0.256 – 0.291)[B]
Peak hip flexor moment	0.390 (0.323 – 0.457)	0.432 (0.347 – 0.518)[C]	0.297 (0.268 – 0.326)[B]
Peak negative MTP power	0.307 (0.283 – 0.330)[B]	0.442 (0.393 – 0.492)[A,C]	0.255 (0.185 – 0.324)[B]
Peak positive MTP power	0.261 (0.035 – 0.487)	0.188 (0.059 – 0.177)	0.146 (0.046 – 0.245)
Peak negative ankle power	0.419 (0.289 – 0.550)	0.418 (0.309 – 0.528)	0.363 (0.180 – 0.545)
Peak positive ankle power	1.206 (1.109 – 1.302)[B]	1.488 (1.454 – 1.523)[A]	1.251 (1.002 – 1.500)
Peak negative knee power (early stance)	0.362 (0.282 – 0.443)[B,C]	0.000 (0.000 – 0.000)[A,C]	0.087 (0.054 – 0.120)[A,B]
Peak positive knee power	0.148 (0.058 – 0.237)[B]	0.422 (0.374 – 0.470)[A,C]	0.249 (0.224 – 0.274)[B]
Peak negative knee power (late stance)	0.206 (0.075 – 0.336)	0.127 (0.075 – 0.179)[C]	0.258 (0.186 – 0.331)[B]
Peak positive hip power	1.450 (1.097 – 1.804)	1.185 (0.929 – 1.442)	0.842 (0.568 – 1.115)
Peak negative hip power	0.535 (0.268 – 0.803)[B]	0.870 (0.804 – 0.936)[A,C]	0.474 (0.258 – 0.691)[B]
Total negative MTP work (M1)	0.042 (0.026 – 0.058)	0.061 (0.054 – 0.067)	0.043 (0.031 – 0.056)
Total positive MTP work (M2)	0.008 (0.005 – 0.011)[B]	0.003 (0.002 – 0.003)[A]	0.004 (0.000 – 0.007)
Total negative ankle work (A1)	0.052 (0.037 – 0.068)	0.067 (0.056 – 0.079)	0.041 (0.022 – 0.061)
Total positive ankle work (A2)	0.175 (0.156 – 0.195)[B]	0.223 (0.213 – 0.232)[A,C]	0.163 (0.138 – 0.188)[B]
Total negative knee work in early stance (K1)	0.025 (0.014 – 0.036)[B,C]	0.000 (0.000 – 0.000)[C]	0.001 (0.000 – 0.002)[A]
Total positive knee work (K2)	0.030 (0.022 – 0.039)[B,C]	0.109 (0.087 – 0.130)[A,C]	0.058 (0.039 – 0.076)[A,B]

Total negative knee work in late stance (K3)	0.020 (0.003 – 0.037)	0.010 (0.003 – 0.017)	0.025 (0.008 – 0.041)
Total positive hip work (H1)	0.191 (0.140 – 0.242)	0.215 (0.187 – 0.243)	0.180 (0.138 – 0.222)
Total negative hip work (H2)	0.038 (0.017 – 0.058)^{B}	0.068 (0.062 – 0.075)^{A,C}	0.033 (0.022 – 0.044)^{B}
Touchdown distance	0.090 (0.053 – 0.126)	0.048 (0.019 – 0.077)	0.055 (0.031 – 0.079)
Touchdown velocity	2.293 (1.506 – 3.079)^{B,C}	0.003 (-0.178 – 0.184)^{A}	0.779 (0.132 – 1.425)^{A}

All normalised values are dimensionless – see methods section for details of normalisation procedures. Superscript letters represent non-overlapping confidence intervals with the respective sprinter indicated by the letter. Abbreviations in parentheses with the joint work data correspond to the phases of positive and negative work illustrated in Figures 1 to 4.
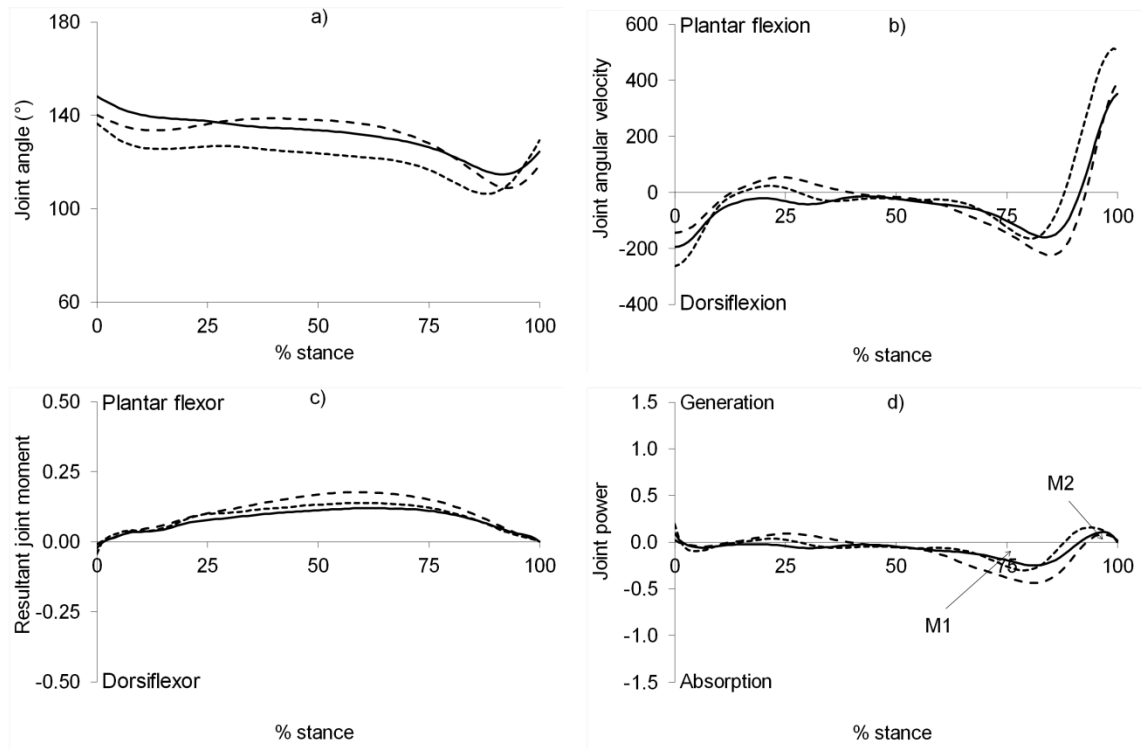
Figure 1. Mean MTP a) joint angle, b) normalised angular velocity, c) normalised resultant joint moment and d) normalised joint power time-histories for sprinters A (dotted line), B (dashed line) and C (solid line).
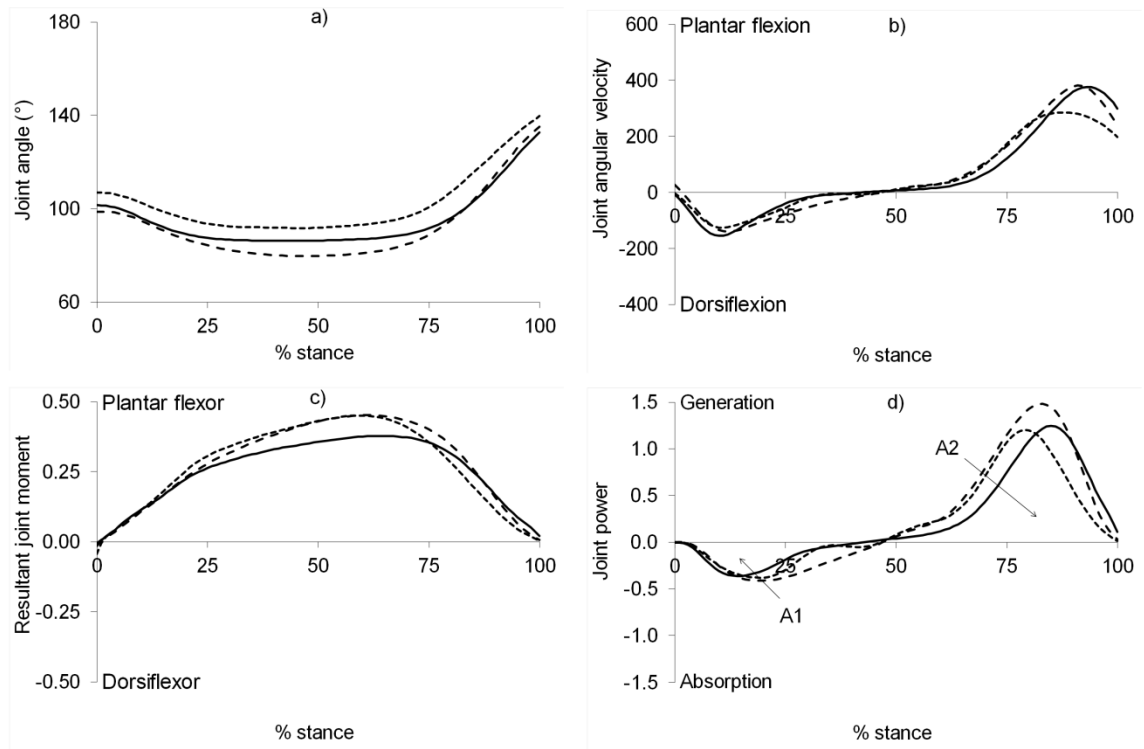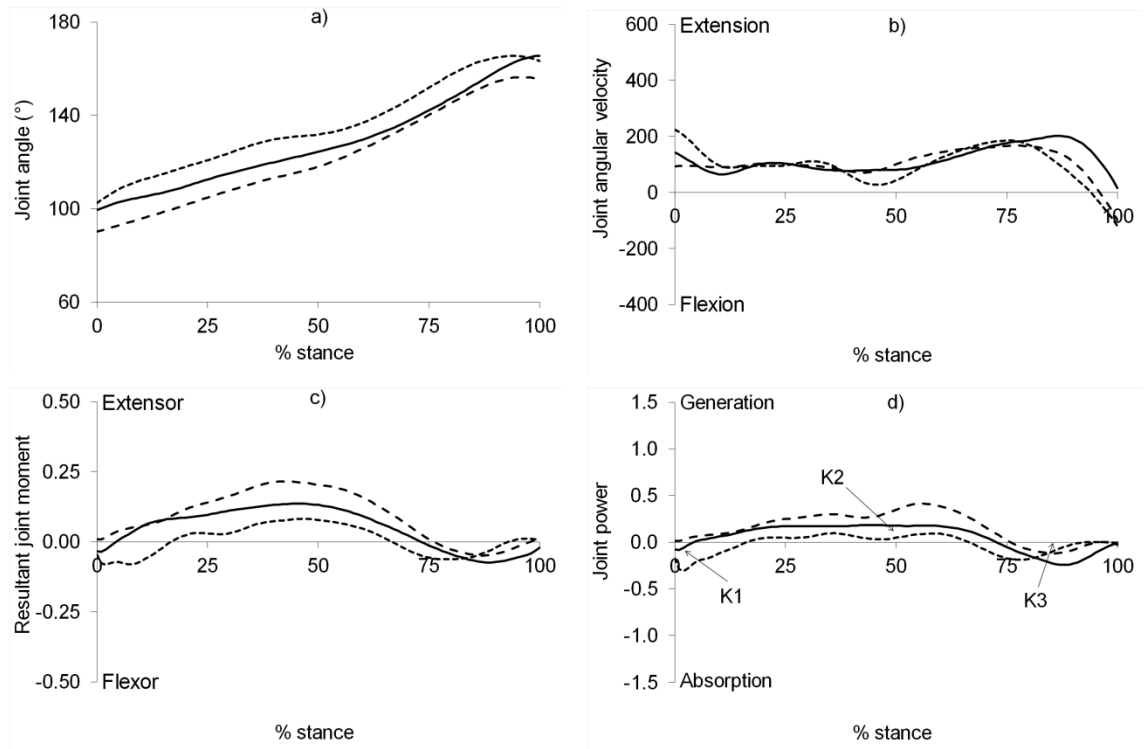
Figure 2. Mean ankle a) joint angle, b) normalised angular velocity, c) normalised resultant joint moment and d) normalised joint power time-histories for sprinters A (dotted line), B (dashed line) and C (solid line).

Figure 3. Mean knee a) joint angle, b) normalised angular velocity, c) normalised resultant joint moment and d) normalised joint power time-histories for sprinters A (dotted line), B (dashed line) and C (solid line).
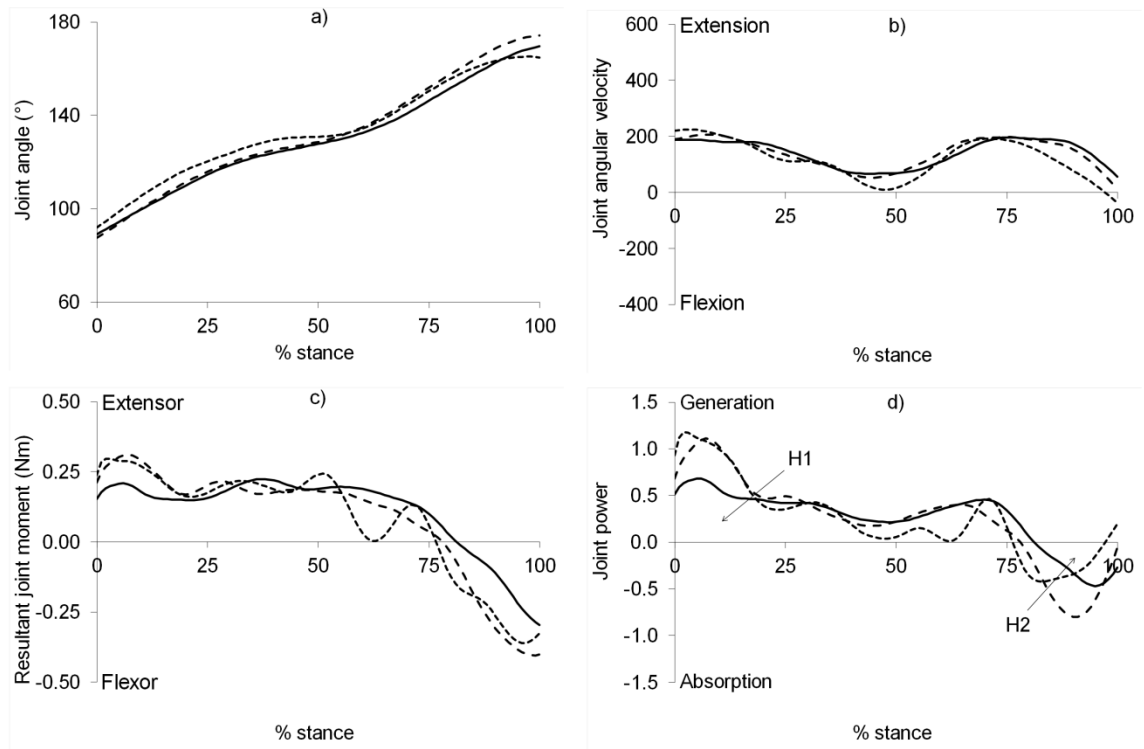
Figure 4. Mean hip a) joint angle, b) normalised angular velocity, c) normalised resultant joint moment and d) normalised joint power time-histories for sprinters A (dotted line), B (dashed line) and C (solid line).