Lower limb joint kinetics in the starting blocks and first stance in athletic sprinting

Abstract

The aim of this study was to examine lower limb joint kinetics during the block and first stance phases in athletic sprinting. Ten male sprinters (100 m PB, 10.50 ± 0.27 s) performed maximal sprint starts from blocks. External force (1000 Hz) and 3D kinematics (250 Hz) were recorded in both the block (utilising instrumented starting blocks) and subsequent first stance phases. Ankle, knee and hip resultant joint moment, power and work were calculated at the rear and front leg during the block phase and during first stance using inverse dynamics. Significantly ($P < 0.05$) greater peak moment, power and work were evident at the knee joint in the front block and during stance compared with the rear block. Ankle joint kinetic data significantly increased during stance compared with the front and rear block. The hip joint dominated leg extensor energy generation in the block phase (rear leg, 61 ± 10%; front leg, 64 ± 8%) but significantly reduced during stance (32 ± 9%), where the ankle contributed most (42 ± 6%). The current study provides novel insight into sprint start biomechanics and the contribution of the lower limb joints towards leg extensor energy generation.

Keywords: Sprint start, sprint biomechanics, track and field, sprint running,

Introduction

In short sprint events athletes must accelerate from a stationary position in the starting blocks and continue to accelerate until maximal velocity is reached, before attempting to maintain this velocity for the remainder of the race (Ross, Leveritt, & Riek, 2001). Recently, the ability to accelerate and achieve higher velocity over 40 m was shown to discriminate between elite and sub-elite sprinters (Rabita et al., 2015), supporting that the optimal performance strategy in short sprint events is one that minimises the time spent running at submaximal velocity (van Ingen Schenau, de Koning, & de Groot, 1994). The block phase and subsequent first stance, defined in the current study as the sprint start, is characterised by displaying the highest acceleration during a sprint race, highlighting the critical importance of the starting phase to overall performance.

Given the importance of the sprint start, previous research has attempted to understand the biomechanics of the block and/or first stance phases, investigating external kinetics (Otsuka et al., 2014; Willwacher, Herrmann, Heinrich, & Brüggemann, 2013b), joint kinematics (Bezodis, Salo, & Trewartha, 2015), joint kinetics (Bezodis, Salo, & Trewartha, 2014; Charalambous, Irwin, Bezodis, & Kerwin, 2012, Debaere, Delecluse, Aerenhouts, Hagman, & Jonkers, 2013; Mero, Kuitunen, Harland, Kyröläinen, & Komi, 2006), segment kinetic energy (Slawinski, Bonnefoy, & Ontanon, et al., 2010), and induced acceleration (Debaere, Delecluse, Aerenhouts, Hagman, & Jonkers, 2015). Analysing joint kinetics allows for an understanding of the causes of segment motion and the musculoskeletal demand of performing a particular skill such as the sprint start. During first stance there is common agreement between studies that the hip, knee and ankle joint generate energy during leg extension (Bezodis et al., 2014; Charalambous et al., 2012; Debaere et al., 2013), although it appears that the ankle joint is the main contributor to CM acceleration (Debaere et al., 2015). To the author's knowledge, only Mero et al. (2006) have previously calculated joint kinetics during the block phase by mounting starting blocks onto separate force platforms and combining with two-dimensional video data. External forces were assigned to the location of the metatarsophalangeal (MTP) joint to compute joint moments. Mero et al. (2006) revealed low knee extensor moment and power in the rear leg and large extensor moment and power at both hip joints, alongside periods of energy absorption and generation at both ankle joints. More recently, Slawinski et al. (2010) supported the findings of Mero et al. (2006) by showing large kinetic energy of the thigh segments, suggesting the importance of hip motion during the action of the lower limb in the block phase. However, given that Mero et al. (2006) only presented graphical data, block phase lower limb joint kinetics have not yet been fully quantified.

Although analysing a single phase in isolation provides valuable information, including sequential phases allows quantification of the changes that occur between phases (Debaere et al., 2013, 2015). Therefore, further research is required not only to quantify block phase joint kinetics, but to investigate the changes that occur between the block and first stance phases in order to better understand the musculoskeletal demand of executing the sprint start.

Utilising novel force instrumented starting blocks, the aim of this study was to quantify lower limb joint kinetics during the sprint start and investigate the changes that occur between the block and first stance phases. The purpose was to provide coaches and biomechanists with information relating to the technical and musculoskeletal demand of executing these phases, in order to inform coaching and training practices that can positively impact upon performance.

Methods

Ten male sprinters (mean ± SD: age, 24 ± 4 years; height, 1.78 ± 0.04 m; leg length, 0.89 ± 0.03 m; mass, 76.67 ± 2.74 kg) with 100 m personal best times ranging from 10.10-10.96 s (10.50 ± 0.27 s) gave written informed consent to participate in the study following ethical approval from the Research Ethics Committee at Cardiff Metropolitan University. A cross sectional study design was implemented to understand and compare joint kinetics in the block phase and first stance in athletic sprinting. Participants were tested at the National Indoor Athletics Centre in Cardiff during normal block acceleration training sessions. After a coach prescribed warm up each participant performed five to six maximal 10 m sprints from blocks. Three dimensional external force and three dimensional kinematic data were collected from the initiation of the block phase until first stance take-off, which defined the sprint start in the present study.

******** FIGURE 1 NEAR HERE ********

Kinematic data were collected using a 15 camera three dimensional motion analysis system (Vicon, Oxford Metrics, UK, 250 Hz), calibrated to residual errors of < 0.3 mm using a 240 mm calibration wand. Retro-reflective markers (14 mm) were attached to the participant’s skin bilaterally on the: iliac crest, posterior superior iliac spine, anterior superior iliac spine, lateral and medial femoral epicondyles, lateral and medial malleoli, first and fifth metatarsal heads, calcaneus, and head of the second toe (Fig. 1). Technical clusters comprising of four markers were attached towards the distal end of the thigh and shank segments (Manal, McClay, Stanhope, Richards, & Galinat, 2000). External force data were collected from each block using force instrumented starting blocks with custom made force platforms comprising four piezoelectric load cells (Kistler Instrumente AG, Winterthur, Switzerland) mounted on to separate base units(for a more detailed description see: Willwacher, Feldker, Zohren, Herrmann, & Brüggemann, 2013a). Participants set block spacing and obliquity to their individual preferences (all opted for block angles of 50° to the horizontal). Force data were sampled at 10000 Hz (post-processed to 1000 Hz), externally amplified (8 channel amplifier, Kistler, Switzerland), AD converted and stored on a laptop using customised Labview software (Willwacher et al., 2013a). Block force signals were low-pass filtered (4^{th} order Butterworth, 120 Hz cut-off) prior to analysis and were time synchronised with the kinematic data using a known voltage rise prior to the starting sound. To measure external forces during the subsequent first stance, a single force platform (9287BA, Kistler, Switzerland, 1000 Hz) was mounted underneath a Mondo (Warwickshire, UK) track surface, and signals were internally amplified and collected simultaneously with the kinematic data.

The block phase was separated into two sub-phases: rear block (rear leg) and front block (front leg). Each sub-phase was defined between the instance of block start (earliest detection in which the first derivative of either the front or rear resultant force-time curve > 500 $N.s^{-1}$), and the end of the respective sub-phase (resultant force < 50 N). The first stance phase was defined when vertical force was > 10 N (Rabita et al., 2015).

After labelling of marker trajectories (Nexus, v1.8.5, Vicon, Oxford Metrics, UK), data processing was performed using Visual 3D software (C-Motion Inc, Germantown, USA). Raw marker coordinates were low-pass filtered (4^{th} order Butterworth) with a cut-off frequency of 12 Hz, determined using residual analysis (Winter, 2009). A nine segment model of the lower limb (pelvis and bilateral thigh, shank, foot and toe) was created with hip joint centres defined using regression equations (Bell, Brand & Pedersen, 1989). Knee and ankle joint centres were defined as the midpoint between the medial and lateral femoral epicondyles, and malleoli, respectively. The MTP joint centre was defined as the midpoint between the first and fifth metatarsal heads (Smith, Lake, & Lees, 2014). A static calibration was used to define each segment's local coordinate system (SCS). For each SCS the x-axis pointed to the right, y-axis pointed forwards and z-axis pointed upwards. Joint angular velocity (°/s) was calculated as the rate of change of the distal SCS relative to the proximal described by an X, Y, Z Cardan sequence of rotations. Newton-Euler inverse dynamics procedures (Selbie, Hamill, & Kepple, 2014) were used to calculate resultant joint moments at the ankle, knee and hip joints and were resolved in the proximal SCS. Only x-axis (flexion-extension) data were reported as sprinting is predominantly sagittal, and extension/ plantarflexion were defined as positive. Based on the work by Mero et al. (2006), a virtual landmark that projected the MTP joint centre onto the surface of the block was used to define centre of pressure for the front and rear leg. For inverse dynamics calculations during stance, force platform data were filtered with the same cut-off frequency as the kinematics to prevent the generation of artefacts around touchdown (Bisseling & Hof, 2006). Joint power was calculated as the product of joint moment and angular velocity and the main phases of positive and negative power were defined. Peak positive joint power was quantified during joint extension. Joint work was then calculated for each phase by integrating power data (trapezium rule) which quantified energy absorption (negative power) and generation (positive power). Relative work

(W_{rel}) was calculated as the percentage of each joint's positive extensor work phase to the sum of all positive extensor work phases. Thus W_{rel} represented each joint's contribution towards total leg extensor energy generation. All joint data were normalised to dimensionless values using the formulas provided by Hof (1996) with the power adjustment outlined by Bezodis, Salo, and Trewartha (2010).

Joint kinematic and kinetic time-histories were normalised to 100% of each phase using a cubic spline. Ensemble mean and standard deviation time histories were produced to show the average and between-sprinter variation in joint kinematic and kinetic patterns. Group mean and standard deviations were calculated for peak moment, peak power, work and W_{rel} using each sprinter's mean data. To analyse the differences in joint kinetic variables between the rear block, front block and stance phases a repeated measures analysis of variance (ANOVA) was employed and Bonferonni post-hoc tests were conducted when significant main effects were detected. Partial Eta^2 ($\eta^2_{partial}$) effect sizes were also calculated to indicate the ratio of variance from ANOVA accounted for by each effect. Greenhouse-Geisser values were used when data was confirmed to be aspherical (Mauchley's test $P < 0.05$ or epsilon < 0.75). All data were confirmed to be normally distributed (Shapiro-Wilk $P > 0.05$) prior to analysis. Statistical significance was accepted at $P < 0.05$.

Results

Mean (± SD) rear block, front block and stance times were 0.193 ± 0.012 s, 0.359 ± 0.014 s, and 0.193 ± 0.017 s, respectively.. Joint angular velocity, moment and power at the ankle, knee and hip joint during the rear block, front block and stance phases are presented in Figures 2-4. In all phases the ankle joint exhibited an initial period of dorsiflexion followed by plantarflexion (Fig. 2) and a net plantarflexion moment (Fig. 3) leading to energy absorption (Fig. 4, A1) followed by generation (Fig. 4, A2). A small extensor moment at the knee joint lead to minimal energy generation in the rear block, whereas there were clear and larger periods of energy generation in the front block and stance (Fig. 4, K1). Extensor moments at the hip joint dominated the majority of the rear and front block phases, and the first 60-70% of stance (Fig. 3) leading to clear periods of energy generation (Fig. 4, H1) whilst the hip joint was extending (Fig. 2). As the hip joint attained maximal extension angular velocity in the front and stance leg (Fig. 2) the resultant hip moment was flexor (Fig. 3) and thus a clear period of energy absorption (Fig. 4, H2) was evident. A proximal-distal pattern of peak joint powers was observed in the front and stance leg but was absent in the rear leg in which a knee-hip-ankle pattern was identified (Fig. 4).

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ANOVA results revealed a significant main effect for all other joint kinetic variables except peak hip moment ($P < 0.05$, $\eta^2_{partial}$ =0.60-0.98). Post-hoc tests revealed significant ($P < 0.05$) between-phase comparisons which are detailed in Table 1. Peak knee extension moment, positive power, and positive extensor work were significantly greater in the front block and stance compared with the rear block whereas significantly greater ankle kinetic data were evident during stance compared with either leg in the block phase. Although no significant main effect was found for peak hip extension moment, peak positive power was significantly greater in the front block (0.576 ± 0.071) compared with the rear block (0.408 ± 0.152), and significantly greater during stance (0.908 ± 0.185) compared with both the front and rear block. However, positive extensor work was significantly greater in the front block (0.338 ± 0.034) compared with the rear block (0.101 ± 0.042) and stance (0.132 ± 0.040). Hip W_{rel} significantly decreased between the block phase (rear block, 61 ± 10%; front block 64 ± 8%) and stance (31 ± 8%), whereas ankle W_{rel} was significantly greater during stance (43 ± 6%) and the rear block (35 ± 8%) compared with the front block (15 ± 2%). Knee W_{rel} was similar between the front block (21 ± 8%) and stance (26 ± 8%) and both were significantly greater than the rear block (4 ± 3%).

******** TABLE 1 NEAR HERE ********

Discussion

The aim of this study was to investigate lower limb joint kinetics in the block and first stance phases of a maximal sprint using novel, bespoke instrumented starting blocks to provide new insight into the musculoskeletal demand of executing the sprint start. Key findings highlighted the asymmetrical nature of the block phase was most pertinent at the knee joint, and that leg extensor energy was predominantly generated at the hip joint in both the front and rear block whereas during first stance energy generation favoured the ankle joint as a result of a significant reduction in relative hip work.

Front and rear ankle joint kinetic patterns (Fig. 3-4) were similar to what has previously been shown in the block phase (Mero et al., 2006) and first stance (Bezodis et al., 2014; Charalambous et al., 2012; Debaere et al., 2013), by showing a constant plantarflexion moment resulting in a period of energy absorption followed by generation, indicating a stretch-shortening action (Mero et al., 2006; Slawinski et al., 2010). Peak plantarflexion moment was significantly greater during stance compared with both the front and rear leg (Table 1) and may be explained by increased vertical forces during stance (Otsuka et al., 2014). Greater angular velocities (Fig. 2) were also observed during stance which helped to explain the increases in positive and negative peak power and extensor work compared with the block phase. Within the block phase, significantly higher peak positive power (0.388 ± 0.084 vs. 0.236 ± 0.066) and work (0.081 ± 0.015 vs. 0.053 ± 0.014) were observed in the front block (Table 1). A lower magnitude of positive power and work in the rear block may be due to the absence of a proximal-distal strategy of power generation, decreasing the amount of energy that could be liberated from the knee joint to assist with ankle plantarflexion (Jacobs, Bobbert, & van Ingen Schenau, 1996).

Significantly lower magnitudes of moment, power and work were observed in the rear leg compared with the front leg during the block phase (Table 1), and a distinct difference in the pattern of joint kinematics and kinetics was observed (Fig. 2-4). Although significant differences in kinetic variables were also observed at the ankle and hip joint between the front and rear leg, temporal patterns were similar between legs, indicating that the primary source of asymmetry in the block phase was at the knee joint. A low rear knee moment for the first 80% of the rear block phase may indicate a specific role of the rear knee joint to stabilise the lower limb and facilitate the large forces generated at the hip and ankle being effectively applied to the block. This specific technique appeared to result from a low moment arm caused by the orientation of the resultant force vector with respect to the knee joint location, a potential constraint of the starting blocks placing the rear leg into a more extended position. Front and stance knee peak power (0.440 ± 0.177 and 0.468 ± 0.145, respectively) and work (0.114 ± 0.051 and 0.107 ± 0.037, respectively) (Table 1) were similar, indicating comparable musculoskeletal demand and confirmed the important energy generating role of the knee joint during the sprint start (Bezodis et al., 2014; Debaere et al., 2013). A proximal-distal pattern of peak joint powers was evident in the front block and first stance and is a strategy often adopted in power demanding tasks (Jacobs et al., 1996). Inherent with this strategy during sprint acceleration is delayed active extension at the knee and ankle joints until the CM has been sufficiently rotated in front of the foot in order to maximise forward propulsion (Jacobs & van Ingen Schenau, 1992). Whilst commonly described during stance (Bezodis et al., 2014; Debaere et al., 2013), results of the present study indicated that this also occurred in the block phase, with the main periods of positive extensor power at the front ankle and knee occurring after the rear foot had left the blocks (Fig. 4).

No significant main effect of phase was found for peak hip extension moment (Table 1), however the relative timing of its occurrence was much earlier during stance and occurred at touchdown (Fig. 3). Peak positive power during stance also occurred at touchdown (0.908 ± 0.185) and was significantly greater than during the rear block (0.408 ± 0.152) and front block (0.576 ± 0.071) phases due to higher hip extension angular velocity at the instance of peak power (Fig. 2 and 4). The rapid decrease in hip power after touchdown (Fig. 4) meant that positive work during stance (0.132 ± 0.040) and the rear block phase (0.101 ± 0.042) were similar. Positive hip work was significantly higher in the front block (0.338 ± 0.020), and may be explained by a longer absolute time compared with the rear block and stance phases as well as a significantly higher peak power compared with the rear block (Table 1).

The calculation of relative work (W_{rel}) permitted the contribution of each joint to total leg extensor energy generation to be quantified and provided insight into the major generators of leg extensor energy during each phase. Results highlighted large W_{rel} at the hip joint during the block phase (rear, 61 ± 10%; front, 64 ± 8%, Table 1), supporting the importance of the hip joint for block phase execution (Bezodis et al.,2015; Mero et al., 2006; Slawinski et al., 2010). These findings suggest dissimilarity in relative work between the block phase and squat jumping, a common strength training and diagnostics exercise also initiated from a stationary position, as Hubley and Wells (1983) reported a dominant (49.0%) contribution of the knee joint, followed by the hip (27.5%) then ankle (23.5%). During stance W_{rel} became more evenly distributed but favoured ankle dominance (43 ± 6%, Table 1). The observed differences may be due to the block phase beginning from a stationary position, placing high demand on the powerful hip extensors to initiate motion, and the ankle joint being the major contributor towards vertical and horizontal CM propulsion during first stance (Debaere et al., 2015). The contribution of each joint to CM propulsion cannot be established from the current data, but W_{rel} indicated the large energy generating role of the ankle, knee and hip joint at various instances during the sprint start. The importance of ensuring high strength and power capacity of the hip and knee extensor and plantarflexor musculature was therefore apparent. However, the temporal organisation of joint powers (Fig. 4) suggests that simply improving the strength and power capacity at each joint may not translate into performance improvements, and promoting coordination specificity in supplementary training exercises may enhance the transfer of such training (Bobbert & van Soest, 1994). The quantification of W_{rel} in future biomechanics studies could have many applications, including the identification of athletes being ankle, knee, or hip dominant when executing particular tasks.

The magnitude of ankle, knee and hip moment, power and work data were in line with previous research investigating first stance (Bezodis et al., 2014; Charalambous et al., 2012), and the normalisation of data to dimensionless values permits future comparison between studies. When using raw power data, the magnitude of rear and front leg peak negative ankle power (-229 ± 113 W and -132 ± 47 W), and peak positive ankle (524 ± 147 W and 860 ± 180 W), knee (105 ± 60 W and 968 ± 365 W) and hip (912 ± 354 W and 1282 ± 193 W) power, were similar to those presented graphically by Mero et al. (2006). A limitation of the current work is that centre of pressure in the block phase was estimated based on the location on the MTP joint. However, the MTP location was projected onto the surface of the block advancing the work of Mero et al. (2006). Furthermore, the authors chose to focus the present analysis on flexion/extension of the lower limb, as the main goal of the study was to understand the musculoskeletal demand and kinetic organisation of leg extension, which is a primary focus of physical preparation and is lacking in the current sprint literature. Previous work has established that the hip joint undergoes a combination of flexion-extension, abduction-adduction and internal-external rotation during the block phase (Slawinski et al., 2010), and should be considered when interpreting the present data. Hand forces (Graham-Smith, Natera, & Saunders, 2014) and upper body and trunk motion (Slawinski et al., 2010) have also been found to determine the overall motion of the CM, however the primary aim of this study was to quantify kinetic data of the lower limbs. Close inspection of the variability at the rear hip and front knee (Fig. 4) suggested the largest between-sprinter differences occurred at these joints and therefore may be indicative of where differences in performance may have manifested. Further research is therefore required to elucidate the kinetic variables associated with performance to more completely understand sprint start performance and focus physical preparation programmes to maximise performance enhancement.

In conclusion, the current study has identified the dominant energy generating role of the hip joint in the block phase which significantly reduced during stance where the ankle contributed most. The asymmetrical nature of the block phase was most evident at the knee joint and may reflect a stabilising role to effectively apply forces to the rear block. Utilising instrumented starting blocks, the current data provides important biomechanical evidence to further understand lower limb musculoskeletal demand during the sprint start and the contribution of the ankle, knee and hip joint towards leg extensor energy generation.

Practical Implications

The large role played by the hip extensor musculature when executing the block phase encourages coaches to target hip extension within physical preparation. However, the more balanced generation of energy between the ankle, knee and hip during stance, and the temporal organisation of joint power must be acknowledged within physical and technical training to ensure strength and power are developed effectively for the nature of the sprint start.

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Table I. Joint kinetic variables for the rear block, front block and stance phases.

	Rear Block	Front Block	Stance		
Variable	Mean ± SD	Mean ± SD	Mean ± SD	$\eta^2_{partial}$	Symbol
Peak ankle extension moment	0.236 ± 0.044	0.172 ± 0.032	0.388 ± 0.035	0.91	⁺ † ǂ
Peak knee extension moment	0.054 ± 0.020	0.199 ± 0.067	0.242 ± 0.068	0.73	⁺ †
Peak hip extension moment	0.315 ± 0.086	0.349 ± 0.035	0.330 ± 0.071	0.05	
Peak negative ankle power	-0.103 ± 0.053	-0.060 ± 0.022	-0.317 ± 0.108	0.81	† ǂ
Peak positive ankle power	0.236 ± 0.066	0.388 ± 0.084	1.093 ± 0.069	0.98	⁺ † ǂ
Peak positive knee power	0.047 ± 0.026	0.440 ± 0.177	0.468 ± 0.145	0.74	⁺ †
Peak positive hip power	0.408 ± 0.152	0.576 ± 0.071	0.908 ± 0.185	0.78	⁺ † ǂ
Peak negative hip power	N/A	-0.421 ± 0.148	-0.740 ± 0.257	0.61	ǂ
Negative ankle work (A1)	-0.012 ± 0.008	-0.014 ± 0.007	-0.043 ± 0.014	0.78	† ǂ
Positive ankle work (A2)	0.053 ± 0.014	0.081 ± 0.015	0.173 ± 0.021	0.94	⁺ † ǂ
Positive knee work (K1)	0.006 ± 0.004	0.114 ± 0.051	0.107 ± 0.037	0.74	⁺ †
Positive hip work (H1)	0.101 ± 0.042	0.338 ± 0.034	0.132 ± 0.040	0.92	⁺ ǂ
Negative hip work (H2)	N/A	-0.038 ± 0.020	-0.084 ± 0.029	0.60	ǂ
W_{rel} Ankle (%)	35 ± 8	15 ± 2	43 ± 6	0.85	⁺ ǂ
W_{rel} Knee (%)	4 ± 3	21 ± 8	26 ± 8	0.74	⁺ †
W_{rel} Hip (%)	61 ± 10	64 ± 8	31 ± 8	0.83	† ǂ

Note: Symbols denote significant ($P < 0.05$) differences between the rear and front block (⁺), rear block and stance (†) and front block and stance (ǂ). $\eta^2_{partial}$ = partial Eta^2 effect size.

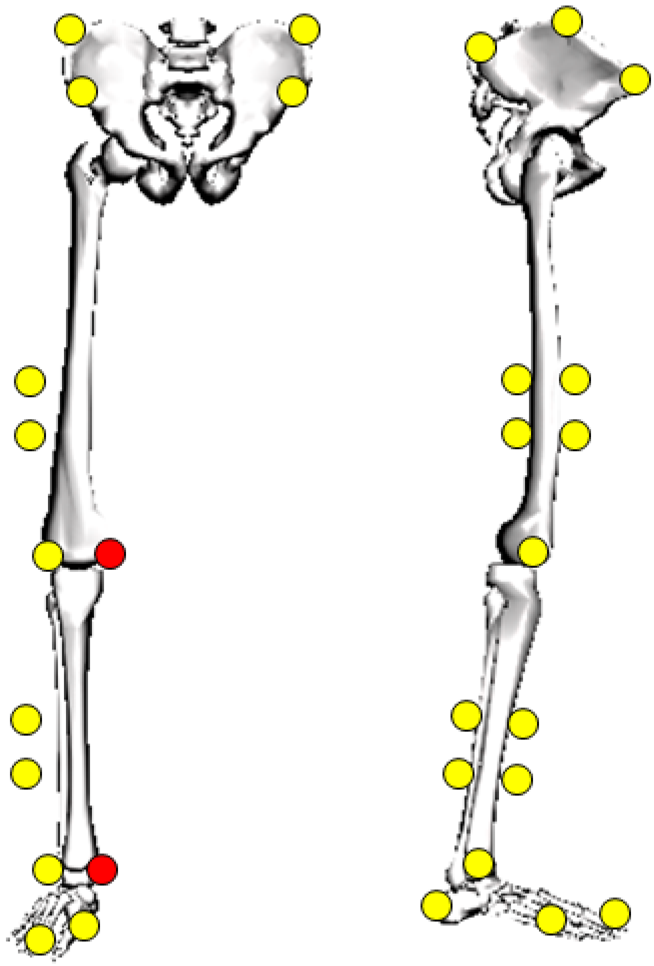

Figure 1. Marker locations used to define a lower limb model (unilateral shown). Medial femoral epicondyle and malleoli markers (red) were removed for the motion trials.

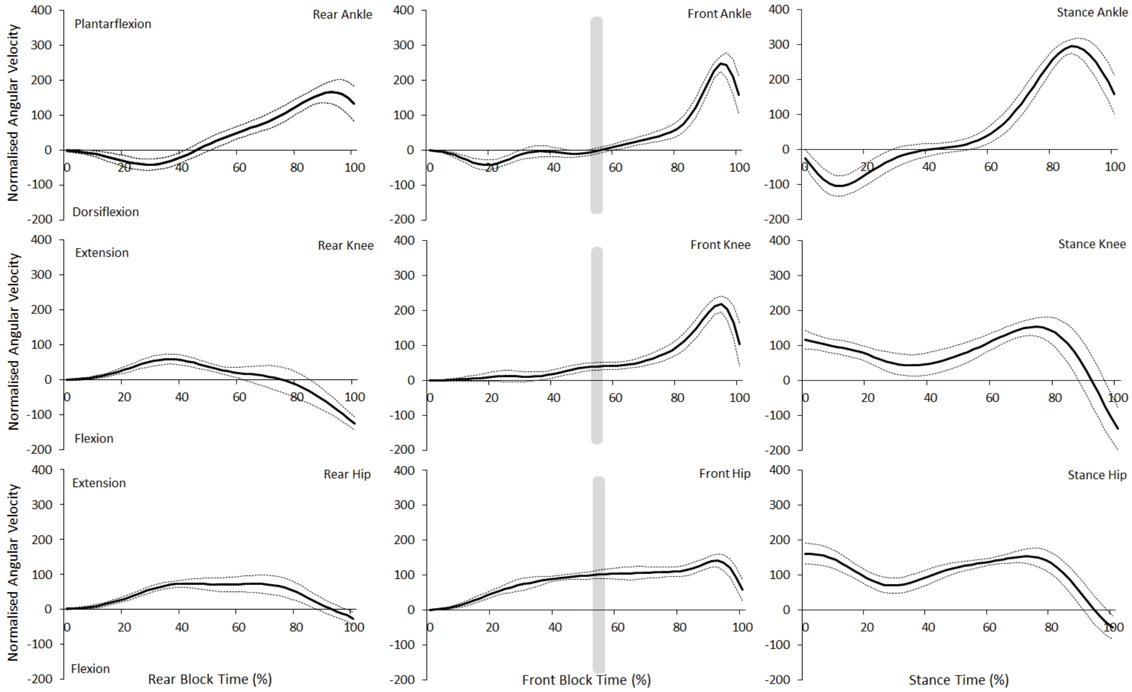

Figure 2. Ensemble group mean (solid line) and standard deviation (dotted line) normalised flexion-extension joint angular velocity- time histories for the ankle (first row), knee (second row) and hip (third row) joint during the rear block (first column), front block (second column), and stance (third column) phase. Grey shaded area indicates the standard deviation of the end of the rear block phase.

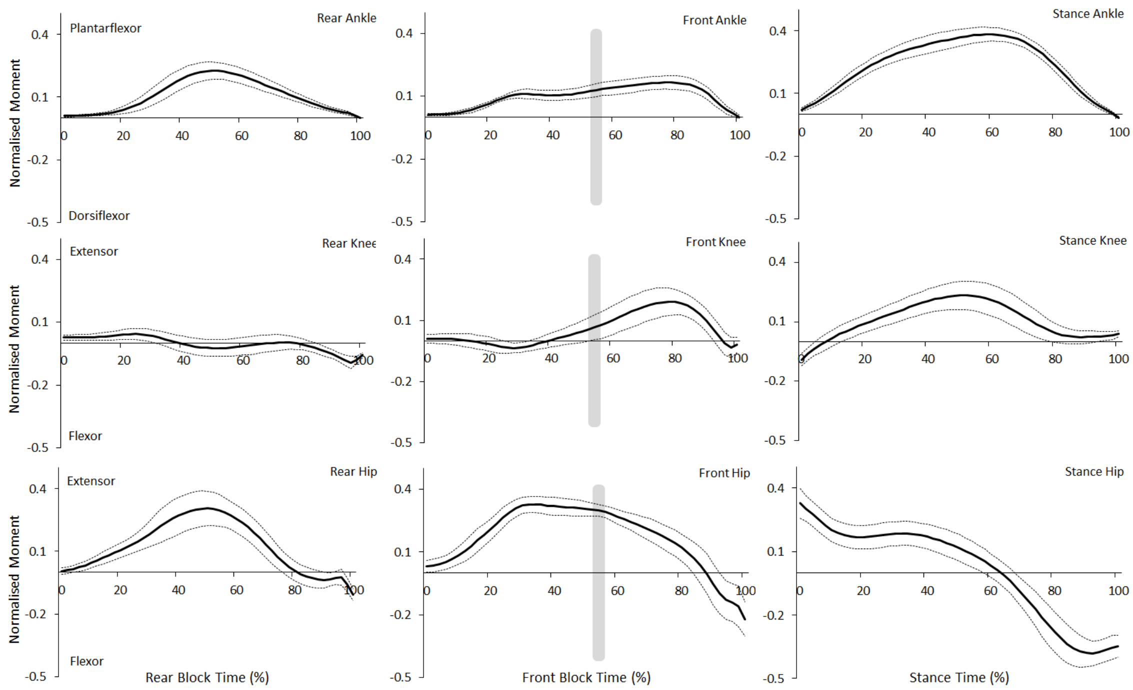

Figure 3. Ensemble group mean (solid line) and standard deviation (dotted line) normalised joint moment- time histories for the ankle (first row), knee (second row) and hip (third row) joint during the rear block (first column), front block (second column), and stance (third column) phase. Grey shaded area indicates the standard deviation of the end of the rear block phase.

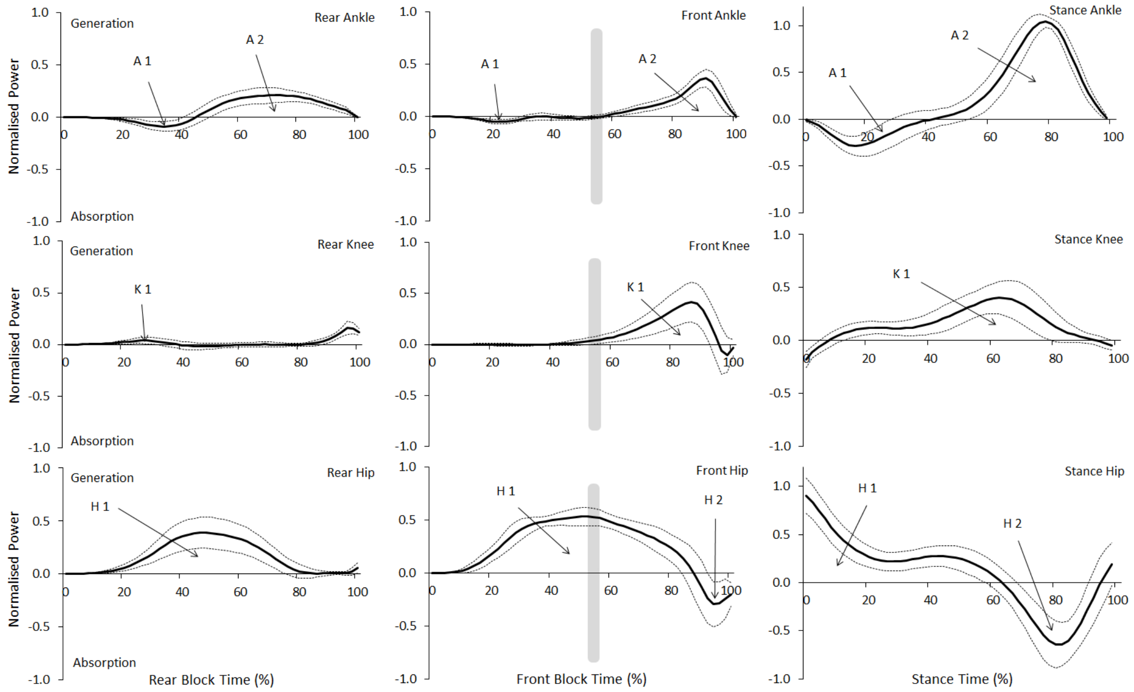

Figure 4. Ensemble group mean (solid line) and standard deviation (dotted line) normalised joint power- time histories for the ankle (first row), knee (second row) and hip (third row) joint during the rear block (first column), front block (second column), and stance (third column) phase. Grey shaded area indicates the standard deviation of the end of the rear block phase. Labels indicate the main power phases that are quantified in Table I.