Joint Kinetic Determinants of Starting Block Performance in Athletic Sprinting

Abstract

The aim of this study was to explore the relationships between lower limb joint kinetics, external force production and starting block performance (normalised average horizontal power, NAHP). Seventeen male sprinters (100 m PB, 10.67 ± 0.32 s) performed maximal block starts from instrumented starting blocks (1000 Hz) whilst 3D kinematics (250 Hz) were also recorded during the block phase. Ankle, knee and hip resultant joint moment and power were calculated at the rear and front leg using inverse dynamics. Average horizontal force applied to the front (r = 0.46) and rear (r = 0.44) block explained 86% of the variance in NAHP. At the joint level, many "very likely" to "almost certain" relationships (r = 0.57 to 0.83) were found between joint kinetic data and the magnitude of horizontal force applied to each block although stepwise multiple regression revealed that 55% of the variance in NAHP was accounted for by rear ankle moment, front hip moment and front knee power. The current study provides novel insight into starting block performance and the relationships between lower limb joint kinetic and external kinetic data that can help inform physical and technical training practices for this skill.

Introduction

In the short sprint events, performance of the starting block phase can be of critical importance to the outcome of a race as an athlete attempts to maximise centre of mass (CM) acceleration from the stationary 'set' position. Horizontal acceleration of the CM is determined by the propulsive forces generated by the sprinter in the blocks. When propulsive forces are accompanied with displacement of the sprinters CM, work is performed in the horizontal direction. The rate at which this work is achieved is equal to average horizontal power, which when normalised to body mass and leg length (NAHP), has been identified as the best descriptor of starting block performance (Bezodis, Salo, & Trewartha, 2010). Recently, NAHP (using height instead of leg length) has been found to account for 42% of the variance in 100 m personal best (PB) time in a large sample of 154 sprinters with PB's ranging from 9.58 to 14.00 seconds (Willwacher, Hermann, & Heinrich et al., 2016), confirming the critical nature of the block phase to overall sprint performance. The evidence by Willwacher et al. (2016) supports the importance of

proficient execution of the starting block phase and encourages researchers to gain a deeper understanding of the determinants of performance of this crucial aspect of sprinting.

Previous evidence based research has identified several key external kinetic variables separating different levels of sprint ability, including: greater front and rear block rate of resultant force development (Willwacher, Hermann, Heinrich & Brüggemann, 2013b), more balanced front and rear peak resultant force (Willwacher et al., 2013b), greater rear block peak force (Fortier, Basset, Mbourou, Faverial & Teasdale, 2005), greater front block average horizontal force (Brazil et al., 2015) and greater total (front + rear) average horizontal force (Otsuka et al., 2014; Brazil et al., 2015). Interpreting the relative importance of external force applied to the front and rear block from the aforementioned studies can be difficult. For example Otsuka et al. (2014) found that better sprinters produced significantly higher total average horizontal force, although between-group differences for the front and rear block were not found to be significant. Conversely, Brazil et al. (2015) found an almost perfect (r = 0.98) relationship between total average horizontal force and NAHP, with correlations of r = 0.78 and 0.16 for the front and rear block, respectively, highlighting greater importance of the front block. The inconsistency between studies may be accounted for by the different athletes used, different statistical analyses, or that between-group analyses have not been based on block performance, but overall sprint performance. Recently, Willwacher et al. (2016) utilised exploratory factor analysis and multiple regression in order to identify the key external kinetic factors of starting block performance, progressing beyond simpler between-group comparisons or bivariate correlation techniques enabled by their large sample size. From their analysis, 86% of the variance in block performance was explained by the magnitude of force applied to the both blocks, and the horizontal orientation of these forces, ultimately concluding that high average horizontal force must be applied to the front and rear block in order to maximise start performance.

Although external kinetic analyses provide valuable insight into starting block performance, analysis of lower limb joint kinetics allows for an increased understanding of the causes of segment motion that are responsible for CM acceleration. Recently, Brazil et al. (2017) concluded that the hip joint was the largest generator of leg extensor energy in the front (61 ± 10%) and rear (64 ± 8%) block, highlighting its importance in block performance. This supported previous investigations that also found large hip extensor moments and power generation (Mero, Kuitunen, Harland, Kyröläinen, & Komi, 2006), high energy of the thigh segment (Slawinski, Bonnefoy, & Ontanon, et al., 2010), and significant

relationships for hip peak angular velocity and rear hip range of motion with NAHP (Bezodis, Salo & Trewartha, 2015). However, Brazil et al. (2017) and Mero et al. (2006) also demonstrated large knee and ankle extensor moments and power generation, which could influence performance given the temporal differences between joint moment/power curves during the block phase. Currently, the relationship between lower limb joint kinetics and external kinetic data in the starting block phase remains unclear.

Therefore, the aim of the current study was to investigate the relationship between lower limb joint kinetics, external force production and overall performance of the starting block phase in athletic sprinting. The purpose of this study was to gain a greater understanding of the determinants of block performance in order to maximise physical preparation and technical coaching for this skill.

Methods

Seventeen male sprinters (mean ± SD: age, 23 ± 4 years; height, 1.79 ± 0.05 m; leg length, 0.88 ± 0.03 m; mass, 76.20 ± 5.33 kg) with 100 m personal best times ranging from 10.10-11.20 s (10.67 ± 0.32 s) gave written informed consent to participate in the study following institutional ethical approval. A cross sectional study design was implemented to understand the external and lower limb joint kinetic determinants of starting block performance. Data were collected at the National Indoor Athletics Centre in Cardiff during normal block acceleration training sessions and all participants performed five to six maximal 10 m sprints from blocks following a coach prescribed warm up. Synchronised three dimensional external force and kinematic data were collected during the block phase and each athlete's best trial (based on NAHP) was used for analysis.

External force data were collected using force instrumented starting blocks (Brazil et al., 2017; Willwacher, Feldker, Zohren, Herrmann, & Brüggemann, 2013a). 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). Force signals were low-pass filtered (4th order Butterworth, 120 Hz cut-off) prior to analysis. Front and rear block force data were used to define the start (first derivative of the resultant force-time curve > 500 N.s^{-1}) and end (resultant force < 50 N) of the front and rear sub-phases, respectively, and these sub-phases were combined to define the total block phase. Average horizontal force (F_Y) was calculated for the rear block, front block and in total using the respective rear, front and total (front + rear) force-time

signals and were normalised to bodyweight. Horizontal power was calculated from the product of the total horizontal force- and velocity-time signals, with velocity obtained through numerical integration of the total F_Y signal using the trapezium rule. To quantify block performance, horizontal power was then averaged over the duration of the block phase and normalised to body mass and leg length (Bezodis et al., 2010) to obtain NAHP.

Kinematic data were collected using a 15 camera three dimensional automated 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. Technical clusters comprising of four markers were attached towards the distal end of the thigh and shank segments (Manal, McClay, Stanhope, Richards, & Galinat, 2000). Further information on marker locations and model definitions can be found in Brazil et al. (2017).

After labelling of marker trajectories and gap filling (≤ 5 frames) in Nexus (v1.8.5, Vicon, Oxford Metrics, UK), data processing was performed using Visual 3D (v6, C-Motion Inc, Germantown, USA). Raw marker coordinates were low-pass filtered (4th order Butterworth) with a cut-off frequency of 12 Hz, determined using residual analysis (Winter, 2009). A static calibration was used to define the local coordinate system (SCS) of nine lower limb segments (pelvis and bilateral thigh, shank, foot and toe). For each segment the x-axis pointed to the right, y-axis pointed forwards and z-axis pointed upwards. Synchronisation of external force and kinematic data was achieved through a known voltage rise present in both datasets. Newton-Euler inverse dynamics procedures (Selbie, Hamill, & Kepple, 2014) were used to calculate resultant joint moments at the ankle (ANK), knee (KNE) and hip joints (HIP) and were resolved in the proximal SCS. Segment mass (Dempster, 1955) and inertial characteristics (Hanavan, 1964) were consistent with the default values prescribed in Visual 3D. Only x-axis (flexion-extension) data were reported as sprinting is predominantly sagittal, and extension/ plantarflexion were defined as positive. A virtual landmark that projected the metatarsophalangeal (MTP) joint centre onto the surface of the block was used to define centre of pressure for the front and rear leg (Brazil et al., 2017). Joint power was calculated as the product of the joint moment- and angular velocity-time signals and the main phases of positive extensor power for the ankle, knee and hip joint were identified. Average

extensor moment (M) and average positive extensor power (P) (i.e. variables explaining leg extension) were calculated and used for further analysis. Joint data were normalised using the formulas provided by Hof (1996) with the power adjustment outlined by Bezodis et al. (2010).

To assess the relationships between external kinetics (front and rear F_Y), lower limb joint kinetics (ankle, knee and hip moment and power), and overall starting block performance (NAHP), Pearson correlation coefficients were calculated and magnitude based inferences were made using 90% confidence intervals and a threshold of 0.1 for the smallest practically important correlation (Batterham & Hopkins, 2006). The percentage likelihood of the true correlation coefficient being substantially positive (> 0.1), trivial (-0.1 to 0.1) and negative (< -0.1) was used to make the following inferences: unclear (25-75% positive and > 5% negative), likely (75-95% positive and < 5% negative), very likely (95-99.5% positive), and almost certainly (>99.5% positive). For this sample, r values of 0.33, 0.50 and 0.66 indicated the thresholds for likely, very likely and almost certain positive relationships.

To more completely understand the determinants of starting block performance, multiple regression analysis (SPSS v. 22.0) was performed at the external and joint kinetic level. Firstly, front and rear F_Y were used as independent variables in a multiple regression with NAHP to understand the relationship between horizontal force production and block performance. Joint kinetic variables that possessed a likely (r > 0.33) relationship with NAHP were then used as independent variables in a stepwise multiple regression with NAHP in order to investigate the main joint kinetic determinants of block performance. The criterion value of entry for a variable in the regression model was set at 0.1. Consistency of the residuals for multiple regressions were evaluated using homoscedasticity and normality tests, and the Durban-Watson statistic assessed autocorrelation.

Results

Likely positive relationships of r = 0.44 and r = 0.46 with NAHP were found for rear and front F_Y, respectively, and regression analysis revealed that 86% of the variance in NAHP was explained by front and rear F_Y (Table 1). Within the regression model, standardised coefficients and squared part correlations were of similar magnitude for front and rear F_Y (Table 1).

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

The correlation values between internal (joint moment and power) and external (F_Y and NAHP) kinetics for the rear and front block are presented in Figures 1 and 2, respectively. Almost certain positive relationships with rear F_Y were found for M_{ANK} (r = 0.83), M_{HIP} (r = 0.80) and P_{HIP} (r = 0.73). For the front block M_{ANK} was almost certainly related to F_Y (r = 0.83), whilst M_{KNE} (r = 0.63), and M_{HIP} (r = 0.43) were very likely and likely positively correlated with F_Y, respectively. Only P_{KNE} (r = 0.57, very likely) shared a clear positive relationship with F_Y, whilst relationships for P_{HIP} (r = 0.32) and P_{ANK} (r = 0.13) were deemed unclear. When assessing relationships with NAHP (Figures 1, 2) likely positive correlations were found for rear M_{ANK} (r = 0.42), and front M_{ANK} (r = 0.41), P_{ANK} (r = 0.39), M_{HIP} (r = 0.46), P_{HIP} (r = 0.39), and P_{KNE} (r = 0.42). Time series data for external, and ankle, knee and hip kinetic data are presented in Figure 3 and illustrate the temporal characteristics between joint moment and power data and respective external force and power for each block.

*****FIGURES 1 & 2 & 3 NEAR HERE*****

Based on the bivariate correlations, rear M_{ANK} alongside front M_{ANK}, M_{HIP}, P_{ANK}, P_{KNE} and P_{HIP} were used as independent variables in a stepwise multiple regression with NAHP as the dependent variable. The best model included three of the six variables (rear M_{ANK}, front M_{HIP} and front P_{KNE}) and possessed an R^2 of 0.55 (Table 2). Normality of the residuals, and homoscedasticity were confirmed, and there was minimal autocorrelation (Durbin-Watson = 1.40). The following equation could thus be formed using unstandardised coefficients, reflecting the lower limb joint kinetics of the current study:

$$NAHP = 0.240 + (1.040 \times \text{rear } M_{ANK}) + (0.687 \times \text{front } M_{HIP}) + (0.241 \times \text{front } P_{KNE})$$

Assessing the squared part correlations for each predictor variable revealed that 23%, 15% and 15% of the total variance in NAHP was uniquely explained by rear $M_{ANK,}$ front M_{HIP} and front P_{KNE}, respectively, meaning that 2% was explained by shared variance amongst the predictors.

*****TABLE 2 NEAR HERE*****

Discussion

The aim of this study was to investigate the relationships between lower limb joint kinetics, external kinetics, and overall performance in the starting block phase of athletic sprinting in order to further understand the lower limb joint kinetic determinants of performance. Key findings highlighted that 86% of the variation in block performance was explained by the horizontal force applied to the front and rear blocks, and at the joint level 55% of the variation in block performance was explained by average rear ankle extensor moment, front hip extensor moment and front knee positive extensor power.

The importance of maximising total F_Y was confirmed with NAHP sharing 86% of its variance with the magnitude of average horizontal force produced in the front and rear block. The standardised regression coefficients (0.964 and 0.951) and Part^2 correlations (0.66 and 0.65) for front and rear F_Y, respectively (Table 1) suggest neither front nor rear F_Y had significantly greater predictive ability for NAHP. The lack of front or rear block dominance is somewhat in agreement with Willwacher et al. (2016) who showed a tendency towards force application in the rear block being of greater importance for block performance but ultimately demonstrated the importance of high force application to both blocks. Therefore, from an external kinetic perspective, maximising total average horizontal force appears to be the key characteristic of successful block performance. Interestingly, the sum of the front and rear Part^2 was greater than the model R^2 (Table 1), indicating a situation of cooperative suppression (Cohen, Cohen, West, & Aiken, 2003) which can be explained by the negative correlation between front and rear F_Y (r = -0.53). Therefore, a scenario by which a negative interaction between front and rear F_Y may exist and therefore athletes may have individual preferences on either rear or front block force production. Negative interactions in sprinting have also been identified for step length and frequency (Hunter, Marshall, & McNair, 2004) with the existence of individual reliance (Salo, Bezodis, Batterham, & Kerwin, 2011) typically being attributed to different neuromuscular factors. From the current data, it is difficult to elucidate the mechanisms underpinning individual preference for front or rear force production, although differences in set position and the neuromuscular capacity of each leg could be interesting avenues for future research.

Given the importance of maximising total F_Y highlighted in this investigation and others (Otsuka et al., 2014; Rabita et al., 2015; Willwacher et al., 2016), the next step was to explore the relationships between kinetic data at the ankle, hip and knee joint and external F_Y, in order to gain a deeper understanding of the strategies that superior performers adopt during the starting block phase. For the

rear block, both M_{ANK} and M_{HIP} were almost certainly positively related to rear F_Y (r = 0.83 and 0.80, respectively, Figure 1) which supports previous findings of the large role of the ankle and hip joint in generating force in the rear block (Brazil et al., 2017; Mero et al., 2006). At the joint power level the strength of relationship for the ankle joint decreased considerably (r = 0.41, likely), whilst P_{HIP} was still almost certainly positively related to rear F_Y (r = 0.73). Therefore, generating high initial magnitudes of force and power at the rear hip early in the rear block phase (Figure 3) coupled with large ankle moments to effectively apply these forces into the rear block could be the determining characteristics of the magnitude of horizontal force generated in the rear block. Rear knee kinetic data were not included in the present analysis because of the low magnitude of extensor moments and power (Figure 3; Brazil et al., 2017).

In the front block, correlation strength for M_{ANK} (r = 0.83), M_{KNE} (r = 0.63) and M_{HIP} (r = 0.43) with F_Y increased when moving from proximal to distal. Whilst hip joint moments were largest in magnitude for the front leg, the temporal similarity between front F_Y, M_{ANK} and M_{KNE} (Figure 3) may help explain why the more distal joints possessed stronger relationships with the magnitude of horizontal force applied to the front block . Although there was a distinct difference with each r-value, as M_{KNE} and M_{HIP} were still very likely and likely related to front F_Y, respectively, it is very difficult to conclude that there was one joint in the kinetic chain that explained the between-athlete variability in front block horizontal force. At the joint power level, the knee was the only joint that possessed a very likely positive relationship with front F_Y (r = 0.57). Thus, although all joint moments appeared important in explaining front F_Y it was the ability to organise powerful extension at the knee joint that was found to be most strongly related to the magnitude of horizontal force applied to the front block. Therefore, with respect to strength and power development, exercises that elicit large moments at the ankle, knee and hip joint, whilst emphasising knee joint power production during triple extension would satisfy specific-overload with respect to the block start.

Whilst the current data have provided information relating to the joint kinetic determinants of horizontal force applied to the front and rear block, it was of further interest to investigate whether these relationships extended to overall starting block performance. This was exploratory in nature because it was already established that there were clearly different individual strategies with respect to front and rear F_Y but together they explain 86% of the variation in NAHP. Figures 1 and 2 highlighted that one rear leg (M_{ANK}) but five front leg (M_{ANK}, M_{HIP}, P_{ANK}, P_{KNE} and P_{HIP}) joint kinetic variables possessed at

least a likely positive relationship with NAHP (r = 0.39 to 0.46). When evaluating the individual bivariate correlations, the strongest positive relationship with NAHP was found at the front hip joint (M_{HIP} r = 0.46) and supported previous investigations that have detailed the importance of the hip joint in executing the block phase (Bezodis et al, 2015; Mero et al., 2006; Slawinski et al., 2010).The six aforementioned variables were input into a stepwise multiple regression analysis with NAHP and the best regression model utilised three of these variables (front M_{HIP}, rear M_{ANK}, front P_{KNE}) which explained 55% of the variation in NAHP (Table 2). Of the three predictors, it was shown that 15%, 23% and 15% of the variation in NAHP was uniquely explained by front M_{HIP}, rear M_{ANK} and front P_{KNE}, respectively, with the remaining 2% being the shared variance amongst the independent variables (Table 2).

The results of the multiple regression were not necessarily aligned with those variables highly associated with rear or front F_Y (i.e. rear M_{HIP} and P_{HIP}, and front M_{KNE}) and may again reflect individual dominances in front and rear force application. However, results of the current regression analysis can be used to understand the main strategies required for successful starting block performance. Hip moments at the front leg are large and extensor for approximately 80% of the block phase (Figure 3) and thus can have a considerable opportunity to influence block performance, whilst the main phase of positive extensor knee power in the front leg coincides temporally with peak external power (Figure 3) and has previously been shown to have the largest between-athlete variability (Brazil et al., 2017). High extensor moments at the rear ankle may reflect a neuromuscular characteristic of superior block performers that ensures a stiff ankle complex that assists the effective application of the large forces generated in minimal time.

Because the moment and power phases for each joint analysed in the present study occupy different durations of total block time (Figure 3), there may be limitations with bivariate correlations not recognising the importance of a certain joint in a temporal sequence. A specific temporal sequence of leg extension in the block phase has previously been highlighted (Brazil et al., 2017) and therefore coordinating the extension of both legs may be an important factor for maximising start performance. The current data has identified many very likely and almost certain positive bivariate relationships between all joints and their respective F_Y, and therefore the interaction between these joints is conceivably pertinent to block performance. Further research should therefore investigate the kinematic and kinetic interactions to keep improving scientific knowledge of block start performance. Previous research has identified the important contribution of the upper limbs and trunk to overall motion of the

CM during sprint acceleration (Slawinski et al., 2010; 2017). Although upper body joints were not included in the present study, it would be of interest in future work to investigate whether including joint kinetics of the upper body could help to explain more of the variation in starting block performance.

Results from this study can be used to provide practical directions for physical preparation programmes and exercise selection. An emphasis placed on the ankle plantarflexors and hip extensors should occur when selecting exercises to develop lower limb strength, and could be achieved through the use of straight bar deadlifts as opposed to hexagonal bar deadlifts or squat variations (Swinton, Stewart, Agouris, Keogh, & Lloyd, 2011; Swinton, Lloyd, Keogh, Agouris, & Stewart, 2012). However, when selecting exercises that target power development, an emphasis placed on power generation at the knee joint during triple extension could result in the greatest adaptations that can positively impact upon starting block performance. Therefore, with respect to extensor power generation, the more knee dominant jump squat (Jandacka, Uchytil, Farana, Zahradnik, & Hamill, 2014) may be more appropriate than more hip dominant variations of Olympic lifting (Kipp et al., 2016). The temporal pattern of joint moment and power data must be acknowledged within physical preparation in order for strength and power capabilities to be developed effectively for the nature of the starting block phase. At present few investigations exist that directly compare both joint kinematics and kinetics between different strength and power training exercises. Thus, a deeper biomechanical understanding of training exercises is necessary so that more objective decisions can be made to select exercises that target the development of the key determinants of starting block performance.

In conclusion, the current study has confirmed the importance of ensuring high total average horizontal force for successful starting block performance, and added further information identifying that joint moments at the rear ankle and hip, and front ankle, knee and hip were all very likely to almost certainly positively related to the magnitude of horizontal force applied to their respective block. Novel findings identified that the key joint kinetic determinants of block performance were rear ankle extensor moment, front hip extensor moment and front knee positive extensor power, and should be considered alongside the individual bivariate correlations in order to more completely understand the lower limb joint kinetic strategies adopted by superior block performers.

Disclosure Statement

No potential conflict of interest was reported by the authors

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Table 1. External kinetic regression model for starting block performance (NAHP)

Model		Coefficients	95% confidence intervals	Standardised Coefficients	Part^2
Dependent:	NAHP	Con. -0.244	-0.430 – -0.059		
Independent(s):	Front F_Y	0.758	0.555 – 0.961	0.964	0.66
R^2 = 0.86	Rear F_Y	0.527	0.384 – 0.670	0.951	0.65
R^2 Adj. = 0.84					

Note: R^2 Adj = R^2 adjusted, Part^2 = squared part correlation

Table 2. Joint kinetic regression model for starting block performance (NAHP)

Model		Coefficients	95% confidence intervals	Standardised Coefficients	Part^2
Dependent:	NAHP	Con. 0.240	0.062 – 0.418		
Independent(s):	Front M_{HIP}	0.687	-0.027 – 1.402	0.402	0.15
R^2 = 0.55	Rear M_{ANK}	1.040	0.167 – 1.912	0.488	0.23
R^2 Adj. = 0.44	Front P_{KNE}	0.241	-0.013 – 0.495	0.401	0.15

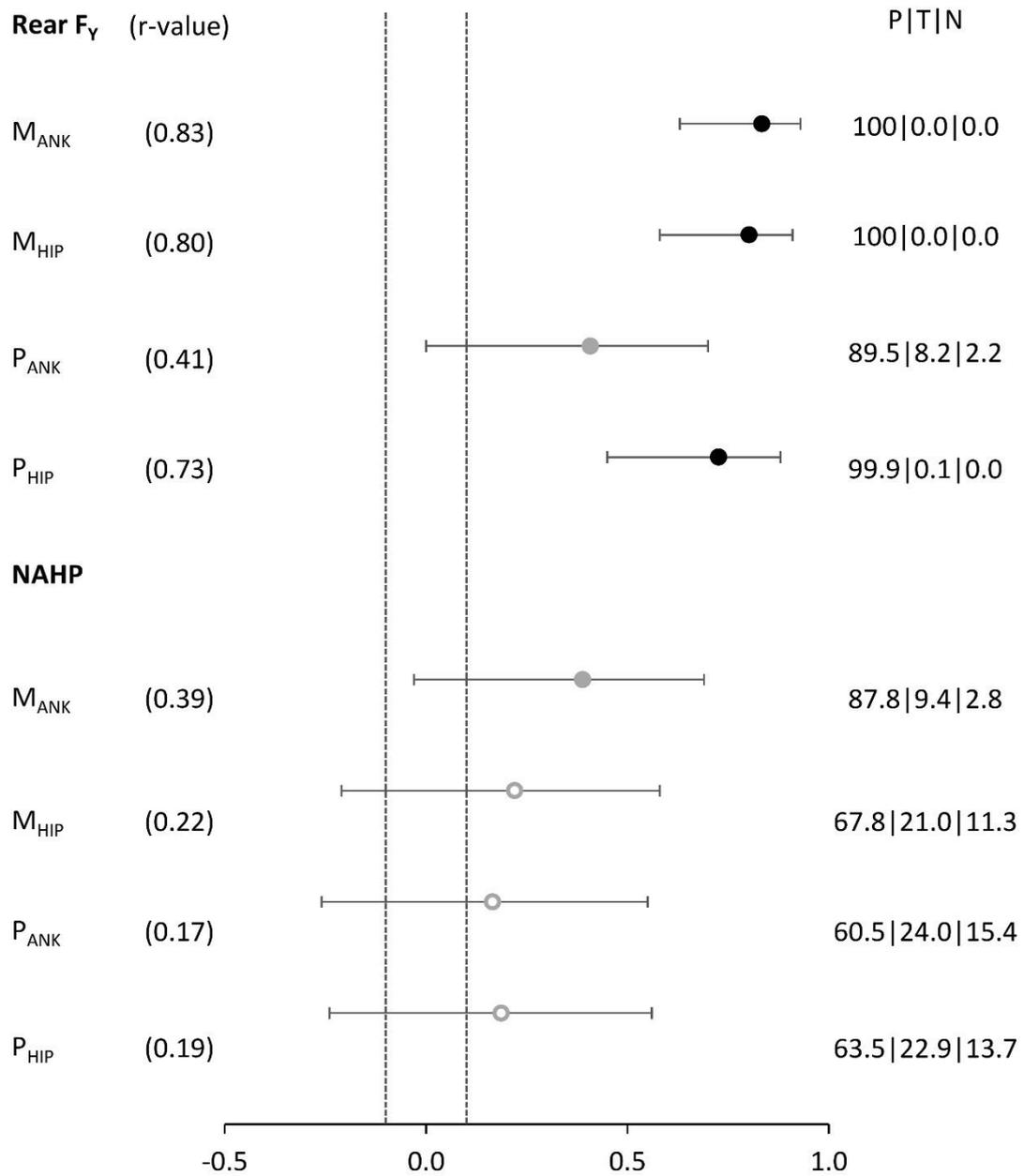Note: R^2 Adj = R^2 adjusted, Part^2 = squared part correlation

Figure 1. Pearson correlation coefficients (± 90% CI) between rear block joint kinetic data and rear block horizontal force (rear F_Y) and starting block performance (NAHP). Central area (r = -0.1 to 0.1) indicates a trivial relationship. Percentages represent the likelihoods that the relationship is truly positive | trivial | negative. Marker colour indicates unclear (grey outline), likely (grey fill), very likely (black outline), and almost certain (black fill) relationships.
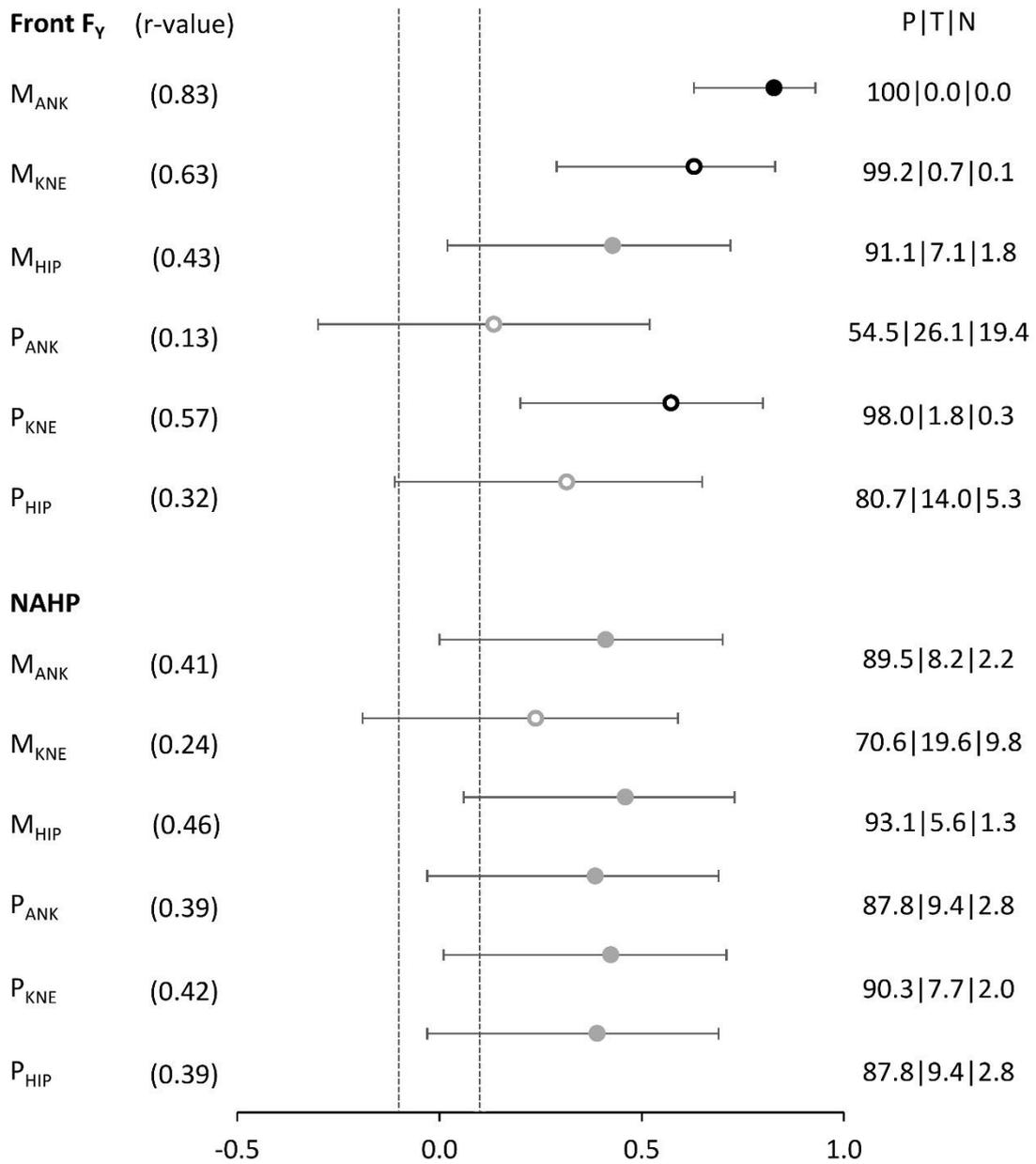
Figure 2. Pearson correlation coefficients (± 90% CI) between front block joint kinetic data and front block horizontal force (front F_Y) and starting block performance (NAHP). Central area (r = -0.1 to 0.1) indicates a trivial relationship. Percentages represent the likelihoods that the relationship is truly positive | trivial | negative. Marker colour indicates unclear (grey outline), likely (grey fill), very likely (black outline), and almost certain (black fill) relationships.
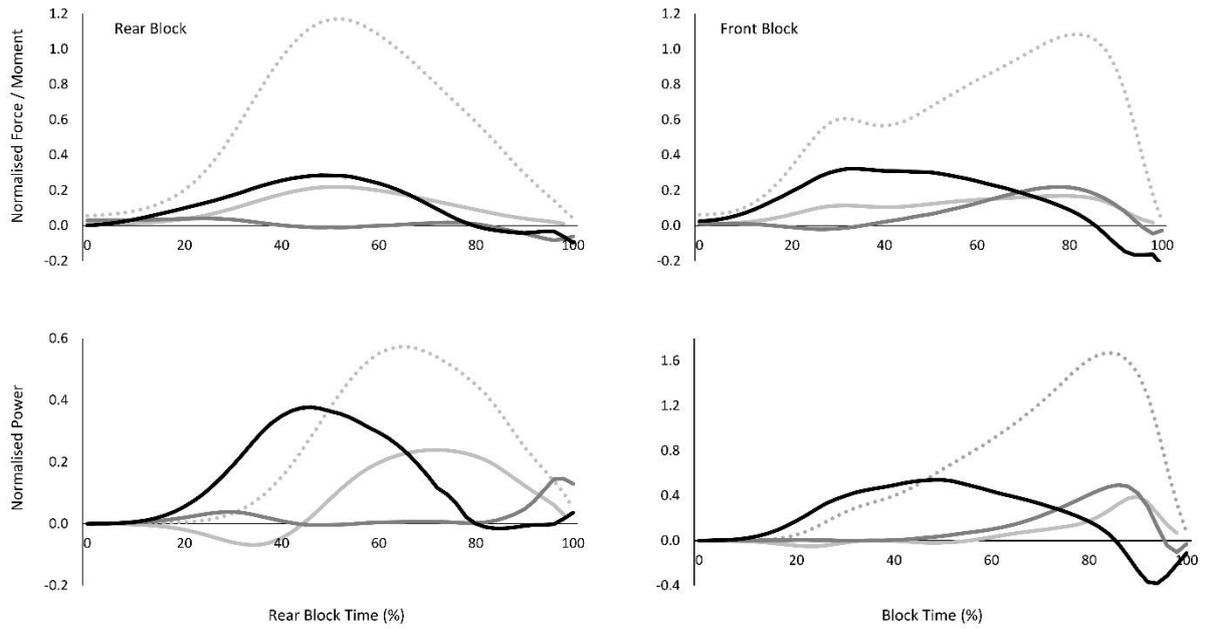
Figure 3. Ensemble mean curves for ankle (light grey line), knee (dark grey line) and hip (black line) moment (top) and power (bottom), and external force (dotted line, top) and power (dotted line, bottom) for the rear (left) and front (right) block during the starting block phase. Note: rear/front external power was calculated as the product of rear or front F_Y and total velocity of the CM.