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Calculation of the centre of pressure on the athletic starting block

Yuji Ohshima[a], Neil E. Bezodis[b], Ryu Nagahara[c*]

a) Institute for General Education, Ritsumeikan University, Kusatsu, Shiga, Japan
b) Applied Sports, Technology, Exercise and Medicine Research Centre, Swansea University, Swansea, Wales, UK
ORCiD: 0000-0003-2229-3310
c) Sports Performance Research Center, National Institute of Fitness and Sports in Kanoya, Kanoya, Kagoshima, Japan
ORCiD: 0000-0001-9101-9759

[*]Corresponding author:
Ryu Nagahara
Sports Performance Research Center, National Institute of Fitness and Sports in Kanoya
Address: 1 Shiromizu-cho, Kanoya, Kagoshima 891-2393, Japan
Tel: +81-994-46-5034
E-mail: nagahara@nifs-k.ac.jp

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Abstract

We aimed to evaluate the accuracy of a new method to calculate the centre of pressure (COP) on a starting block above a force platform, and to examine how this method affected lower extremity joint torques during the block clearance phase compared against a previously used method which projects the COP from the metatarsophalangeal joint. To evaluate the accuracy of the new method, one experimenter applied force at 18 known locations on a starting block (under six block position and orientation conditions), during which ground reaction force was recorded underneath using a force platform. Two sprinters then performed three block starts each, and lower extremity joint torques were calculated during block clearance using the COP obtained from the new method and from the projection of the metatarsophalangeal joint location. The calculated COP using the new method had a mean bias of ≤0.002 m. There were some large differences (effect sizes = 0.11–4.01) in the lower extremity joint torques between the two methods which could have important implications for understanding block clearance phase kinetics. The new method for obtaining the COP on a starting block is highly accurate and affects the calculation of joint torques during the block clearance phase.

Key words: ground reaction force, COP, sprint running, inverse dynamics, track and field

Introduction

Calculating net joint torque and power, as well as the contribution of muscular contractions to whole body acceleration, are of great benefit for understanding the causes of movement. Such calculations have been widely applied in the study of the start and early acceleration in sprinting (Bezodis, Salo, & Trewartha, 2014; Brazil et al., 2017; 2018; Charalambous, Irwin, Bezodis, & Kerwin, 2012; Debaere, Delecluse, Aerenhouts, Hagman, & Jonkers, 2015; Debaere et al., 2017; Mero, Kuitunen, Harland, Kyrolainen, & Komi, 2006). To perform these calculations, a specific location of force application, termed the 'centre of pressure' (COP), is required in addition to the ground reaction force (GRF) magnitude and direction, the position and orientation of all segments within a rigid-body model, and the inertia parameters of these segments (Winter, 2009). The COP is normally determined from the forces applied at each of four triaxial transducers within a force platform (Winter, 2009).

Performance levels during the block clearance phase at the start of a race are strongly associated with 100-m personal best times (Mero, 1988; Bezodis, Salo, & Trewartha, 2015; Willwacher et al., 2016), and thus the block clearance phase is important for overall sprint performance. To perform a lower extremity inverse dynamics analysis during this phase, the COP on the starting block surface, rather than the ground level, is necessary. Although several studies have calculated lower extremity joint torques during the block clearance phase using a force platform embedded in the floor (Debaere et al., 2017; Mero et al., 2006; Otsuka, Kurihara, & Isaka, 2015), these studies did not report how the COP on the starting block surface was determined. Other studies of lower extremity joint torques during the block clearance phase (Brazil et al., 2017, 2018) have used custom-made starting blocks which were instrumented with four triaxial transducers in each block face (Willwacher, Küsel-Feldker, Zohren, Herrmann, & Brüggemann, 2013), and similarly instrumented blocks are now commercially available. In these studies, a 'virtual landmark that projected the metatarsophalangeal (MP) joint centre onto the surface of the block was used to define centre of pressure' (Brazil et al., 2017, p. 1631; 2018, p. 1657) on each block face. Although a projection from the MP joint provides an alternative way to estimate the COP when the COP cannot be directly obtained, this assumption would induce errors in the lower extremity joint torque calculations if the true COP is not located at this point. Moreover, using the MP joint location cannot provide the free moment at the COP. Using a simple coordinate transformation, the COP on a single starting block footplate which is independently secured on a force platform, as depicted in Figure 1, can be calculated theoretically by solving the following simultaneous equation:

$$\left(\begin{bmatrix}\vec{r}_x^{OB}\\ \vec{r}_y^{OB}\\ \vec{r}_z^{OB}\end{bmatrix} + \begin{bmatrix}a_{1,1} & a_{1,2} & a_{1,3}\\ a_{2,1} & a_{2,2} & a_{2,3}\\ a_{3,1} & a_{3,2} & a_{3,3}\end{bmatrix}\cdot\begin{bmatrix}\vec{r}_x^{BP}\\ \vec{r}_y^{BP}\\ \vec{r}_z^{BP}\end{bmatrix}\right)\times\begin{bmatrix}{}^{O}f_x\\ {}^{O}f_y\\ {}^{O}f_z\end{bmatrix} + \begin{bmatrix}a_{1,1} & a_{1,2} & a_{1,3}\\ a_{2,1} & a_{2,2} & a_{2,3}\\ a_{3,1} & a_{3,2} & a_{3,3}\end{bmatrix}\cdot\begin{bmatrix}0\\ 0\\ {}^{B}n_z^{couple}\end{bmatrix} = \begin{bmatrix}{}^{O}n_x^{total}\\ {}^{O}n_y^{total}\\ {}^{O}n_z^{total}\end{bmatrix} \qquad (1)$$

where $\vec{r}_x^{OB}$, $\vec{r}_y^{OB}$ and $\vec{r}_z^{OB}$ are coordinates of the origin of the starting block coordinate system (*B*) in the force platform (global) coordinate system (*O*), in which the origin is set at the centre of force platform at ground level; $a_{1,1}$ to $a_{3,3}$ are the components of a coordinate transformation matrix of the force platform coordinate system (*O*) to the starting block coordinate system (*B*); $\vec{r}_x^{BP}$, $\vec{r}_y^{BP}$ and $\vec{r}_z^{BP}$ are the coordinates of the COP (*P*) in the starting block coordinate system (*B*); ${}^{O}f_x$, ${}^{O}f_y$ and ${}^{O}f_z$ are applied forces onto the ground in the force platform coordinate system (*O*); ${}^{B}n_z^{couple}$ is the free moment applied on the x'y' plane of the starting block coordinate system (*B*); and ${}^{O}n_x^{total}$, ${}^{O}n_y^{total}$ and ${}^{O}n_z^{total}$ are applied moments around the origin of the force platform coordinate system (*O*). In the case where the COP (*P*) is on the x'y' plane of the starting block coordinate system (*B*), $\vec{r}_z^{BP}$ is equal to zero.

The above-described equation makes it possible to define the COP using the coordinate system of the starting block, and GRFs and moments recorded on a force platform underneath the block. Thus, this equation can be used in studies requiring the COP during the block clearance phase, provided that the exact location of each starting block relative to an independent force platform underneath is known (e.g. through direct measurement or the attachment of markers). In this study, we firstly evaluated the accuracy of the aforementioned calculation of the COP on the starting block. Secondly, we examined the influence of the COP on the lower extremity joint kinetics to address the following hypothesis: there will be differences in the lower extremity joint kinetics during the block clearance phase when determining the COP using equation (1) compared with when determining it from a projection from the MP joint. If the suggested calculation is valid and our hypothesis is accepted, these methods will be important for use in future studies which calculate joint kinetics during the block clearance phase in sprinting.

Methods

This study was conducted in two stages. Firstly, the accuracy of the new method to calculate COP was determined by applying force onto multiple known locations on the starting block. Secondly, to address our hypothesis, the influence of different COP calculations on the lower extremity joint kinetics was investigated with data collected during the sprint start. This study was approved by the Ethics Committee of the National Institute of Fitness and Sports in Kanoya, Japan.

Accuracy of centre of pressure location

GRF during the test was recorded using a force platform which has four strain gauge force transducers (0.32 × 1.2 m [width × length]; TF-32120, Tec Gihan, Kyoto, Japan; 1000 Hz; accuracy < 1%; crosstalk < 2%; natural frequency being >185 Hz for the vertical direction and >220 Hz for the anteroposterior and mediolateral directions). A starting block rail (Super III NF155B, Nishi, Tokyo, Japan), which is permitted for use in official races, was bolted at four locations to the force platform covered by athletic track surface as depicted in Figure 2. Thus, the block itself could be relocated easily, and in exactly the same ways as which it could in a race.

One experimenter used a rod with a pointed tip to apply force at 18 specific locations on the starting block in each of three block positions (forward, middle and back on the rail [M1 in Figure 3 was 0.49, 0.28 and 0.08 m in the anteroposterior direction and consistently −0.09 m in the mediolateral direction from the centre of the force platform]) and at two different block angles (low and high inclinations [44.5 and 57.2° between the upper surface and the level ground]) (in total, 6 conditions and 108 trials). The experimenter pressed the block surface with maximal effort (resultant force being 372.2 ± 20.9 N) at an angle of approximately 55° from the ground in the sagittal plane, which is representative of the mean angle of force application against the starting blocks (Rabita et al., 2015).

Before applying force to the block surface, the locations of the force application were determined using a motion capture system (Raptor-E, Motion Analysis Corporation, Santa Rosa, CA, USA; 250 Hz, 10 cameras) for each condition. Small retro-reflective markers (11 mm in diameter) were affixed to the surface of the starting block at 18 specific locations (Figs. 2 and 3), after which they were removed and forces were applied to the locations under the markers (the distance from the centre of the marker to the block surface was 6 mm and was accounted for in subsequent calculations).

Using the marker coordinates on the starting block, recorded raw GRF, and moment data around the centre of the force platform at ground level, COP values on the surface of the starting block were calculated using equation (1). COP values were calculated by separating the starting block surface in to three parts, using each of six markers on lower (M1 to M6), middle (M7 to M12) and higher (M13 to M18) positions on the surface. In the case of the lower part, the origin of starting block coordinate system was set at M1 in Figure 3. The Y-axis (y') of the lower part of the starting block's coordinate system was defined by the vector running from M1 to M3 in Figure 3. The Z-axis (z') of the lower part of the starting block's coordinate system was defined as the vector product of the vector running from M1 to M4 and y' in Figure 3. The X-axis (x') of the lower part of the starting block's coordinate system was defined as the vector product of y' and z'. In the case of the lower part of the starting block's coordinate system, inputs for coordinate transformation in equation (1) were as follows:

$$\begin{bmatrix} \vec{r}_x^{OB} \\ \vec{r}_y^{OB} \\ \vec{r}_z^{OB} \end{bmatrix} = \begin{bmatrix} M1_x \\ M1_y \\ M1_z \end{bmatrix} \quad (2)$$

where M1 is the coordinate of the M1 marker in Figure 3.

$$\begin{bmatrix} a_{1,1} & a_{1,2} & a_{1,3} \\ a_{2,1} & a_{2,2} & a_{2,3} \\ a_{3,1} & a_{3,2} & a_{3,3} \end{bmatrix} = \begin{bmatrix} x'_x & y'_x & z'_x \\ x'_y & y'_y & z'_y \\ x'_z & y'_z & z'_z \end{bmatrix} \qquad (3)$$

where x', y' and z' indicate the coordinate system of the lower part of the starting block. Because all variables except for $\vec{r}_x^{BP}$, $\vec{r}_y^{BP}$ and ${}^{B}n_z^{couple}$ are known ($\vec{r}_z^{BP}$ is 6 mm as the height of the centre of the markers from the starting block surface), equation (1) can be solved, and $\vec{r}_x^{BP}$, $\vec{r}_y^{BP}$ and ${}^{B}n_z^{couple}$ can be obtained. COP values and free moments in the middle and higher parts of the starting block were calculated using the same procedure with their origins at M7 and M13, respectively (Fig. 3).

The COP calculated using equation (1) with the force platform data for each location for 1 s during the middle of the force application duration was averaged for statistical analysis.

Means and standard deviations for values obtained by both the new method and reference values, as well as the difference between the two, were reported for all variables. Moreover, 95% limits of agreement (LoA) between values from the new method and the reference values were calculated.

Comparison of the lower extremity joint kinetics

Two male sprinters participated in this study (age, both 20 yrs; stature, 1.75 and 1.72 m; body mass, 61.5 and 63.6 kg). The participants gave written informed consent before participating in this study. After a self-directed warm-up, the participants, wearing their own spiked shoes, performed three maximal effort 3 m sprints from starting blocks (their feet were only in contact with starting blocks throughout the block clearance phase; no part of the foot touched the ground). Lower extremity motion was recorded using a motion capture system (Raptor-E, Motion Analysis Corporation, Santa Rosa, CA, USA; 250 Hz, 10 cameras). GRF and moment underneath the right block during the block clearance phase were measured using the same force platform mentioned above. The block used was the front block for one participant and the rear block for the other. The locations and block angles were front low and middle high for each respective participant.

Markers were affixed to the toes (superior aspect of the distal ends of the shoes), the posterior aspect of the calcanei, the medial and lateral aspects of the first and fifth metatarsal heads, respectively, malleoli, femoral condyles, greater trochanters, anterior superior iliac spines, and posterior superior iliac spines. Segment endpoints were calculated from the three-dimensional coordinates of the markers to create a 7-segment body model consisting of feet, shanks, thighs and pelvis. Markers affixed to the toes and the posterior aspect of the calcanei were attached to the spiked shoes and were considered as endpoints of the feet segments. The midpoints of the markers affixed to the malleoli and femoral condyles were taken as the joint centres of the ankles and knees, respectively. The midpoints of the markers affixed to the first and fifth metatarsal heads were considered as the MP joint centre. The hip joint centre was defined as the point located 18% of the distance between the right and left great trochanters medially from the point located at one-third of the distance from the greater trochanter to the anterior superior iliac spine (Nagahara, Matsubayashi, Matsuo, & Zushi, 2014).

The segment endpoint coordinates and GRF, as well as moments around the centre of the force platform, were smoothed with a fifth-order spline filter (Woltring, 1986). The cut-off frequency for all data was standardised as 20 Hz (Bezodis, Salo, & Trewartha, 2013; Kristianslund, Krosshaug, & van den Bogert, 2012). Joint torques at the hip, knee and ankle during the block clearance were calculated using a standard inverse-dynamics analysis for the right leg (Winter, 2009). The moments applied around segmental centres of mass were initially calculated by differentiating each segment's angular momentum in the global reference frame. Subsequently, joint torques during the block clearance phase were computed from the lower-extremity kinematics, kinetics and body segment inertia properties based on an analysis of free-body-diagrams for each segment. The location of the centre of mass and the inertia parameters of the respective segments were estimated from the body segment parameters of Japanese athletes (Ae, 1996).

COP values for the inverse dynamics analysis were obtained using two methods: One was the new method based on equation (1), and the other was determined from the location of the MP joint centre. In the COP calculation using force platform data, five coordinate systems (the origin being M1, M4, M7, M10 and M13 in Fig. 3) on the starting block surface were set. When the COP moved below the origin of the used coordinate system, the coordinate system for calculating the COP was changed to the lower one. For the COP estimation from the MP joint coordinate, a location that projected the MP joint centre onto the surface of the block was used based on the approach of Brazil et al. (2017; 2018). Although not stated in the papers by Brazil et al. (2017, 2018), personal communications with the lead author of those studies revealed that the MP joint centre was projected perpendicularly onto the aforementioned block surface coordinate system to estimate the COP location. When the estimated COP moved below the origin of the used coordinate system, the coordinate system for estimating COP from the MP joint centre was changed to the lower one. The start of force production on the starting block was determined using the first derivative of the GRF applied perpendicularly to the block surface with a threshold of >500 N/s (Brazil et al., 2017). Toe-off was defined when the GRF applied perpendicularly to the block surface next fell below 50 N (Brazil et al., 2017). Average positive (extensor / plantar flexor) and negative (flexor / dorsiflexor) torques at the hip, knee and ankle joint were calculated for each trial, and the means and standard deviations across the three trials were determined. This provided consistency with the average positive torques included in the performance-determinant analysis of Brazil et al. (2018), and enabled quantification of some of the gross differences in joint torques between the two methods in addition to a qualitative interpretation of the torque time-histories at each joint. All the joint torque variables were expressed as mass specific values. Cohen's d was used to determine the effect size (ES) of the difference between joint torques calculated using the COP obtained by the new method and by the estimation from the MP joint location (Cohen, 1988). Threshold values for the interpretation of the ES were <0.2 (trivial), 0.2 – <0.6 (small), 0.6 – <1.2 (moderate), and ≥1.2 (large) (Hopkins, Marshall, Batterham, & Hanin, 2009).

Results

Table 1 shows the accuracy of the new method for calculating the COP, compared with the reference values. The mean differences in the COP between the reference and new method in the X, Y and Z axes were 0.002, −0.001 and 0.002 m, respectively. Moreover, the 95% LoA of the COP was $< \pm 0.006$ m for all directions.

Figure 4 shows the differences in the hip, knee and ankle joint torques in the sagittal plane from calculations using the COP values obtained by the new method and by the estimation from the MP joint location. For both participants (right leg on the front and rear block, respectively), hip and ankle joint torques calculated with the COP location estimated from the MP joint location were overestimated and then underestimated during the respective first and second halves of the force production durations during the block clearance phase. In contrast, knee joint torque calculated with the COP location estimated from the MP joint location for both participants were underestimated and then overestimated during the respective first and second halves of the force production durations during the block clearance phase.

Table 2 shows mean positive and negative hip, knee and ankle joint torques in the sagittal plane during the block clearance phase calculated using the COP values obtained by the new method and by the estimation using MP joint location for two participants who used the right leg as the rear and front leg on the block, respectively. Among the mean joint torque variables, positive and negative knee joint torque of the front leg (difference = 39.9 ± 17.5% and −24.9 ± 33.1%, ES = 1.50 and 1.69) and positive ankle joint torque of the front leg (difference = −10.5 ± 6.9%, ES = 2.04), as well as negative knee and positive ankle joint torques (difference = −25.3 ± 7.1% and −7.2 ± 1.6%, ES = 1.75 and 4.01) of the rear leg, showed large differences between the calculations using the COP values obtained by the new method and by the estimation using MP joint location.

Figure 5 shows the trajectories of the COP on the block surface obtained by the new method and by the estimation from the MP joint location for all trials. For both participants (right leg on the front and rear block, respectively), ranges of COP trajectories estimated from the MP joint location were considerably smaller than the ranges of COP trajectories calculated from the force platform data using the new method. Moreover, while the COP calculated using the new method initially moved backward on the block surface, the COP estimated using the MP joint location did not show this characteristic translation.

Discussion and implications

To our knowledge, this is the first study which has examined the accuracy of COP calculation on an athletic starting block using data obtained by a force platform, and which has established the influence of COP calculation methods on joint kinetics during the block clearance phase. The calculated COP using the new method based on equation (1) was accurate - it showed a mean bias of less than 2 mm and a random error (95% LoA) of less than ±6 mm when compared with reference COP locations determined using a motion capture system. Our hypothesis was then accepted as there were some large differences in the lower extremity joint torques during the block clearance phase when determining the COP using equation (1) compared with when determining it from a projection from the MP joint.

The < 2 mm bias for the COP calculated by the new method is small in the context of the distance moved by the COP on both of the blocks during the block clearance phase (Fig. 5), demonstrating the high relative accuracy of the new method for calculating the COP on the starting block. This bias also compares well with other values presented for novel COP determination methods during overground sprinting, such as 3 mm when combining COP data from two adjacent force platforms (Exell, Gittoes, Irwin, & Kerwin, 2012). Exell et al. (2012) reported that their bias in COP calculation equated to a change in joint torques ranging from 0.6% for the hip to 1.4% for the ankle in the sagittal plane during maximal speed sprinting. Based on these results, they concluded that the biases were sufficiently accurate, particularly in the context of errors in other inverse dynamics inputs (e.g. noise in kinematic data) for calculating joint torques (Exell et al., 2012). This provides further confidence that the new method for calculating COP is sufficiently accurate for use in inverse dynamics analysis. Using accurate COP values is very important for calculating net joint torque and power, as well as the contribution of muscular contractions to the body acceleration. Thus, our new method to obtain the COP on the starting block will enable more accurate calculation of joint kinetics during the block clearance phase.

Time-histories of the leg joint torques during the block clearance phase calculated using the COP estimated by MP joint location were visually different from those calculated using the COP computed from force platform data using equation (1) (Fig. 4). In general, for both legs, hip and ankle joint extensor and plantar flexor torques calculated using the COP estimated from the MP joint location were initially over-estimated during the early part of the respective pushing phase and then under-estimated during the second half of the respective pushing phase (Fig. 4). The knee joint torque calculated using the COP estimated from the MP joint location was under- and then over-estimated, during the respective first and second halves of the force production durations during block clearance (Fig. 4). The mean joint torques during the block clearance phase calculated using the COP estimated from the MP joint location showed a large (ES $\geq$ 1.2) under-estimation of ankle plantar flexion (7.2%) and knee flexion torques (25.3%) of the rear leg (Table 2). Moreover, knee extension and flexion torques of the front leg calculated using the COP estimated from the MP joint location were also largely over- (39.9%) and under-estimated (24.9%), respectively (Table 2). These results demonstrate that the calculation of joint torque using COP values estimated from the MP joint location causes errors in the calculated leg joint torque, especially at the knee joint.

As all other input data for the inverse dynamics analysis remained the same, the aforementioned over- and under-estimations of leg joint torques calculated using the COP estimated from the MP joint location resulted from the smaller range of translation of the COP compared with the true COP motion on the block surface (Fig. 5). During the first and second halves of the force production duration during the block clearance phase, the COP estimated from MP joint location was in front of and then behind the true COP calculated from the force platform data. Moreover, the COP estimated from the MP joint location only showed a small anterior motion compared with the more complex and initially posterior motion of the true COP (Fig. 5). These errors in the COP estimated from the MP joint location therefore led to the larger hip extension and ankle plantar flexion torques, as well as the smaller knee extension torques, during the first half of the force production, and then the smaller hip extension and ankle plantar flexion torques, as well as the larger knee extension torques, during the second half of the force production of the block clearance phase. Whilst the general patterns of the leg joint torque time-histories are consistent with those from previous studies of the block clearance phase (Brazil et al., 2017; Mero et al., 2006), there are some important differences. For example, Brazil et al. (2017) showed a flexor torque at the front knee during the early part (~20-40%) of the block clearance phase, and a similar feature was evident in this study when the COP was estimated from the MP joint location (Fig. 4e). Our new COP calculation method has revealed that this knee flexor dominance, which is seemingly counterintuitive given the demands of the movement, is in fact an artefact resulting from errors in COP location, and that an extensor torque is dominant at the front knee joint throughout the early part of the block clearance phase.

The current comparisons were undertaken as two case studies, and the equipment used (force platforms under the blocks in our study versus instrumented starting blocks used by Brazil et al., 2017; 2018), the participant ability levels (average 100 m personal best times of 11.20 s versus 10.50 s) and the anteroposterior lengths of the starting blocks (0.25 m versus 0.15 m) were also different between our study and the studies of Brazil et al. (2017; 2018). Whilst these could lead to some differences in the observed COP locations between studies, the lower extremity joint torque profiles estimated using the MP joint method in our study were consistent with those from previous research (Brazil et al., 2017; Mero et al., 2006). Furthermore, because we included our new COP calculation method as well as the exact one used by Brazil et al. (2017; 2018) in our current study, confidence can be placed in the generalisability of these findings. Where possible, based on the availability of separate block footplates attached to independent force platforms, our new method should be applied when the COP during the block clearance phase is required either as an outcome measure or as an input to further calculations such as in an inverse dynamics analysis. In the case of a commercially available instrumented starting block which can measure GRF and COP, as well as free moment, in the block coordinate system, attaching markers to known locations on the sides of the block will make it possible to obtain the location of COP and the GRF and free moment vectors in the global coordinate system through coordinate transformation so that an appropriate inverse dynamics analysis can be undertaken.

When multiple participants are recorded in one experimental session, the method used to obtain locations and angles of the starting block in the current study will be challenging to employ, because the block locations and angles are likely to be different between participants. However, attaching markers to specific locations on the sides of the starting block will enable these block settings to be determined. When the COP moves below the ground height based on the calculation of the COP on the block, it is considered that the COP is located on the level ground, and the calculation of COP can be done using the normal calculation on the level ground. A further issue could arise if the toe contacts the ground and produces a free moment on the ground when the COP is still on the starting block, as this will affect the location of the COP calculated by the proposed method. However, the effect of the free moment on the calculation of the COP is small, because the magnitude of the free moment is considerably smaller than the magnitude of the GRF. Finally, whilst somewhat high variabilities were evident in the difference in joint torques between the two methods (Fig. 4 and Table 2), these were primarily due to between-trial variability in performance (i.e. GRF production). One specific example of this is evident in the rear ankle joint torques (Figure 4c) - in the second trial, the participant produced a gradual increase in vertical force prior to producing any horizontal force which thus influenced the identification of the onset of force production (determined from the first derivative of the resultant force), explaining the apparent delay in rear ankle torque production. Due to the method-validation focus of this study, the participants were required to perform three maximal effort trials, but their levels of performance or their satisfaction with each attempt were not assessed during data collection. However, the between-trial variability evident in Table 2 serves to illustrate how the assumption of the COP being a projection from the MP joint could lead to inconsistent errors between trials as a result of typical variability in the forces produced by a sprinter.

Conclusions

This study validated a new method that can accurately determine the location of the centre of pressure on a starting block during a sprint start using data from a force platform located underneath the block. Moreover, comparison of the leg joint torques using this new method against those determined using the centre of pressures estimated from the metatarsophalangeal joint location demonstrates clear improvements and sometimes large differences in the calculation of joint torques. These differences may have important implications for the interpretation of joint kinetic strategies during the block clearance phase.

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Declaration of Conflicting Interests

The authors declare that there is no conflict of interest.

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Table 1 Comparison of COP coordinates determined using equation (1) against the reference values (pre-recorded marker coordinates). The values are means and standard deviations across the 108 trials in 6 conditions, except for 95% LoA.

Variables [unit]	Reference (marker)	FP method	Bias	95% LoA
Mediolateral coordinate [m]	−0.059 ± 0.024	−0.056 ± 0.023	0.002 ± 0.001	<0.001 to 0.005
Anteroposterior coordinate [m]	0.213 ± 0.170	0.212 ± 0.172	−0.001 ± 0.003	−0.006 to 0.003
Vertical coordinate [m]	0.084 ± 0.048	0.085 ± 0.048	0.002 ± 0.003	−0.003 to 0.006

LoA, limits of agreement

Table 2 Comparison of mean positive (extensor / plantar flexor) and negative (flexor / dorsiflexor) leg joint torques during the block clearance for each participant (one who used the right leg as the rear leg [Rear], and one who used the right leg as the front leg [Front] on the starting block). The values are means and standard deviations of three trials for each participant, except for ES.

	Variables [unit]		COP	MP	Difference	%Difference	ES
Rear	Positive torque [Nm/kg]	Hip	1.44 ± 0.10	1.36 ± 0.10	−0.08 ± 0.02	−5.7 ± 1.1	0.78
		Knee	0.25 ± 0.06	0.28 ± 0.05	0.03 ± 0.03	−12.4 ± 13.4	0.48
		Ankle	0.68 ± 0.01	0.63 ± 0.01	−0.05 ± 0.01	−7.2 ± 1.6	4.01
	Negative torque [Nm/kg]	Hip	−0.12 ± 0.09	−0.13 ± 0.08	−0.01 ± 0.01	16.3 ± 20.4	0.11
		Knee	−0.30 ± 0.04	−0.22 ± 0.05	0.07 ± 0.01	−25.3 ± 7.1	1.75
		Ankle	−0.01 ± 0.01	−0.02 ± 0.02	−0.01 ± 0.01	140.1 ± 194.0	0.83
Front	Positive torque [Nm/kg]	Hip	1.83 ± 0.03	1.80 ± 0.09	−0.03 ± 0.06	1.9 ± 3.5	0.51
		Knee	0.84 ± 0.12	1.18 ± 0.31	0.35 ± 0.19	39.9 ± 17.5	1.50
		Ankle	0.95 ± 0.07	0.85 ± 0.02	−0.10 ± 0.07	−10.5 ± 6.9	2.04
	Negative torque [Nm/kg]	Hip	−1.29 ± 0.06	−1.33 ± 0.10	−0.04 ± 0.05	3.0 ± 3.6	0.48
		Knee	−0.32 ± 0.06	−0.23 ± 0.05	0.09 ± 0.11	−24.9 ± 33.1	1.69
		Ankle	0	0	0	0	

ES, effect size calculated using Cohen's d.

Figure captions

Figure 1 Schematic of the coordinate transformation from the force platform coordinate system (*O*) to the starting block coordinate system (*B*) for calculating the COP and free moment on the starting block using the GRF and moment data collected by the force platform.

Figure 2 Depiction of the experimental set-up for the COP validation study including the force platform, starting block and rail, and markers on the starting block.

Figure 3 Schematic of marker locations on the starting block for the COP validation study. M1 to M18 indicate marker names.

Figure 4 Hip, knee and ankle joint torques in the sagittal plane for all three trials of each participant calculated using the COP locations obtained by the new method (solid lines) and by the estimation using the MP joint projection (dotted lines). The upper row shows (a) hip, (b) knee and (c) ankle joint torques of the right leg on the rear block for participant 1, while the bottom row shows (d) hip, (e) knee and (f) ankle joint torques of the right leg on the front block for participant 2. Light grey, dark grey and black lines indicate the first, second and third trials, respectively.

Figure 5 COP locations on the starting block surface for two participants calculated using the force platform data with the new method (solid line) and estimated from the MP joint location (dotted line). The left three panels show COP locations for the right leg on the rear block (participant 1), while the right three panels show COP locations for the right leg on the front block (participant 2). ‘Start’ and ‘end’ indicate the start of force production and the toe-off, respectively. The origin in each panel is location M7 (see Fig. 3).

Figure 1

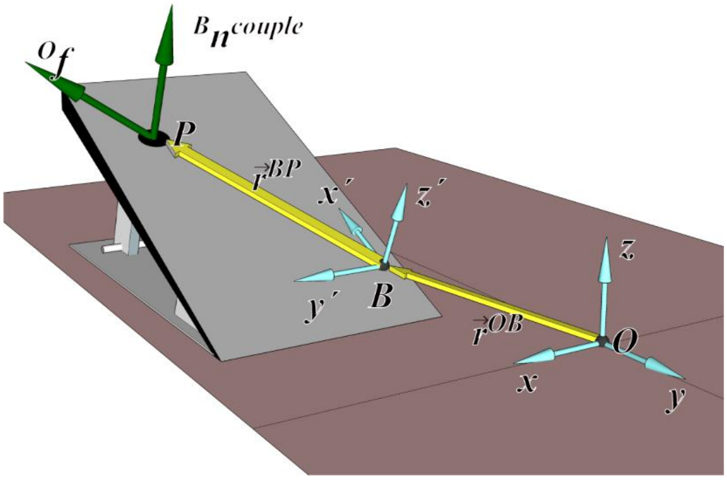


Figure 2

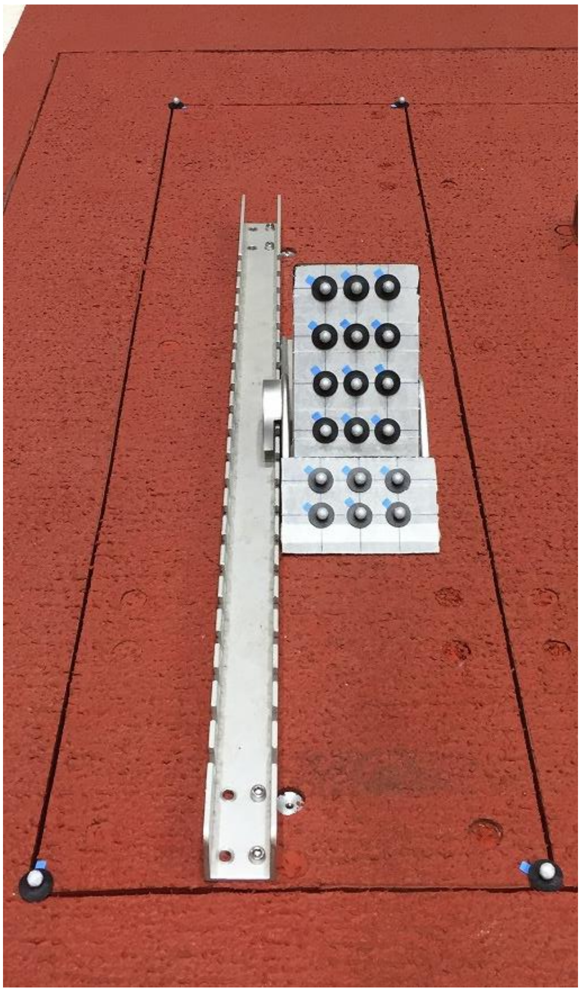


Figure 3

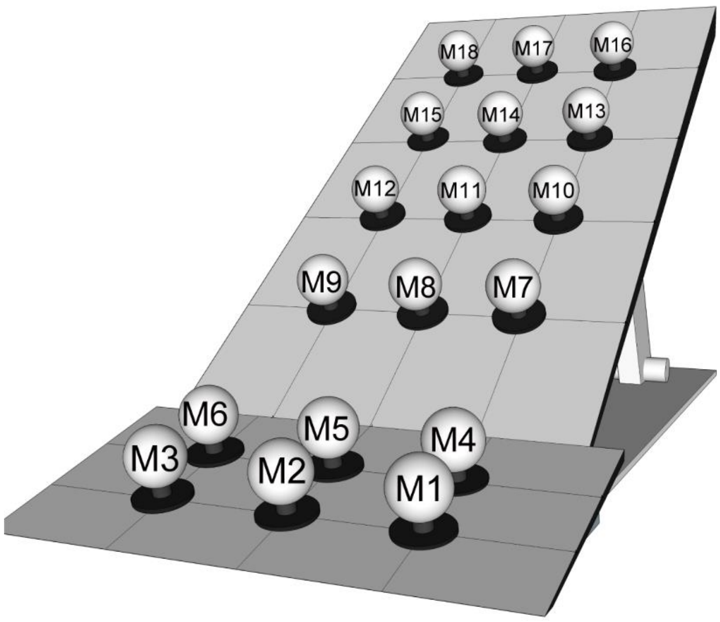


Figure 4

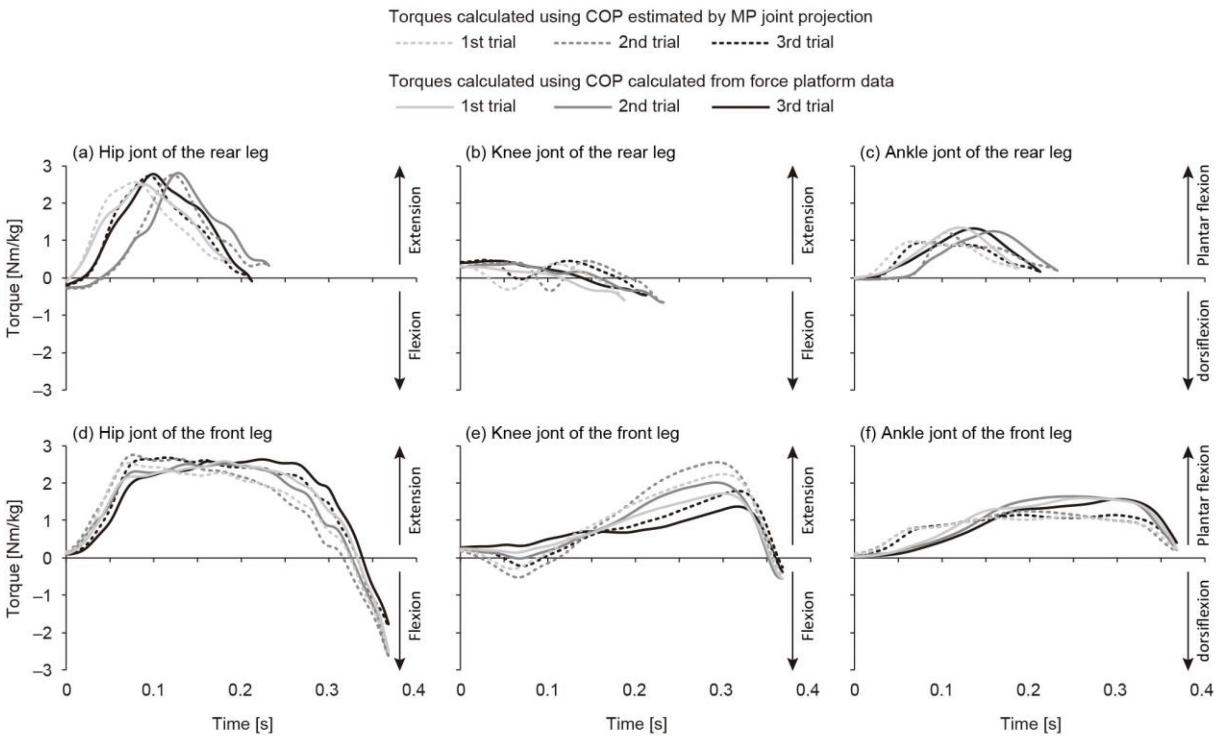
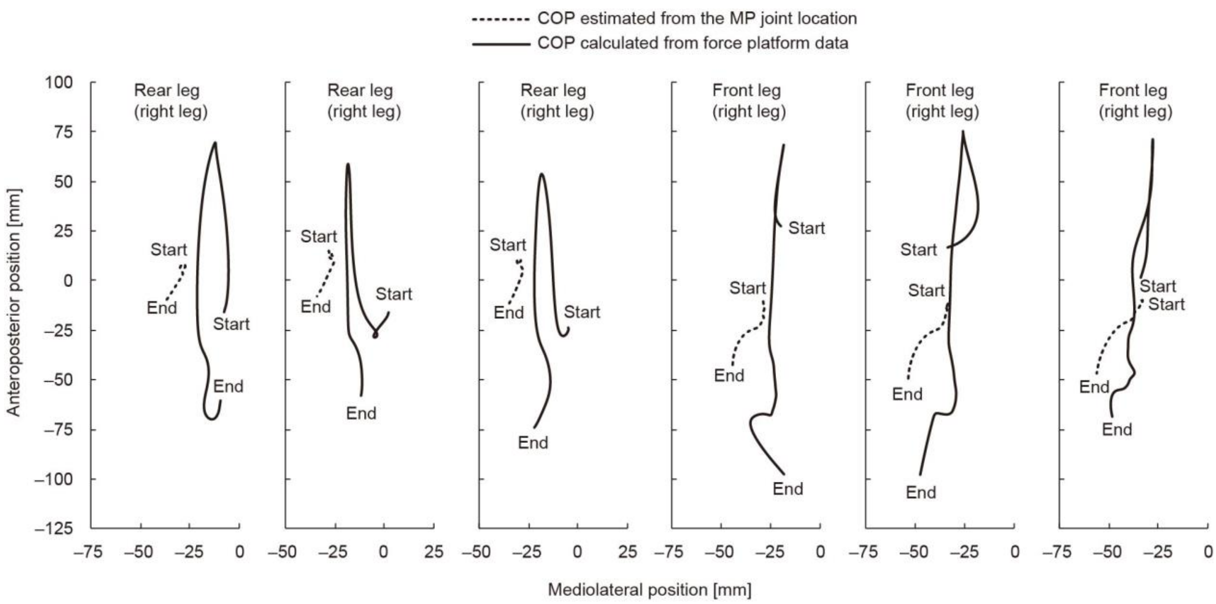

Torques calculated using COP estimated by MP joint projection
1st trial
2nd trial
3rd trial
Torques calculated using COP calculated from force platform data
1st trial
2nd trial
3rd trial
(a) Hip jont of the rear leg
(b) Knee jont of the rear leg
(c) Ankle jont of the rear leg
(d) Hip jont of the front leg
(e) Knee jont of the front leg
(f) Ankle jont of the front leg
Torque [Nm/kg]
Extension
Flexion
Plantar flexion
dorsiflexion
3
2
1
0
−1
−2
−3
0
0.1
0.2
0.3
0.4
Time [s]

Figure 5



COP estimated from the MP joint location
COP calculated from force platform data
Rear leg (right leg)
Rear leg (right leg)
Rear leg (right leg)
Front leg (right leg)
Front leg (right leg)
Front leg (right leg)
Start
End
Anteroposterior position [mm]
Mediolateral position [mm]