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Isolated Unweighted Fast Knee-Flexions Relate to Maximal Step Frequency and Sprint Speed in Female Track Athletes

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ABSTRACT

We recently introduced an on-field test to quantify knee flexor fatigue in male soccer players using Peak Angular Acceleration of the shank (PAA) during isolated unweighted fast knee flexions. Unexpectedly, we found a positive relation between PAA and 45 m sprint performance in the unfatigued players.

This study investigates (1) whether PAA is also positively related to sprint performance in a completely different population—16 female athletes— (2) whether it differs between the first and the second 30 m of a 60 m sprint, and (3) its relationship with step frequency and step length in both phases. Participants wore IMUs on both feet and the shank of the dominant leg. Time gates were placed at 30 and 60 m. Participants performed a series of six fast knee flexions (5s in between) with the dominant leg in a prone position on the floor. The three attempts with the highest PAA were used for analysis. Subsequently, they executed a maximal 60m sprint.

The within-session reliability for PAA of the three fastest attempts was high, with a CV of 1.8% and ICC of 0.97. PAA had very strong significant (p<0.05) relations with step frequency (r≥0.72, p≤0.001), moderate (0-30m: r=-0.49, p=0.05) to small (30-60m: r=-0.22 p=0.42) negative relations with step length, and moderate (0-30m: r=0.49, p=0.06) to strong positive relations with speed (30-60m: r=0.57, p=0.02)

In conclusion, PAA was moderately related to sprint speed during acceleration and at maximal speed. This was probably due to the very strong relations between PAA and step frequency.

Keywords: Fast contractions, Hamstring muscles, Sprinting, Inertial measurement unit, Field test

INTRODUCTION

In many sports, maximal acceleration is a performance-determining factor. Vertical jump performance is positively related to sprint acceleration (Wisloff et al. 2004; Debaere et al. 2013) and widely used in practice for training guidance (Plesa et al. 2024) and monitoring of fatigue (Jimenez-Reyes et al. 2019; de Ruiter et al. 2024) and recovery (Papanikolaou et al. 2021) in explosive-type sports involving sprinting and rapid changes in direction. Although the hamstrings play a crucial role in vertical jumping (Bobbert et al. 1996), a vertical jump test is oriented on joint extension and addresses 'whole-body' function rather than individual muscle groups. Knee flexors are heavily loaded during sprinting (Bramah et al. 2024; Chumanov et al. 2007; Alt et al. 2021), suggesting that greater knee flexor function could lead to faster sprinting. A simple field test specifically assessing knee flexor function would be valuable.

Dynamometry is the gold standard for obtaining knee flexor (and extension) function. However, dynamometry involves complex/expensive equipment, is time-consuming, and is limited to measuring one athlete at a time (de Ruiter et al. 2006; Wilmes et al. 2021). We recently presented a simple 'unweighted' knee flexion test (de Ruiter et al. 2025). In the prone position without any fixation, participants performed a few isolated unweighted maximally fast knee flexions ('butt-kicks') with a small inertial measurement unit (IMU) on their shank. In a group of fourteen amateur football players (one woman), the fatigue-induced decrease in peak angular shank acceleration (PAA) was strongly related (r^2=0.48) to the fatigue-induced percentage increase in sprint time following repetitive 45 m sprints (de Ruiter et al. 2025).

Coincidentally, in the unfatigued state, PAA was found to be related to 45 m sprint time (r^2=0.33) (de Ruiter et al. 2025). If confirmed, this would suggest that in addition to monitoring fatigue and the recovery of knee flexor muscles, the test could have broader application in training monitoring, talent identification, and rehabilitation. For this, it is crucial to establish whether the relation between isolated peak angular acceleration during unweighted knee flexions and sprint performance holds in a completely different population or was simply a one-time incidental finding.

Therefore, in the present study, we investigate whether the relation found in amateur football players could be corroborated in track athletes. Our recent study only included one woman. Given the general lack of data on women in the literature (see, however (Gleadhill and Nagahara 2021; Debaere et al. 2013)), we decided to recruit women for the present study exclusively. In our recent study, only the total sprint time at 45 m was measured and found to be related to the knee flexion test. However, the acceleration and maximal speed phases of sprinting differ in kinematics (de Ruiter et al. 2022) and kinetics (Rabita et al. 2015). Therefore, a second objective of the present study is to investigate the strength of the expected relation for the acceleration phase (0-30 m) and the maximal speed phase (30-60 m) separately.

A relation between the peak angular acceleration in unweighted knee flexions and maximal sprint speed seems plausible because sprinting requires rapid (lower) leg movements and knee flexions. Good sprinters accommodate step frequencies of about 4.5 Hz (Debaere et al. 2013), with knee angular velocities up to 1200 °/s (Kivi et al. 2002). Greater knee flexion angular acceleration after push-off and greater deceleration during the final swing phase could yield increased step frequencies. However, sprint speed is the product of step frequency and step length, and for each athlete individually, it is the optimal combination of both variables that leads to maximal speed (Hunter et al. 2004; Salo et al. 2011). Nevertheless, if, at the group level, PAA were to be strongly positively related to step frequency, and if a high step frequency (relative to leg length) would not be negatively associated with step length, a positive relation between PAA and sprint speed might be expected. Therefore, we hypothesize that peak angular acceleration (PAA) will be positively related to step frequency and sprint speed.

Despite the differences in kinematics and kinetics between sprint phases (Rabita et al. 2015; Gleadhill and Nagahara 2021), a high step frequency is achieved after just a few steps and is maintained throughout the remainder of a 60 m sprint (Debaere et al. 2013; de Ruiter et al. 2022). We therefore hypothesize that the shank's PAA during unweighted isolated maximal knee flexions will be positively related to step frequency and speed during the first (acceleration) and second (flying) 30 m of a maximal 60 m sprint. Additionally, we will explore simplifying the method of calculating knee angular acceleration to improve its practical feasibility.

METHODS

Participants

Sixteen, mainly adolescent, female track athletes (age: 18.9±3.5 years, body mass: 62.3±5.1 kg, height: 1.71±0.06 m) who trained on average 6.8±3.7 hours weekly (Table 1) participated after providing informed consent. They were injury-free and did not sustain a hamstring injury in the last 6 months. They were recreationally active and participated in sprint competitions ranging from 60 m to 400 m. The study was conducted following the Declaration of Helsinki (2013) and received approval from the local scientific and ethics review board (VCWE-2019-070R1). All participants were individually tested. The study was conducted in an indoor facility with a tartan floor with ambient temperatures ranging between 18-20 °C. Participants performed their preferred pre-competition warm-up, including a few minutes of instructed practice on correct execution of the maximal knee flexions (see Fast Knee Flexion execution and 60 m sprint) and some maximal sprints on spiked shoes through the mechanical

Table 1. Participant characteristics.

Number	Age(Yr)	Body Mass (Kg)	Height (m)	P.b. 60 m (s)	Weekly Training (Hrs)
1	18	52	1.66	8.72	10
2	19	66	1.77	8.24	8
3	18	61	1.73	9.61	8
4	23	60	1.59	n.a.	2
5	18	59	1.6	8.24	8
6	21	54	1.73	8.5	9
7	17	63	1.75	8.79	7.5
8	18	67	1.79	8.06	10
9	16	65	1.83	8.77	3
10	18	63	1.7	8.42	3
11	17	64	1.75	n.a.	2
12	16	64	1.72	8.04	10
13	16	59	1.66	8.16	6
14	30	72	1.7	7.39	15
15	19	60	1.69	8.07	4.5
16	19	68	1.74	8.93	3

For participants 4 and 11, an official 60 m personal best (p.b.) time from the past three years' competition wasn't available (n.a.).

time gates for familiarization.

Inertial Measurement Units (IMUs)

Following the warm-up, custom-made sensors (9 gr, 33x22x8 mm) were switched on and automatically time-synchronized during startup. The IMUs of the sensors continuously sampled 3D linear acceleration (±30 g) and 3D angular velocity (4000 deg·s^{-1}) at 1125 Hz and 3D magnetic field strength at 1000 Hz. The data was stored on an internal SD card. Further details can be found at https://vuws.bitbucket.io/. Using double-sided tape and a sleeve, one IMU was fixated on the tibial bone of the dominant leg below the knee joint at about one-third of the distance between the knee and ankle, while avoiding contact with muscles as described in detail before (de Ruiter et al. 2025). The IMUs' longitudinal axis (y direction) was carefully aligned with the longitudinal axis of the shank. The rear leg in the three-point start position was defined as the dominant leg. Further IMUs were attached to the lateral aspects of the insteps of both feet, and on mechanical time gates placed at 30 and 60 m from the start line, detecting the moments when participants passed through the gate's swivel from the peaks in the IMU signals as detailed elsewhere (de Ruiter and van Dieen 2019). Gyroscopes are sensitive to temperature; to remove any baseline offset, the sensors were laid still for a minute at the beginning and end of each measurement. This allowed correcting for the small offsets (subtracting the mean values of these minutes) usually present in the data. Changes in offsets between the beginning and end of each measurement did not occur.

Fast Knee Flexion execution and 60 m sprint

Following the warm-up, participants performed a series of six (5s in between) maximally fast knee flexions in a prone position on the floor. As detailed previously (de Ruiter et al. 2025), they started from a relaxed position and were instructed to flex the knee of the dominant leg as fast as possible: 'kick your butt as fast as possible' and 'Let your heel bounce back from your buttocks'. Two minutes following the fast knee flexion test, participants executed a maximal 60 m sprint, starting with the foot of the non-dominant leg at the starting line and one hand on the floor. All fast knee flexions were video recorded in the sagittal plane with a smartphone (iPhone 15, 60Hz) placed at 1.5 m and 0.3 m height, and the sprints were recorded with a pending camera at 30 m. This was done to verify correct execution in case any anomalies were found during data analysis.

Data analysis

Fast knee flexions

Custom-written Matlab scripts (version R2022b, The MathWorks, Inc, Natick, MA, USA) were utilized to save the raw data as .mat files with data resampled to 1000Hz. These files were further analysed with custom-written Python (Version 3.11) scripts. The orientation of the shank IMU was derived using a gradient descent Madgwick algorithm (Madgwick et al. 2011). As described before in detail (Wilmes et al. 2020), sensor-to-segment calibration of the shank was derived using data of a 10s period of upright stance to align the gravity vector with the vertical alignment of the shank and a calibration movement (thigh rise) about the frontal axis was used to establish the participant's sagittal plane. However, in previous studies (Wilmes et al. 2020; de Ruiter et al. 2025), we noticed that some participants found it difficult to raise their upper leg to establish the sagittal plane of the body while balancing on the contralateral leg. Therefore, in the present study, instead of the thigh rise, the second fast knee flexion in the series of six served as a calibration movement, which avoided balance problems.

The shank's angular velocity about the frontal axis of the body frame (i.e. flexion-extension in the sagittal plane) was low-pass filtered (6 Hz) using a second-order Butterworth filter. During fast knee flexions, the thigh remains horizontal, therefore, the shank's angular speed is equivalent to the angular knee flexion speed. Angular knee flexion acceleration was the time derivative of angular velocity. Our primary outcome measure was peak angular acceleration (PAA).

An alternative PAA determination (Supplementary material)

We explored using the magnitude of the angular acceleration vector as a measure of knee flexion acceleration. The raw gyroscope data (x, y, and z) were 6 Hz low-pass filtered and time-differentiated (central differences for interior points, numpy. gradient in Python) to obtain angular acceleration about the three axes, the root mean square value of these accelerations was taken as the magnitude of the angular acceleration vector. Using this vector norm for angular acceleration would make estimating the shank sensor's orientation (Madgwick filtering) and the calibration movements unnecessary, thereby simplifying the procedure considerably. We found that a more rigorous filtering (6 Hz instead of 12 Hz in our previous work(de Ruiter et al. 2025)) improved the signal stability of the angular acceleration norm vector. Therefore, we also used the 6 Hz filter to calculate PAA about the frontal axis of the body frame (original method). Importantly, this did not significantly affect the results of the present study or our previous study (de Ruiter et al. 2025). We re-analysed the latter data using a 6 Hz instead of a 12 Hz low-pass filter, also for direct comparison with our previous work in the discussion section.

Sprints

The sprint start time was defined as the first moment when the dorsiflexion of the rear foot changed to plantar flexion during push-off. The instances of ground contact of the feet during sprinting were derived from the IMUs on the feet (de Ruiter and van Dieen 2019). For every participant, instances of ground contact were used to determine step frequency. Combined with the timing of the first 30 m (0-30 m) and second 30 m (30-60 m), average speed, step frequency, and step length were calculated for both phases of the 60 m sprint (de Ruiter and van Dieen 2019). To compare the data with our recent study, 45 m sprint time was calculated as 30 m gate time + 0.5*(60 m gate time – 30 m gate time), which will provide a good estimate because athletes of this level already run at maximal speed at 30 m. To get insight into the potential effect of differences in the participants' height on sprint speed, speed was scaled to estimated leg length by expressing speed in the form of non-dimensional numbers (Hof 1996) using the following equation: Froude number = v/sqrt(g*L) with v denoting running speed in $m.s^{-1}$, g the gravitational constant ($9.81m.s^{-2}$), and L leg length (m), which was taken as 49.9% of body height (Plagenhoef et al. 1983).

Statistical analysis

A priori power calculation (G*Power software version 3.1.9.7), assuming a moderate correlation of 0.6, indicated that 15 participants would suffice (α=0.05) to detect a significant correlation with 80% power; 16 participants were recruited. Statistical analysis was done using R version 4.2.2 (R Development Core Team, 2023). All data are presented as means ± standard deviation (SD). Normal distributions of the data were checked using Q-Q plots, histograms, and Shapiro-Wilk tests.

The three attempts with the highest PAA were used for analysis. To corroborate the reported within-session reliability of the fast knee flexion test (de

Ruiter et al. 2025), a two-way random Intra Class Correlation coefficient (ICC(2,1), agreement) and a coefficient of variation (CV) were calculated. Within-session reliability was expected to be high (CV ≤5.0%) for both methods, and ICC values were expected to be excellent (>0.90) (Koo and Li 2016). The averaged values of the three attempts with the greatest PAA in the BF-method were used to calculate Pearson's correlation coefficients and coefficients of determination (r^2) between PAA and the sprint variables from both sprint phases. Interpretation of the correlation coefficients was done according to (Hopkins et al. 2009):0-0.09 trivial, 0.1-0.29 small, 0.3-0.49 moderate, 0.5-0.69 strong, 0.7-0.89 very strong, 0.9-0.99 almost perfect, and 1.00 perfect.

To assess the statistical significance of differences in sprint variables between both (0-30 m and 30-60 m) sprint phases, paired t-tests (α=0.05) were applied, with effect sizes (Cohen's *d*) reported as the mean of the paired differences divided by the standard deviation of these differences.

A Bland-Altman analysis (bias ±95% limits of agreement), accommodating repeated (three) measures within participants (Zou 2013), was performed between PAA and the alternative PAA, calculated as the vector norm. Repeated measures correlation coefficients between PAA derived from both methods were calculated and presented in the supplementary material to assess agreement within the three attempts using the "rmcorr" package in R (Bakdash and Marusich 2017).

RESULTS

Peak Angular Acceleration (PAA) was 91.5±20.1 rad·s^{-2} with excellent within-session reliability for the three fastest attempts as shown by the CV of 1.8 % and ICC of 0.97 (95% CI: 0.84-0.99). PAA was reached 115±41ms after contraction onset following a change in knee flexion of 14±3°.

Knee flexions and 60 m sprint performance

Step frequency, step length, and speed were significantly greater in the second (30-60 m) than in the first phase of the sprint (Table 2). PAA was positively related (r=0.72, Table 3, Figure 1) to step frequency over the first 30 m of the sprint, and negatively with step length (r=-0.49). This resulted in a non-significant (r=0.049, *p*=0.06) relation between PAA and average sprint speed over the first 30 m (Figure 1). This relation was significant (r=0.62, *p*=0.02) when speed was scaled to leg length (Table 3, Figure 1).

Similar to the first 30 m, in the second sprint phase (30-60 m), PAA was positively related to step frequency (r=0.74, Table 3, Figure 1), but the negative relation with step length (r=-0.22) was not significant. This resulted in a significant relation (r=0.57) between PAA and 30-60 m sprint speed. The strength of this relation increased slightly (r=0.65) after scaling for leg length (Table 3).

Supplementary analysis

The alternative PAA (derived from the norm vector

Table 2. Sprint variables in the two sprint phases.

	Step Frequency (Hz)	Step Length (m)	Speed (m·s^{-1})	Scaled Speed (Froude Number)
0-30 m	4.12 ± 0.28	1.54 ± 0.08	6.35 ± 0.30	2.19 ± 0.10
30-60 m	4.18 ± 0.31	1.92 ± 0.11	8.00 ± 0.60	2.76 ± 0.21
p	0.01	<0.001	<0.001	<0.001
Cohen's *d*	0.70	5.86	4.97	4.97

Values are means ± sd. Sprint speed scaled to leg length is denoted in Froude number. All values were significantly (p<0.05) different between 0-30 m and 30-60 m.

Table 3. Pearson's correlation coefficients between Peak Angular Acceleration and sprint variables

	Step Length	Step Frequency	Speed	Scaled Speed
0-30 m	-0.49 [-0.79;0.01] *p*=0.05	**0.72** [0.36; 0.90] *p*=0.001	0.49 [-0.01;0.79] *p*=0.06	**0.62** [0.17; 0.85] *p*=0.01
30-60 m	-0.22 [-0.64;0.31] *p*=0.42	**0.74** [0.39;0.90] *p*=0.001	**0.57** [0.11;0.83] *p*=0.02	**0.65** [0.22;0.86] *p*=0.006

Pearson's correlation coefficients [95% confidence intervals] between shank Peak Angular Acceleration (rad·s^{-2}) during isolated maximal fast knee flexions executed in prone position and sprint variables (step frequency, step length, speed, scale speed (Froude numbers) for the first (0-30 m) and second (30-60 m) sprint phase. Significant correlations are denoted in bold (n=16).

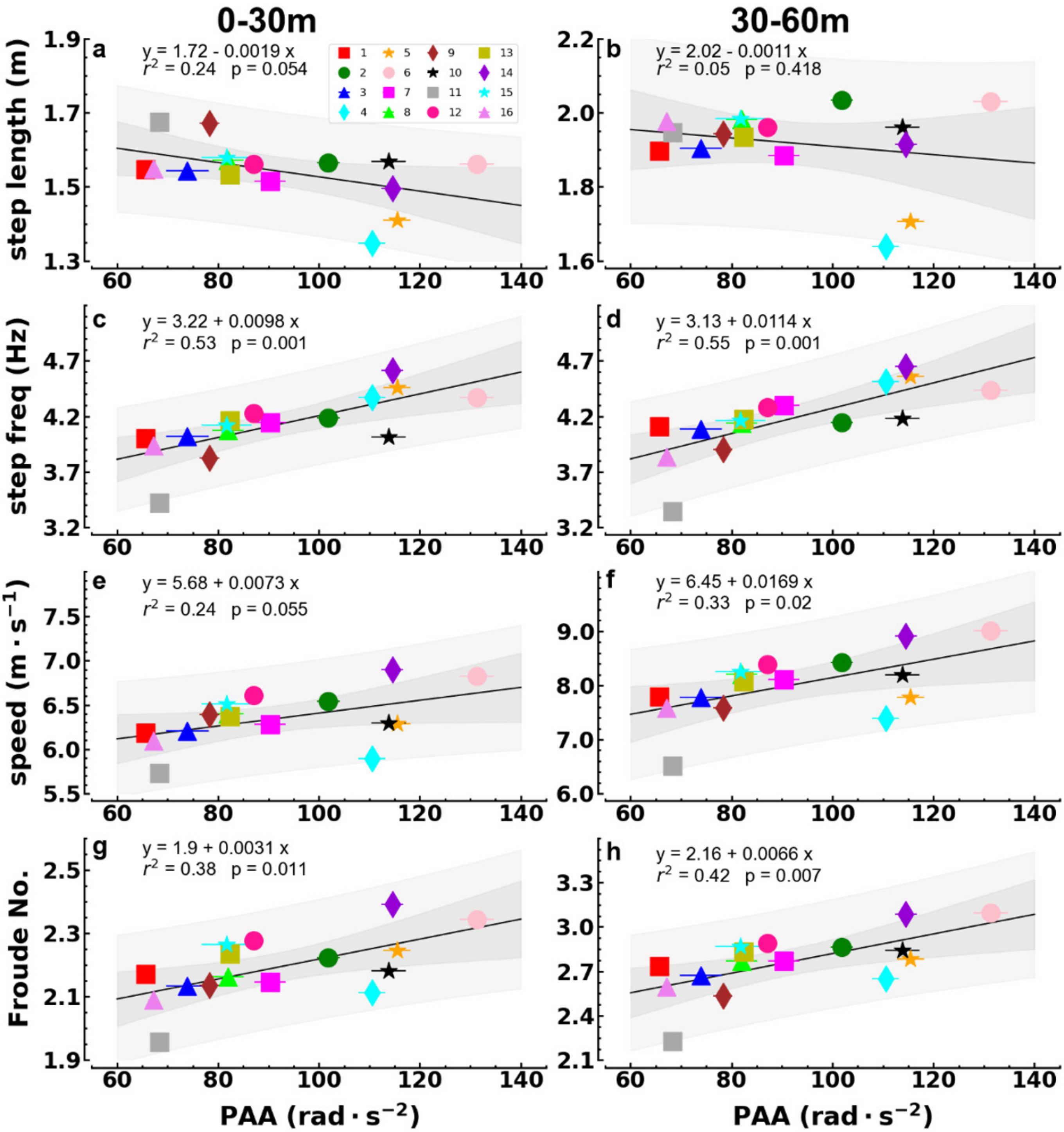

Figure 1. From top to bottom on the y-axis: step length (a, b), step frequency (c, d), speed (e, f), and scaled speed (Froude No. in g and h) as a function of peak knee angular acceleration during fast knee flexions (mean values of three fastest attempts ± standard deviations) on the x-axis. Regression lines with 95% confidence limits (dark grey) and prediction limits (light grey). Results for 0-30 m are on the left and for 30-60 m on the right. The legend for participant symbols is shown in panel a.

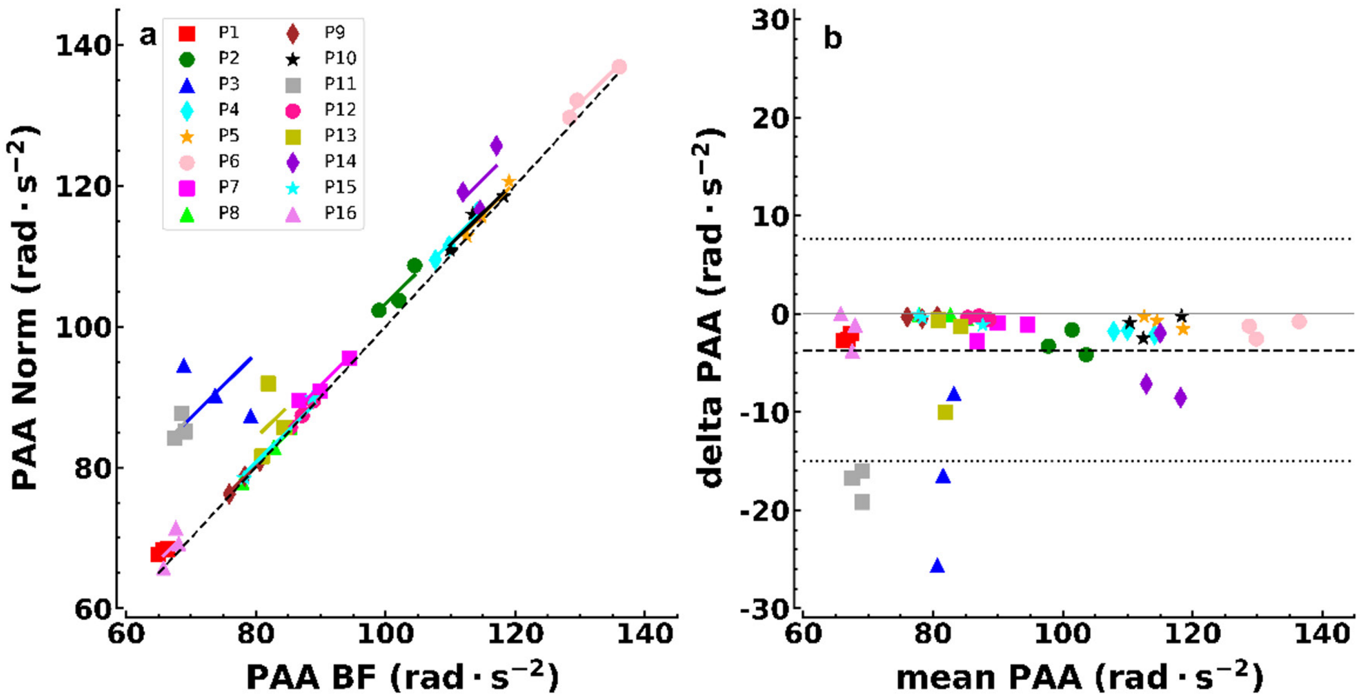

Figure S1. Repeated measures correlation (a) between Peak Angular Acceleration (PAA) during maximally fast knee flexions calculated using axes transformation of the IMU to the Body Frame (BF) and calculated from the IMUs' x,y,z norm vector (Norm): r=0.68 [0.44.0.83], *p*<0001. The line of identity is dashed. Bland Altman plot (delta=PAABF-PAANorm) of the same data is shown in b. The three attempts with the highest PAA BF are included for all 16 (P1-P16) participants

of angular acceleration) showed a significant repeated measures correlation (*p*<0.001, r=0.68 [0.44;0.83], Supplementary Figure 1a) with the original PAA (body frame). As could be expected, PAA derived from the norm vector on average was slightly greater (3.72 rad·s^{-2}, *p*=0.01, *d*=0.19) than PAA (body frame). This was particularly the case for participants 3,11, and 14, leading to relatively large limits of agreement (-15.2;7.8 rad·s^{-2}) in the Bland-Altman plot (Supplementary Figure 1b).

DISCUSSION

The present study aimed to establish the relation between isolated peak knee flexion angular acceleration (PAA) during isolated unloaded fast knee flexions and sprint performance during a 60 m sprint in a group of female sprint athletes. Significant moderate linear relations have been found between PAA and sprint speed, confirming our hypothesis. Importantly, and in line with our expectations, the relationship between PAA and speed appears to be mainly driven by the very strong positive relations between PAA and step frequency rather than the moderate negative relations between PAA and step length. Additional context is provided by showing that the relation between PAA and speed significantly improves after adjusting for differences in stature (scaling to leg length) and is somewhat stronger in the maximal speed phase than the acceleration phase of a 60 m sprint.

The relations between PAA and sprint speed were moderate to strong (r=0.49 and 0.57, n=16, *p*=0.06 and 0.02). In our previous study (de Ruiter et al. 2025), the strength of the relation between PAA and 45 m sprint was comparable (r=0.57, n=14, *p*=0.03, and after reanalysing the data with 6Hz filtering: r=0.59, *p*=0.03). It may be argued that the present study is on the verge of being underpowered. To gain further insight, we combined the results of the present study (n=16) with those of our recent study (n=14), for which we calculated the 45 m time in the present study using the gate times (see methods). The combined correlation coefficient between PAA and 45 m sprint time was -0.42 (*p*=0.02, n=30).

In principle, short individuals like participant 4 might have an advantage in tasks involving rapid knee flexions. For a given torque, a lower moment of inertia of the leg would result in a higher angular acceleration. There is some debate about whether scaling is useful in a group of human adults who are all of relatively similar size compared to the differences between species (Hof 1996; Steudel-Numbers and Weaver 2006). Nevertheless, when running speed was scaled to leg length, the

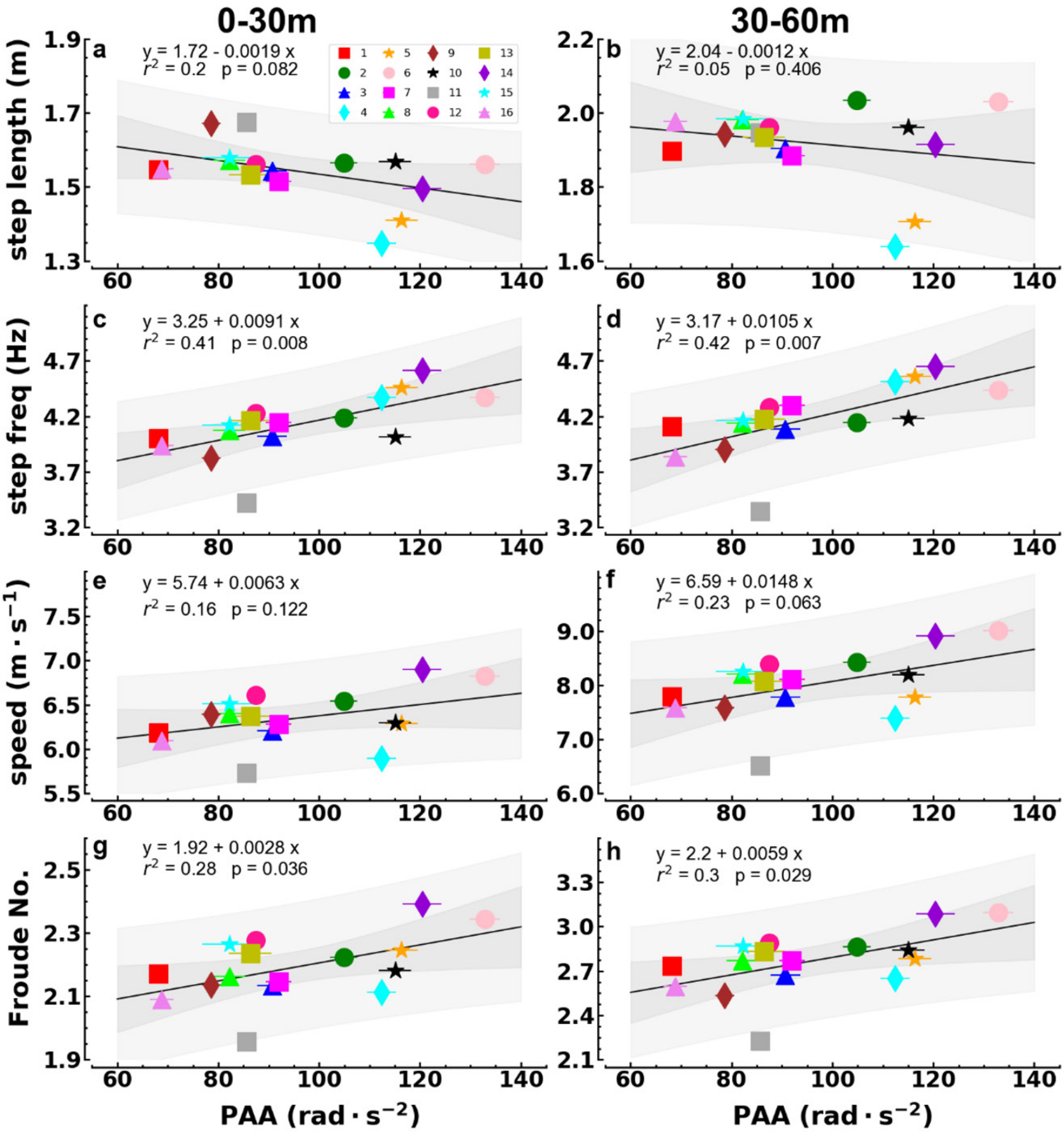

Figure S2. From top to bottom on the y-axis: step length (a, b), step frequency (c, d), speed (e, f), and scaled speed (Froude No. in g and h) as a function of peak knee angular acceleration (PAA) during fast knee flexions calculated from the IMUs' x,y,z norm vector (mean values of three attempts ± standard deviations) on the x-axis. For each participant, the same three attempts that generated the highest values using axes transformation of the IMU to the Body Frame (applied in the main document) are used. Regression lines with 95% confidence limits (dark grey) and prediction limits (light grey). Results for 0-30 m are on the left and for 30-60 m on the right. The legend for participant symbols is shown in panel a.

relations between PAA and sprint speed became slightly stronger (Table 3). In the present study, scaling aids in clarifying some of the speed differences between participants. Participant 11 had a very low step frequency and remained the slowest participant after scaling (Figure 1g, h). Participant 4 was the shortest in the group (Table 1). Her speed came within the range of the other athletes after scaling (Figure 1g, h), because she accommodated high step frequencies (Figure 1c, d). However, despite the high step frequency, her absolute sprint speed remained relatively low (Figure 1c, d). Please note that scaling to leg length is used as an analytical tool; scaled values cannot be used as a performance metric. The expression of speed in non-dimensional Froude numbers sheds some light on the inter-participant differences. However, absolute speed determines performance, which remains the primary interest of coaches and athletes.

Positive relations (Figure 1) between the angular acceleration of the lower leg about the knee joint in unweighted contractions and step frequency (and maximal sprint speed) may not seem surprising, as sprinting requires fast leg movements with rapid knee flexions (Debaere et al. 2013; Kivi et al. 2002). However, during sprinting, the knee flexor muscles are predominantly active during the late swing and stance phase. They are relatively inactive (about 20% of MVC values) during the early swing phase (Higashihara et al. 2018; Suskens et al. 2023), when knee flexion occurs. Knee flexion is driven by the powerful hip flexion that follows toe-off, with the shank acting as an inertial pendulum. In contrast, during the fast knee flexion test, flexion can only be initiated by the knee flexor muscles. Furthermore, contractions during the fast knee flexion test are purely concentric, executed at a constant hip angle with 5s rest in between. In contrast, during sprinting, knee flexors are eccentrically loaded during combined hip flexion and knee extension before foot touchdown (Chumanov et al. 2007; Alt et al. 2021) and, in addition, undergo rapid cyclic alternations of muscle activation and relaxation (Higashihara et al. 2018; Suskens et al. 2023). Taken together, the functional dissimilarities between the fast knee flexion test and sprinting make the relation between PAA measured in isolation and step frequency (and speed) during sprinting quite remarkable and less self-evident. However, since we have found the relation between PAA and speed in two different populations, and the relations between PAA and step frequency in the present study were robust, it seems valid to conclude that these relations exist.

Given the specific loading of the knee flexor muscles during sprinting, it is logical that research has focused on eccentric rather than concentric knee flexor strength in injury prevention, e.g. (Rudisill et al. 2023) and sprinting e.g. (Alt et al. 2021). Nevertheless, the present results align with some scarce studies reporting associations between concentric knee flexor function and sprint performance. Nagahara and Mureta (2020) reported significant positive correlations between, on the one hand, unweighted knee flexion angular impulse and positive work measured in the right (but not the left) knee of athletes strapped on a specific platform and, on the other hand, sprint acceleration (r=0.52-0.72) and step frequency (r=0.51-0.57), but not step length, during different sprint phases (Nagahara and Murata 2020). Of note, their test could be regarded as more sprint-specific as it involved rapid cyclic extension-flexion movements. Others reported positive relations (r= 0.46-0.56) between time to peak concentric hamstring muscle torque in a dynamometer (at 240°.s^{-1}) and (5-20m) sprint acceleration (Bračič et al. 2011).

PAA in the fast knee flexion tests was reached 115ms after contraction onset, following a relatively small change in knee angle of about 14°. As such, PAA seems (Macdonald et al. 2019) a measure of early explosive contraction capacity, comparable to the measures of early torque development reported for other muscle groups, which, in addition, were shown to depend strongly on the capacity for fast neuromuscular activation (de Ruiter et al. 2006; Tillin et al. 2010; Del Vecchio et al. 2019). It remains to be established whether the differences in PAA among participants are caused by differences in their capacity for fast neuromuscular activation. In addition, differences in fibre type composition of the knee flexor muscles may also contribute to the presented relations between PAA, step frequency, and sprint speed. Good sprinters have muscles with a relatively high proportion of fast-twitch fibres (Trappe et al. 2015)

PRACTICAL IMPLICATIONS AND LIMITATIONS

The fast knee flexion test is easy to perform and can be used to quantify knee flexor fatigue (de Ruiter et al. 2025). We confirm a moderate relation between its main outcome measure (PAA) and sprint speed. The present result indicates that this outcome builds on the very strong relations between PAA and step frequency during acceleration and sprinting at maximal speed. It remains to be seen whether the test can be used to study changes in knee flexor contractile function following (de)training, which could especially be relevant during rehabilitation from a hamstring injury. The test is unweighted and might be safely used relatively early in rehabilitation, in addition to the commonly used eccentric tests that are more demanding. (Macdonald et al. 2019) The test may also have potential in talent identification. However, its added value to, for example, a vertical jump test that is now frequently used to identify 'explosiveness' remains to be established.

A limitation of the present study is that we did not obtain any measures of neuromuscular activation. Future studies should investigate the proposed differences in neuromuscular activation onset and PAA. We also acknowledge that we didn't correct for multiple comparisons of the correlation coefficients (e.g., Table 3), but our main conclusions rely on consistent patterns in the correlation coefficients between the 0-30m and 30-60m phase, rather than on isolated coefficients.

Our attempt to simplify PAA determination was only partially successful (Supplementary Figure 1). There were a few participants (no. 3, 11, 14) for whom the difference in PAA between methods was relatively large and variable. Speculatively, this could be due to a relatively large rotational component about the longitudinal axis of the shank during knee flexion and/or a relatively large influence of soft tissue artefacts, potentially in combination with a less tight fit of the calf sleeve. This slightly increased variability in PAA (CV=3.0 % versus 1.8 %) and decreased the strength of the relations between PAA and sprint variables (compare Figure 1 with Supplementary Figure 2), resulting in a decline in explained variance (r^2) of about 0.1 for all variables. However, calculating PAA based on the vector norm of the shank's angular accelerations has important benefits over the original method. Firstly, a carefully executed calibration movement is not required, reducing the execution time of the fast knee flexion test. Secondly, minor sensor calibration errors that easily occur in sports practice may substantially affect the Madgwick filtering of the original method, which would decrease the reliability of the fast knee flexion test in practice. In contrast, the vector norm method does not rely on accurate sensor orientation estimation, which further increases the practicality of the fast knee flexion test. For research purposes, the original method seems slightly better, but in field practice, because of its simplicity, the vector norm may be preferred. However, regardless of the method used, a very tight fixation of the sensor to the shank is crucial to minimize variability.

CONCLUSION

The unweighted fast knee flexion test is easy to perform, which was confirmed by the very good within-session CV and ICC. PAA is related to step frequency and speed, both in the acceleration phase and maximal speed phase of a sprint. Therefore, besides monitoring fatigue, the test may have added value in monitoring training effects, recovery in rehabilitation, and talent identification.

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CONFLICTS OF INTEREST

The authors have no financial or non-financial interest to disclose.

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ETHICAL APPROVAL

The study received approval from the local scientific and ethics review board (VCWE-2019-070R1).

AUTHOR CONTRIBUTIONS

Conceptualization: C.J. de Ruiter, M. Heiden, Z.Sedney; Methodology: C.J. de Ruiter, M. Heiden, Z.Sedney, E. Wilmes; Writing: C.J. de Ruiter; Writing-review and editing: C.J. de Ruiter, M. Heiden, Z.Sedney, E. Wilmes.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPLEMENTARY DATA AND ANALYSIS

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