

## RELATIONSHIP BETWEEN STEP-BY-STEP FOOT KINEMATICS AND SPRINT PERFORMANCE

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The purpose of the study was to investigate the relationship between angular foot step-by-step kinematics and sprint performance during a 50 metre sprint in experienced male sprinters. Foot kinematics were measured using IMU devices integrated with a 3-axis gyroscope and a laser gun. The main findings were that maximal angular velocities increased until strides 6-7, where it stabilised. Time from touch down to dorsal flexion velocity was similar over all strides, whereas time from dorsal flexion velocity to toe off decreased until stride 6. Plantar flexion velocities, especially in toe off, showed the greatest associations with sprint times, whereas maximal dorsal flexion velocity presented no association with sprint times. Time from dorsal flexion velocity to toe off from stride 7 onwards determined the sprint performance and were shorter for faster sprinters.

**KEYWORDS:** foot stiffness, contact time phase, ankle angular velocity, sprint time, IMU

**INTRODUCTION:** During sprinting, it is known that the work required to move the body in a forward direction is mostly modulated at first instance by the foot and ankle joint and thereafter by the hip (Schache et al., 2019), with the moment arm of the ground reaction force being the greatest in the foot and ankle joint (Kuitunen et al., 2002). Since sprint performance is highly dependent on the maximal production of power from the first step of the sprint, it has been hypothesised that reducing dorsiflexion with its concomitant increase in ankle plantar flexor moment would enhance sprint time (Bezodis et al., 2015; Charalambous et al., 2012; Kuitunen et al., 2002). Leg stiffness could therefore be a modulator of sprint performance since; for instance, a “stiffer” foot and ankle during the initial stance phase of the dorsiflexion would be a beneficial technical feature for the horizontal velocity and therefore for the time of the sprint (Bezodis et al., 2015; Charalambous et al., 2012; Schache et al., 2019).

Earlier studies have analysed the relationship between ankle plantar flexion stiffness and sprint performance using dynamometers (Takahashi et al., 2018) force platforms (Charalambous et al., 2012; Kuitunen et al., 2002), and video analysis with motion capture systems (Charalambous et al., 2012; Miyashiro et al., 2019). However, those methods are expensive, require a confined area and take a large data processing time. Thus, more accessible techniques are needed to obtain such data that are not restricted to those limits.

Wearable inertial measurement units (IMUs) have previously been used to measure kinematic data such as sprint times, angular velocities or sprint velocities (Struzik et al., 2016; van den Tillaar, 2021). For example, Struzik et al. (2016) analysed the relationship between ankle kinematics and sprint times using IMUs. However, to the best of our knowledge, no study has assessed ankle performance and foot angular velocities in the different events within the contact time phase of the sprint using IMUs. The ease that IMU devices provide for the measurement of such kinematics could be an interesting tool for professionals when it comes to sprint performance.

Therefore, the purpose of the study was to investigate the relationship between angular foot step-by-step kinematics measured by IMUs and sprint performance during a 50 m sprint in experienced male sprinters. It was hypothesised that faster maximal plantar flexion velocity and a lower velocity change from touch down to maximal dorsal flexion velocity followed by faster plantar flexion again (incremental foot stiffness) would result in faster sprint times.

**METHODS:** Seventeen experienced male sprinters (age  $24.4 \pm 7.8$  years, body mass  $77.1 \pm 7.2$  kg, body height  $1.82 \pm 0.07$  m, with best 100m times of  $11.15 \pm 0.60$  s) performed two 50 m sprints each on spikes with a 6–10 min rest between each sprint. Subjects initiated each sprint from a three-point start (one hand on the floor) in a split stance, with the hand behind the line. Speed measurements and distance were recorded continuously during each attempt

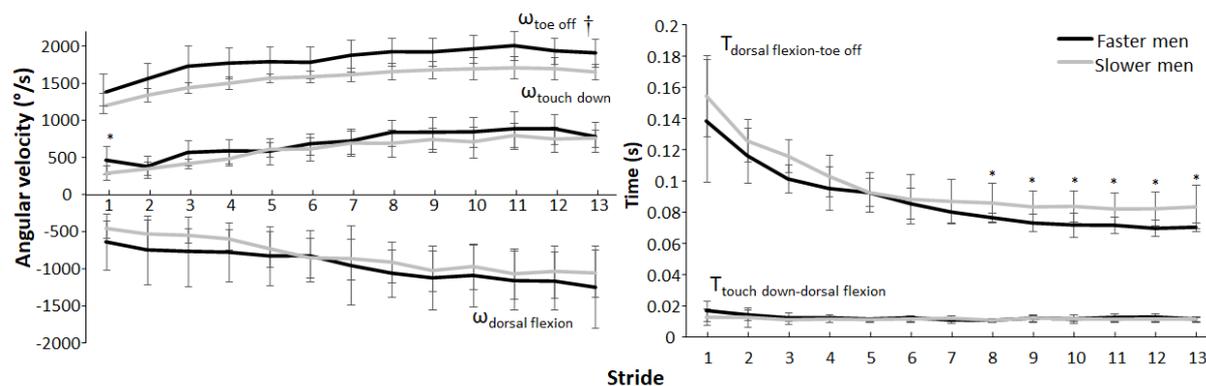
using a CMP3 Distance Sensor laser gun (Noptel Oy, Oulu, Finland), with sampling at 2.56 KHz. Total sprint times were derived from the laser distance over 50 m.

Angular velocities and timing of the foot kinematics for each step throughout the sprint were derived from using using a wireless 9 dof IMU, which included a 3-axis gyroscope, attached on top of the shoelaces of the spikes of each foot with tape. The sampling rate of the gyroscope was 500 Hz, with a maximal measurement range of  $2000^{\circ}\cdot\text{s}^{-1} \pm 3\%$  (Ergotest Technology AS, Langesund, Norway).

The angular foot kinematics were measured by the two IMUs during the entire sprint and detected at three events: plantar flexion velocity at first foot contact (touch down), maximal dorsal flexion velocity and plantar flexion velocity at toe off with the timing between the three events. The laser gun and IMUs were synchronised with the MuscleLab v10.202 (Ergotest Technology AS, Langesund, Norway). The step kinematics were evaluated for the first thirteen strides (one left and right step) as all participants had at least that many strides to cover the 50 m distance.

To investigate the correlations between the sprint times and foot kinematics Pearson's correlation was used with threshold values for interpretation 0.1–0.3 (trivial), 0.3–0.5 (moderate), 0.5–0.7 (large), and 0.7–0.9 (very large). To compare the 50 m sprint times, foot kinematics between the eight fastest and the slowest sprinters, two-way ANOVA with repeated measured (strides) was used on these parameters. Effect size was evaluated with eta squared ( $\eta^2$ ) where  $0.01 < \eta^2 < 0.06$  constituted a small effect,  $0.06 < \eta^2 < 0.14$  a medium effect, and  $\eta^2 > 0.14$  a large effect (Cohen, 1988). The level of significance was set at  $p < 0.05$ , and all data are expressed as mean  $\pm$  standard deviation (SD). Analysis was performed with SPSS Statistics for Windows, version 27.0 (IBM Corp., Armonk, NY, USA).

## RESULTS:



**Figure 1: Comparison of the angular plantar and dorsal flexion velocities at touch down and toe off and at maximal dorsal flexion velocity (left) and time variables (right) for each stride between faster men and slower men.**

\* Indicates a significant difference between faster and slower men for this stride ( $p < 0.05$ ).

† Indicates a significant difference between faster and slower men for each stride ( $p < 0.05$ ).

Maximal angular dorsal flexion and plantar flexion velocity at touch down and toe off increase significantly every stride ( $p \leq 0.001$ ,  $\eta^2 \leq 0.41$ ) until stride 6-7, where they stabilise (Figure 1). The time from touch down to maximal dorsal flexion velocity did not change significantly over the strides ( $p = 0.092$ ,  $\eta^2 = 0.11$ ), while the times from maximal dorsal flexion velocity to toe off significantly decreased each stride for the first 6 strides ( $p < 0.001$ ,  $\eta^2 = 0.87$ , Figure 1).

When comparing the eight faster sprinters to the eight slower some kinematic differences were noted. Evidently, sprint times significantly differed ( $p < 0.001$ ) between fast and slow sprinters ( $5.82 \pm 0.13$  s vs.  $6.39 \pm 0.28$  s), Furthermore, the faster sprinters presented higher touch down plantar flexion velocity during stride 1 ( $p = 0.011$ ,  $\eta^2 = 0.20$ ), and higher toe off velocities during all strides ( $p \leq 0.025$ ,  $\eta_p^2 \geq 0.156$ ) compared to the slower sprinters. Times between maximal dorsal flexion velocity to toe off during strides 8 to 13 and total contact time – from touch down

to toe off – during strides 8 to 13 ( $p \leq 0.014$ ,  $\eta^2 \geq 0.186$ ) were significantly shorter for the faster men in comparison to the slower men (Figure 1).

Pearson's correlation coefficients showed moderate to large associations between sprint time and foot kinematics when all strides taken together (averaged) for most variables except not for maximal dorsal flexion velocity, and time from touch down to maximal dorsal flexion velocity (Table 1).

When analysing relationships between sprint time and foot kinematics per stride, touch down and toe off velocity correlated moderately to well for almost each step. This also resulted in significant moderate to large positive correlations for stride 7 onwards in the time from maximal dorsal flexion velocity to toe off and the total contact time (touch down-toe off) (Table 1).

**Table 1: Pearson's bivariate correlations analysis evaluating associations between velocities and timing variables with sprint times per stride.**

Grey means a significant correlation on a  $p < 0.05$  level. dip: maximal dorsal flexion velocity

Stride	Correlations with 50m sprint times													All
	1	2	3	4	5	6	7	8	9	10	11	12	13	
Touch down velocity	-.65	-.36	-.57	-.61	-.19	-.51	-.37	-.48	-.47	-.40	-.38	-.43	-.18	-.51
Maximal dorsal flexion velocity	.13	.18	-.01	.03	-.03	-.15	-.13	.00	-.04	-.10	-.01	.05	-.18	-.06
Toe off velocity	-.47	-.48	-.54	-.59	-.48	-.51	-.59	-.61	-.62	-.64	-.66	-.52	-.53	-.63
Time from touch down to dip	-.43	-.22	-.31	-.17	-.25	-.01	.33	-.08	-.06	-.05	-.18	-.34	-.27	-.28
Time from dip to toe off	.27	.27	.43	.35	.27	.25	.42	.56	.64	.63	.59	.70	.47	.46
Time from touch down to toe off	.19	.21	.38	.32	.24	.26	.46	.55	.64	.64	.56	.62	.42	.42

**DISCUSSION:** The purpose of the current study was to investigate the relationship of angular foot step-by-step kinematics and sprint performance during a 50 m sprint in experienced sprinters. The main findings were that maximal angular velocities increased until strides 6–7, where it stabilised. Moreover, the time from touch down to maximal dorsal flexion velocity was constant over strides, whereas the time from maximal dorsal flexion velocity to toe off decreased until stride 6. Plantar flexion velocities showed the greatest associations with sprint times, especially toe off velocity, whereas maximal dorsal flexion velocity showed no association with sprint times. Time from maximal dorsal flexion velocity to toe off from stride 7 onwards determined sprint performance and differentiated between faster and slower sprinters.

A negative significant association between toe off maximal plantar flexion velocity and sprint times was shown which followed our hypothesis. The higher toe off velocities is explained by the greater ankle plantar flexor impulse that faster sprinters display (Bezodis et al., 2015; Schache et al., 2019; Takahashi et al., 2018). The higher plantar flexion velocity at toe off gives faster athletes the ability to create more propulsive force which results in faster sprints.

The plantar flexion velocity at touch down showed the highest correlation to sprint times at the first stride, which is in accordance with previous studies showing that better sprint performance was associated with greater propulsive impulse at the initial acceleration phase of the sprint (Bezodis et al., 2019). This higher velocity at the first stride enables good early acceleration due to the exertion of the maximal force from the beginning of the sprint. Therefore, a successful sprint start, with its concomitant peak touch down and toe off velocity in the initial strides, would facilitate a shorter sprint time by reaching the maximal sprint velocity earlier (Murphy et al., 2003).

Another key finding was the absence of significant moderate/strong correlations for maximal dorsal flexion velocity and time from touch down to maximal dorsal flexion velocity (braking phase) with sprint times. Despite the faster plantar flexion shown in faster sprinters, this unexpectedly showed no connection to a reduced dorsal flexion velocity, so the previous theory

relating stiffer feet to faster sprinters did not explain the best sprint times. Such parameters are similar between faster and slower sprinters, and foot/ankle stiffness during this phase remains apparently constant throughout the strides for all sprinters, based on angular velocities and times. An explanation for this finding could be that from touch down to maximal dorsal flexion, muscles need to resist an overload of the body weight driving in a forward direction plus the gravity component. As for any stretch-shortening cycle (SSC), the spring-like motion of the foot is also modulated by the range of motion of the lever arm of the involved joints, so the sprinter would need to overtake such load within a specific range of motion (Murphy et al., 2003). However, it is likely that better sprinters might elicit optimised pro-active and reactive motor strategies, anticipating the motor response simultaneously to the touch down moment. Eventually, due to the anticipation mechanism, better sprinters seem to be capable of exerting a greater linear impulse despite having a similar braking phase in terms of time and the change in velocity (Helm et al., 2019). This is most visible once the maximal velocity of the sprint was reached (around stride 7 onward) as times from the maximal dorsal flexion velocity to the maximal plantar flexion velocity at toe off stabilises and more strongly determines the sprint performance. The significant correlations to sprint time draw a distinction between the faster and slower sprinters, explainable by the higher plantar flexion velocity of the better sprinters, resulting in a shorter time to move through the same range of motion as the slower sprinters.

**CONCLUSION:** Foot kinematics during the contact phase of a sprint for each stride provides useful information on the foot performance during the actual sprint. The analysis of such variables reports essential information that may help to enhance the quality and efficiency of the sprint cycle by giving detailed information of each single stride of the sprint. Furthermore, emerging methods that could make it easier to analyse and interpret such variables, by developing an algorithm that automatically can detect these parameters, might be elaborated in further research.

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