Sports Medicine (2024) 54:585–606
https://doi.org/10.1007/s40279-023-01967-1

REVIEW ARTICLE

Ankle and Plantar Flexor Muscle–Tendon Unit Function in Sprinters: A Narrative Review

Evan D. Crotty[1] · Laura-Anne M. Furlong[1,2] · Andrew J. Harrison[1]

Accepted: 1 November 2023 / Published online: 21 November 2023

Abstract

Maximal sprinting in humans requires the contribution of various muscle–tendon units (MTUs) and joints to maximize performance. The plantar flexor MTU and ankle joint are of particular importance due to their role in applying force to the ground. This narrative review examines the contribution of the ankle joint and plantar flexor MTUs across the phases of sprinting (start, acceleration, and maximum velocity), alongside the musculotendinous properties that contribute to improved plantar flexor MTU performance. For the sprint start, the rear leg ankle joint appears to be a particularly important contributor to sprint start performance, alongside the stretch–shortening cycle (SSC) action of the plantar flexor MTU. Comparing elite and sub-elite sprinters revealed that elite sprinters had a higher rate of force development (RFD) and normalized average horizontal block power, which was transferred via the ankle joint to the block. For the acceleration phase, the ankle joint and plantar flexor MTU appear to be the most critical of the major lower limb joints/MTUs. The contribution of the ankle joint to power generation and positive work is minimal during the first stance, but an increased contribution is observed during the second stance, mid-acceleration, and late-acceleration. In terms of muscular contributions, the gastrocnemius and soleus have distinct roles. The soleus acts mainly as a supporter, generating large portions of the upward impulse, whereas the gastrocnemius acts as both an accelerator and a supporter, contributing significantly to propulsive and upward impulses. During maximum velocity sprinting the ankle joint is a net dissipater of energy, potentially due to the greater vertical loading placed on the plantar flexors. However, the ankle joint is critical for energy transfer from proximal joints to ground force application to maintain velocity. In terms of the contribution of musculoskeletal factors to ankle joint and plantar flexor performance, an optimal plantar flexor MTU profile potentially exists, which is possibly a combination of several musculoskeletal factors, alongside factors such as footwear and technique.

1 Introduction

Maximal sprinting requires high levels of positive muscular power to be produced by multiple muscle–tendon units (MTUs) acting in series with and acting around the joints of the lower limb in a limited time frame (0.09–0.13 s [1, 2]). The MTU consists of the connection between muscles and tendons, through which contractile forces are generated and transmitted. The anatomy of the leg and the mono- and biarticular muscles facilitate the transmission of power during explosive movements (i.e., sprinting) from larger, proximal muscles to smaller, distal muscles, and finally to the track surface [3, 4]. The intermuscular coordination pattern during the sprint start is characterized by a proximal to distal sequencing in monoarticular muscle activation reaching its maximum activation [5]. Crucial within this sequence is that monoarticular muscles shorten over their full range, while biarticular muscles transport energy produced by the proximal muscles to distal joints. The concept of the transfer of mechanical energy states that biarticular muscles transfer energy produced from proximal muscles to distal joints [4]. For example, co-activation of the gastrocnemius and knee extensor muscles during late push-off phase in a vertical jump enables mechanical energy transfer from the knee to ankle [5]. This sequential muscle activation pattern of proximal to distal is reflected in the net joint powers. For example,

✉ Evan D. Crotty
evan.crotty@ul.ie

[1] Sport and Human Performance Research Centre, Department of Physical Education and Sport Sciences, University of Limerick, Limerick, Ireland

[2] School of Sport, Exercise, and Health Sciences, Loughborough University, Loughborough, Leicestershire, UK

Key Points

For the sprint start, the rear leg ankle joint appears to be a particularly important contributor to sprint start performance, alongside the stretch–shortening cycle (SSC) action of the plantar flexor muscle tendon unit (MTU).

The ankle joint and plantar flexor MTU appears to be the most critical of the major lower limb joints/MTUs during the acceleration phase.

Most likely, an optimal plantar flexor MTU profile exists for maximal sprinting. Potentially, this is a combination of several musculoskeletal factors.

the rectus femoris facilitates the transfer of energy generated by the hip extensors from the hip to the knee [5]. The plantar flexor MTU and ankle joint are important due to their role in applying force to the ground and as primary contributors to supporting and accelerating the body across the sprint phases [6, 7]. The primary ankle plantar flexor muscles are the monoarticular soleus (SOL) and the biarticular gastrocnemius (GAS), comprised of the lateral gastrocnemius (LG) and medial gastrocnemius (MG). All three muscles connect to the Achilles tendon and as a MTU are the main contributors to ankle torque generation.

The mechanical behavior of the plantar flexor muscles, alongside the interaction between muscle fascicles and tendinous tissue, has been shown to differ across running speeds [8]. The contribution of the ankle joint and plantar flexor MTU performance in the key phases of sprinting (start, acceleration, and maximum velocity) is unclear, warranting a synopsis of the available literature. Examining the musculotendinous properties that contribute to improved plantar flexor MTU performance is also of interest as a plantar flexor MTU with more architecturally favorable and more rapid contractile kinetics can enable greater ground forces to be applied during progressively shorter ground contact periods as sprinting speed increases [9, 10]. This literature review has two main aims: (1) To review the importance of the ankle joint and plantar flexor MTU across the phases of maximal sprinting (start, acceleration, and maximum velocity); (2) To delineate the musculotendinous properties that contribute to improved plantar flexor MTU performance.

1.1 Delimitations of the Review

The articles discussed in this review were initially sourced using a combination of the keywords (sprint AND (“plantar flexor” OR “triceps surae” OR “soleus” OR “medial gastrocnemius” OR “lateral gastrocnemius” OR “ankle”)) in PubMed and Google Scholar databases. All full-text articles in peer-reviewed journals were initially retained. Subsequently, one author screened all titles and abstracts to reject irrelevant articles. All remaining articles were next included in a database, where one author read them in full to identify the relevant primary research articles. Finally, specific aspects of the articles were discussed with the other authors before a consensus was reached on inclusion. Given the narrative nature of this review, reference lists of these articles were also screened to identify any further relevant articles for the review that had not been retrieved through the initial search. Finally, some additional manual research was conducted as the review progressed to explain the general scientific aspects of this review.

The predefined search strategies yielded a preliminary pool of 212 possible papers, 84 of which remained following the removal of duplicates and abstracts had been screened. Following careful review of the 84 full texts, 31 papers were excluded (primarily due to the participants not being sprinters). Fifty-three articles were included, alongside 12 additional articles identified through the screening of references. A total of 65 studies were included in the current narrative review.

2 Ankle Joint and Plantar Flexor Muscle–Tendon Unit Function: Sprint Start

The sprint start phase is a critical component of sprint performance, characterized by considerable levels of acceleration. World-class 100-m sprinters accelerate to ≈ 33% of maximum velocity by the end of the block clearance [11]. The sprinters’ ability levels for the examined sprinting studies are reported in Table 1.

2.1 Joint and External Kinetics/Kinematics

2.1.1 Joint Kinetics

In quantifying good sprint start performance, key determinants can be extracted from the sprint start deterministic model and examined [12]. Normalized average horizontal external power (P_N) has been suggested as a key parameter in characterizing sprint start performance [13] as it encompasses block clearance time and block clearance velocity, two key parameters of the sprint start deterministic model. P_N is calculated as:

Table 1 Studies that investigated plantar flexor or ankle joint function across the sprint start phase of sprinting

Study details			Participants		Ankle variables of interest
Study	Phase of sprint	Design	Sample	Ability level[a]	Ankle parameters examined
Brazil et al. [6]	Block and first stance	Cross-sectional analysis	10 M	10.50 ± 0.27 s	Kinematics, kinetics
Bezodis et al. [14]	Block phase	Cross-sectional analysis	16 M	10.95 ± 0.51 s	Kinematics
Slawinski et al. [15]	Block phase and first two steps	Between-group comparison	12 M	10.27 ± 0.14 s (Gp 1) 11.31 ± 0.28 s (Gp 2)	Kinematic, kinetics
Brazil et al. [25]	Block phase	Cross-sectional analysis	17 M	10.67 ± 0.32 s	Kinematics, kinetics
Slawinski et al. [16]	Block phase	Cross-sectional analysis	8 participants	10.30 ± 0.14 s	Kinematics, kinetics
Čoh et al. [27]	Block phase and first two steps	Single-subject analysis	1 F	13.19 s (100 mH)	Kinematics, kinetics, EMG
Čoh et al. [28]	Block phase and first two steps	Single-subject analysis	1 F	13.19 s (100 mH)	Kinematics, kinetics, EMG
Debaere et al. [19]	Block phase and first two steps	Group-based description	11 M, 10 F	10.62 ± 0.18 s (M) 11.89 ± 0.30 s (F)	Kinematics, kinetics
Guissard and Duchateu [30]	Block phase and first two steps	Group-based description	7 M	10.8–11.2 s	Kinetics, EMG
Mero and Komi [26]	Block phase and first stance	Cross-sectional analysis	8 M	10.76 ± 0.19 s (Gp 1) 10.82 ± 0.23 s (Gp 2)	Kinematics, kinetics, EMG
Pain and Hibbs [7]	Block phase	Intervention (within-group)	9 participants	Sprinters–county-international level	Kinetics, EMG
Schrödter et al. [18]	Block phase	Cross sectional analysis + between-group comparison	54 M, 30 F	10.98 ± 0.58 s (M) 12.12 ± 0.68 s (F)	Kinematics, kinetics
Guissard et al. [20]	"Set" position	Intervention (within-group)	14 M, 3 F	10.4–11.9 s (M/F)	Kinematics, EMG
Mero et al. [21]	"Set" position	Intervention (within-group)	9 M	10.86 ± 0.34 s	Kinematics, kinetics
Piechota et al. [29]	Block phase	Between-group comparison	54 M	Expert sprinters and physical educ students	EMG

The study design, participant sample, ability level, and ankle variables of interest are provided

Gp group, *mH* meter hurdles, *M* male, *F* female, *PB* personal best

[a] Ability level of the participants are reported as 100-m PB times (when reported in the studies) or the athletes' main sprint event PB times. All other descriptors are verbatim from the methods section of the cited study

$$\left(P_{\mathrm{N}} = \frac{\overline{P}}{m.g^{\frac{3}{2}}.l^{\frac{1}{2}}}\right), \tag{1}$$

where $\overline{P}$ is average horizontal external power, m is the mass of the sprinter, g is the acceleration due to gravity, and l is the leg length of the sprinter. In combination, the average ankle, hip, and knee joint power explain 55% of the variation in block power during the push phase. Additionally, 23% of the total variance in normalized average horizontal external power is explained by the rear leg ankle joint alone [6]. During the sprint start, the front block leg exhibits a proximal-to-distal power generation strategy, while in the rear block leg, peak angular velocity occurs in the knee before the hip or ankle [6, 14, 15]. The absence of a proximal-to-distal power generation strategy in the rear block led to lower positive power and work, possibly reducing energy available from the knee joint to assist ankle plantarflexion [6]. Maximal kinetic energy of the foot (front: 4.6 ± 1.0 J; rear: 25.3 ± 4.5 J) was observed to be lower than the thigh (front: 64.7 ± 12.6 J; rear: 91.4 ± 12.4 J) and leg (front: 22.5 ± 5.0 J; rear: 69.1 ± 11.1 J) segments for the front and rear block [16]. Despite this, large energy-generating capacities of the ankle, knee, and hip joint at various instances during the sprint start have been observed [6]. Joint angular velocities were also measured using 3D analysis [16]. During the block push phase, maximal joint angular velocities for the ankle joint are reduced compared to the first stance. Notably, rear knee (651.4 ± 112.3° s^{-1}) maximal joint angular velocity is higher than the rear ankle (462.9 ± 74.7° s^{-1}) and rear hip (425.7 ± 61.0° s^{-1}). Front knee (660.2 ± 40.5° s^{-1}) and front ankle (641.5 ± 44.9° s^{-1}) have similar values, with front hip (456.3 ± 17.7° s^{-1}) lower than both [16]. Front block peak positive power and work have been observed to be higher compared to the rear block, potentially explained by the power generation strategy of each leg [6]. The absence of a proximal-to-distal power generation strategy in the rear leg could limit the transfer of energy generated by the knee joint toward assisting in ankle PF [17].

2.1.2 Stretch–Shortening Cycle (SSC) Action and Block Face Inclination

During the block phase, the ankle joint initially dorsiflexes (front block: 15.8 ± 7.4°, rear block: 8.0 ± 5.7° [18]), potentially caused by hip and knee extensor propulsion forces, followed by a PF (front block: 43.1°, rear block: 49.2° [19]). The rear ankle displays a more extended PF phase (50% of block push phase) compared to the front ankle (20% of block push phase [16]). The joint exhibits a net PF moment throughout the block phase, resulting in an energy absorption period followed by generation, typical of a stretch–shortening cycle (SSC) action [15, 20, 21]. This SSC action of the plantar flexor MTU has been observed in both blocks, with a relationship demonstrated between magnitude and velocity of dorsiflexion (DF), and enhanced horizontal block impulse, maximal push force, and block power [18]. This increased force output from the SSC action could be attributed to the force–length (F–L) relationship during the eccentric phase, or from muscular preactivation patterns in the set position. The SSC mechanism is likely influenced by the inclination of the block footplate. The SSC pattern of initial whole muscle lengthening (SOL and MG) followed by shortening was observed across block angles of 30° and 50°. However, when the block inclination was increased to 70°, the MG only lengthened without shortening, and the SOL displayed minimal length changes (~ 1%) compared to other block inclination angles (6–10%; [20]). The muscle length change of the SOL and MG was measured by examining the angular variation in the ankle and knee joint to predict the change in muscle length. When analyzed cross-sectionally across a range of sprinter abilities, self-selected footplate inclination did not impact horizontal block power production [18]. However, the rear block mean horizontal force was increased at a steeper block angle (65° vs. 57°: 9.96 ± 1.45 vs. 8.81 ± 1.27 N kg^{-1} [18]). When examined within sprinters, reducing footplate inclination of both blocks (65°–40°) increased peak joint moment of front and rear block ankles, increased power at the rear ankle, and increased final block velocity (40° vs. 65°: 3.39 vs. 3.30 m s^{-1} [21]). Similar increases in block velocity were observed when front block inclination was reduced (70° vs. 30°: 2.37 vs. 2.94 m s^{-1}) in a group of sprinters of varying abilities [20]. In summary, block inclination angles greater than 65° may place the plantar flexor MTU at an unfavorable portion of the F–L curve and be disadvantageous for ankle joint function during the sprint start. Reduced block inclination angles demonstrated increases in block velocity, which could be attributed to a longer plantar flexor MTU length at these footplate inclinations, enabling the muscle to work at a more effective part of the F–L curve.

Ankle DF range and mean stretch velocities are positively correlated with block power [18]. The potential discrepancy between cross-sectional [18] and within-sprinter evidence [20, 21] on block inclination may occur as a result of different footplate surface lengths across studies, impacting the initial DF. A greater initial ankle joint angle may enhance the magnitude of DF during push-off, and the average speed of the eccentric stretch with significant moderate correlations observed [18]. These findings contrast with other research [20] by suggesting a steeper block benefits block push-off performance attributed to either the F–L relationship or different muscular preactivation patterns [18]. However, this study did not systematically vary block conditions for individual athletes [18], limiting conclusions on the observed results.

2.1.3 External Kinetics

Sprinters with faster personal best (PB) times [11] and with higher velocities after 2.5 m [22] differ from their slower counterparts in the generation of larger relative horizontal block impulses, achieved in similar or shorter push-phase durations. In agreement with this, elite Jamaican sprinters compared to national level sprinters demonstrated significantly greater RFD (elite vs. national level: 259 vs. 175 N kg^{-1} s^{-1}) and normalized average horizontal block power (elite vs. national level: 0.360 vs. 0.305), despite similarities in ankle push-off kinematics [18]. Alongside higher RFD [15], peak and average forces [23, 24] potentially explain improved block force production in faster sprinters. At the joint level, greater average block force production is associated with higher rear ankle extensor joint moment and higher front hip extensor joint moment, alongside increased front knee positive extensor joint power [25]. Therefore, enhancing the force-producing capabilities of those joints, particularly of both ankle joints, is critical in improving starting ability.

2.1.4 Deterministic Model of Sprint Start

The deterministic model identifies several biomechanical determinants of the sprint start including horizontal block clearance time, velocity, and displacement. The single parameter that most affects the sprint start is the horizontal impulse, which determines the change in velocity during the push phase. Additionally, sprint start response time (encompassed within block clearance time), contributes to sprint start performance. The majority of studies examining ankle joint and plantar flexor MTU performance in relation to sprint start performance typically examine correlates between ankle/plantar flexor MTU parameters and sprint start, rather than determinants. This dependency on correlates is problematic since correlation only indicates the strength of the relationship between two variables. Regression-based techniques or the explanation of outcomes via mechanical-deterministic model type approaches are more suitable for this type of work as they give more insight into the determinants of an outcome. Determinants are typically expressed through mathematical and mechanical laws, and therefore should be prioritized in sprint start research above correlates. Assessing the relationship between biomechanical determinants of the sprint start and ankle joint/plantar flexor MTU parameters may provide more meaningful insights into the contribution of these parameters to sprint start performance.

2.2 Muscle Activation

Muscle activation during the sprint start is closely linked to muscle–tendon unit function, as the rapid muscular contraction synergizes with the elastic properties of tendons, facilitating maximal force production to generate powerful and efficient block propulsion. This interdependent relationship underscores the critical role of neuromuscular coordination and tendon mechanics in optimizing sprint performance. Due to the multi-joint characteristic movement of the sprint start, muscle activation increases occur before block force production for some, but not all, muscles [26]. Muscle activation patterns during the sprint start appear individual-specific [26]; however, a general muscle activation sequence can be identified from the sprint start literature. Muscle activation studies that examined GAS EMG but did not specify if the examined muscle was LG or MG will be referred to as GAS. Muscle activation patterns for the primary muscles contributing to ankle joint motion (i.e., LG, MG, SOL, and tibialis anterior (TA)) differ across rear and front block legs. While the GAS of both legs exhibits an eccentric contraction before the concentric phase [26, 27], the timing of peak activation, and the sequence of activation compared to other muscles, differs between the front and the rear block leg. For the rear block leg, plantar flexor muscle excitation typically occurs toward the end of the rear leg push, with the gluteus maximus typically first [26, 28], followed by the semitendinosus [29], biceps femoris, quadriceps, and plantar flexors [26, 30]. While the LG demonstrated increased activation observed during the first third of the block phase [26], potentially as a result of the DF caused by early-phase hip and knee extensor moments, peak activation of the GAS has been observed in the final phase of push off for both front and rear legs [26, 28]. For the front block leg, SOL activation increases considerably earlier than the GAS [30], potentially due to the "set" position inducing knee flexion, which shortens the biarticular GAS [18, 30]. In the front leg, the GAS was the first of five muscles examined (SOL not examined) to increase activation; however, peak activation of the muscle occurred at the end of the block phase [26]. TA muscle excitation for both legs occurs during the beginning of the flight phase [30], which is somewhat surprising as hip and knee extension, along with ankle DF, generate the initial propulsive block forces. TA muscle activation was only examined in one of the sprint start muscle sequence of activation studies, and warrants further investigation [30].

2.3 Sprint Start Response Time: Muscle Activations and Mechanical Delays

Sprint start response time is a relevant measure of block performance and is influenced by the sequence of neuro-physiological and non-neuro-physiological components. For this review, we examine the neuro-physiological factors and the processes from the start signal to movement initiation focusing on the primary muscles contributing to ankle joint motion. Signal processing (or premotor) time represents the delay period from the start stimulus to the onset of muscle EMG activity. Electromechanical delay constitutes the time between the onset of EMG activity and initiation of joint motion. Force development time constitutes the delay between the onset of EMG activity in a muscle and force production [31]. The faster muscle activity occurs, the faster an individual can maximize neuromuscular performance through a greater number of muscles contributing to force production earlier in the start phase. As a result, measures of signal processing time and force development time are important for improved start performance. For the front block leg, observed LG signal processing time was the shortest of five muscles (LG, vastus lateralis, biceps femoris, rectus femoris, and gluteus maximus), and was the first activated muscle as observed by the largest force development time (0.057 ± 0.050 s [32]). In contrast, the rear leg LG had the longest signal processing time, and for two participants, EMG activity did not increase during the response time process, suggesting inefficient use of the rear leg during the push phase [26]. Signal processing time and force development time are variable across individuals and at times force development time cannot be calculated, with muscle activity starting after block force production, due to the multi-joint character of the sprint start [26]. Despite the variability in the measure, reduced plantar flexor electromechanical delay has been moderately associated with reduced sprint start response times [33]. Increased pre-tensioning of the muscular-tendinous system while avoiding excessive tensioning [7], and positioning of the distal spikes in the track [26], are proposed mechanisms for earlier GAS muscle activation. Whilst the available muscle activity information during the start suggests a high level of variability across sprinters, further research is necessary.

3 Ankle Joint and Plantar Flexor Muscle–Tendon Unit Function: Acceleration and Stance

The acceleration phase of the sprint follows the block phase, and coupled with the block phase, accounts for approximately two-thirds of a world-class sprinter's final race time [34, 35]. In world-class sprinters, this acceleration phase may extend to the 50- to 80-m mark of a 100-m race before maximum velocity is achieved [36, 37]. The acceleration phase is characterized by high force generation to increase the forward momentum of the body's center of mass. Following block exit, the first stance phase contains the highest velocity increase during any stance across a maximal sprint [38], meaning the ability to generate maximal external power in this phase is important for sprint performance [39, 40]. The acceleration phase of sprinting is primarily dependent on the hip and ankle joint, with research suggesting the ankle as the most critical [41, 42]. Aligning with this, the plantar flexor muscles are potentially the largest contributor to generating the support and increase in forward momentum to accelerate toward maximum velocity [43]. However, the contribution of the plantar flexor muscles changes as the acceleration phase progresses [41]. The sprinters' ability levels for the examined sprinting studies are reported in Table 2.

3.1 Joint and External Kinetics/Kinematics

During sprint acceleration, the ankle joint absorbs energy during the first half of stance while dorsiflexing, followed by energy generation in the second half while plantarflexing [6, 44, 45], demonstrating an SSC action [46–49]. The magnitude of DF is highest during the initial two stance phases (first stance: 17 ± 3°, second stance: 18 ± 3° [49]). As forward acceleration magnitude decreases, the profile of the ankle angle remains similar but with progressively reduced DF [41].

During the initial steps of acceleration, elite sprinters tend to produce increased ground reaction force impulse [50] and larger propulsive forces [50–52] compared to sub-elite counterparts. The ankle joint and plantar flexor MTU largely contribute to impulse and propulsive forces during the acceleration phase. Across the acceleration phase, the impulse of the ankle PF moment was greatest during the early phase (0.38 ± 0.04 N m kg^{-1} s^{-1}) and smallest approaching maximum velocity (0.23 ± 0.03 N m kg^{-1} s^{-1} [41]). The impulse of the ankle plantar flexor moment has been observed to be greater than impulses of positive hip extensor moment and positive knee extensor moment across the acceleration phase [41]. The impulse of the ankle plantar flexor moment, along with the impulse of the hip extensor moment, have exhibited strong relationships with forward acceleration magnitude [41]. Magnitudes of ankle power and work also differ across the acceleration phase. Ankle joint power during the first and second stance [53], and in the mid-acceleration phase (14 m [42]) are negative following touchdown, and positive for the second half of the stance. The contribution of the ankle joint to power generation and positive work (15%) is minimal during the first stance [19] compared to the knee (31%) and hip (54%) joints, but an increased contribution is observed during the second stance (ankle: 38–48% [5, 22]), mid-acceleration (ankle: 48–59% [41, 42]), and late-acceleration (ankle: 61% [41]). The lower contribution observed during the first stance is potentially related to the increased contribution of the knee joint during the first stance for transitioning from block clearance to sprinting, compared to its contribution at second stance [19]. For the first and second stance, net ankle joint work is positive and similar in magnitude [53]. Contrasting these results, subsequent research reported that during first stance the ankle joint predominantly generated energy with reduced hip and knee work (ankle: 43 ± 6%, hip: 31 ± 8%, knee: 26 ± 8% [6]). In line with these results, the ankle was observed to generate up to four times more energy than absorbed, unlike the zero net energy generation observed in mid-acceleration [42]. Potential differences in joint contribution to the first stance may stem from higher performing sprinters producing larger resultant moments of the aforementioned lower limb segments compared to lower performing sprinters [54]. Impulse for the ankle, knee, and hip joint moments was calculated from motion analysis and force plate data [41]. Joint power across these studies was calculated from motion analysis data and 3D inverse dynamic calculations, and joint work calculated from the joint powers [5, 19, 41, 42, 53].

Compared to the knee and hip, net work for the ankle across the acceleration phase demonstrated the strongest association with forward acceleration [41]. In this study, a single foot contact for each of three acceleration conditions were selected for analysis per participant. 'High' acceleration was defined as a foot contact that occurred close to when participants started sprinting, 'low' acceleration was defined as a foot contact that occurred close to when participants were approaching maximum sprinting speed, and 'mid' acceleration was defined as a foot contact that occurred mid-way between these two extremes. While the amount of positive work done by each individual joint decreased as forward acceleration magnitude declined, ankle joint work remained relatively stable compared to positive

Table 2 Studies that investigated plantar flexor or ankle joint function across the acceleration phase of sprinting

Study details			Participants		Ankle variables of interest
Study	Phase of sprint	Design	Sample	Ability level[a]	Ankle parameters examined
Schache et al. [41]	First step—maximum acceleration (~40 m)	Cross-sectional analysis	5 M, 3 F	Sub-elite track and field athletes	Kinematics, kinetics
Bezodis et al. [44]	First stance phase	Theoretical intervention based on simulation model	1 M	10.28 s	Kinematics, kinetics
Stefanyshyn and Nigg [45]	Acceleration phase (data collected @ 15 m)	Between-group comparison	10 M	Competitive sprinters (Gp 1) Competitive distance runners (Gp 2)	Kinematics, kinetics
Werkhausen et al. [53]	First two steps	Cross-sectional analysis	11 F	12.66 ± 0.49 s	Kinematics, kinetics, MG muscle architecture
Johnson and Buckley [42]	Acceleration phase (data collected @14 m)	Group-based description	6 M	10.75 ± 0.26 s	Kinematics, kinetics
Debaere et al. [19]	Block phase and first two steps	Group-based description	11 M, 10 F	10.62 ± 0.18 s (M) 11.89 ± 0.30 s (F)	Kinematics, kinetics
Jacobs and van Ingen Schenau [5]	Second stance phase	Group-based description	7 M	10.6 ± 0.2 s	Kinematics, kinetics, EMG
Brazil et al. [6]	Block and first stance	Cross-sectional analysis	10 M	10.50 ± 0.27 s	Kinematics, kinetics
Debeare et al. [55]	First and second stance phases	Group-based description based on simulation model	2 M, 5 F	11.10–11.77 s (M) 12.05–12.36 s (F)	Kinematics, kinetics, EMG + modelling
Charalambous et al. [56]	First stance phase	Single-subject analysis	1 M	13.48 s (110 mH)	Kinematics, kinetics
Pandy et al. [43]	Acceleration phase (first 19-foot contacts)	Simulation model	4 M, 1 F	10.4–12.7 s (M/F)	Kinematics, kinetics, EMG + modelling
Lai et al. [8]	Prescribed running speeds: jogging (2.1 m s^{-1}); slow running (3.5 m s^{-1}); medium-paced running (5 m s^{-1}); fast running (7 m s^{-1}); sprinting (8 m s^{-1} or greater)	Simulation model and cross-sectional analysis	5 M, 4 F	Experienced runners	Kinematics, kinetics, EMG + modelling
Čoh et al. [27]	Block phase and first two steps	Single-subject analysis	1 F	13.19 s (100 mH)	Kinematics, kinetics, EMG
Lai et al. [57]	Acceleration phase (first 19-foot contacts)	Simulation model and cross-sectional analysis	5 M, 3 F	National level 100- to 400-m sprinters	Kinematics, kinetics, EMG + modelling

The study design, participant sample, ability level, and ankle variables of interest are provided

Gp group, *mH* meter hurdles, *M* male, *F* female, *PB* personal best

[a] Ability level of the participants are reported as 100-m PB times (when reported in the studies) or the athletes' main sprint event PB times. All other descriptors are verbatim from the methods section of the cited study

work decreases in the hip and knee joint (~50%) from 'high' to 'low' acceleration conditions [41]. For the ankle, positive work is similar between 'high' and 'mid' conditions and only decreased by 20% comparing 'mid' to 'low' acceleration [14]. Observed decreases in net joint work and increases in power absorption as forward acceleration magnitude decreases can primarily be attributed to the ankle joint in the early stance phase and hip joint during late stance [41]. These joint kinetics suggest that the ankle and hip joints may increase their reliance on elastic strain energy as forward acceleration magnitude decreases and the athlete approaches maximum velocity [41]. Similar results on the large contribution of ankle joint positive work for the first stance phase were observed in elite male sprinters, with proportional contributions of the lower limbs reported as 43%, 31%, and 26% for the ankle, hip, and knee, respectively [6].

Increasing propulsive force is a key component of accelerated sprinting. Small increases in ankle power generation during the initial steps of acceleration can positively impact acceleration performance [55]. Additionally, increasing negative power phase ankle joint stiffness during the support phase can contribute to greater propulsive force [56]. A reduced range of DF of the ankle during the early support phase can also benefit early acceleration performance [44] potentially due to both shorter ground contact times and increased net horizontal impulse [44]. Reducing the DF range of the ankle requires sprinters to increase the stiffness of the ankle joint [56], with potential benefits for early stance performance. The ankle joint and the plantar flexor MTU play a key role in accelerating the body forward across the acceleration phase but particularly during early acceleration [41], evidenced by the contribution of the individual muscles to propulsion being greatest during the first 3- to 4-foot contacts of the acceleration phase [43].

3.2 Muscle Contributions

Following block exit, during the flight phase, the TA muscle activates to assist the ankle in dorsiflexing in preparation for ground contact [20]. Before ground contact, the SOL and MG/LG are excited and remain excited throughout the first stance touchdown [20, 27].

The plantar flexor MTU contributes largely to the support and propulsion of the body's center of mass (COM) during the acceleration phase [43]. Musculoskeletal modelling of maximum acceleration sprinting for sub-elite sprinters identified the SOL functions primarily as a supporter, contributing 44% of the total upward impulse generated by all the examined muscles across the sprint (19-foot contacts). SOL peak forces generated across the acceleration phase ranged from 8.4 to 10.7 times bodyweight and tended to peak near mid-stance. The GAS also contributed largely to the support impulse, contributing 21% of the total upward impulse [43]. Focusing on the propulsive force, which is critical for maximizing the increase in forward momentum of the body during sprinting, the plantar flexors provided the largest propulsive impulse for the whole acceleration phase [43]. In particular, the GAS functioned largely as an accelerator, generating the highest propulsive force of any muscle at each foot contact. The peak propulsive force of the GAS was observed during the first foot contact of acceleration and decreased steadily across subsequent foot contacts. Despite this, GAS continued to produce propulsive forces and contribute to the acceleration of the center of mass. SOL also contributes significantly to propulsive force during the initial steps of acceleration [43, 55]. SOL generated 23% of the total propulsive impulse of all examined muscles over the 19-foot contacts; however, unlike the GAS, the contribution lessened after the initial few steps, with the muscle inducing a braking force during the first half of stance that tended to increase in magnitude with increases in running speed [43]. The GAS and SOL appear to have distinct roles from block exit to maximum acceleration. The SOL acts mainly as a supporter, generating large portions of the upward impulse, whereas the GAS acts as both an accelerator and supporter, contributing significantly to propulsive and upward impulses [43].

Muscle fascicle behaviors (SOL vs. MG) slightly differ across plantar flexor muscles during acceleration. Previous research has employed ultrasonography [53] and simulation [57] to estimate muscle fascicle behavior during accelerated sprinting. The ultrasonography study demonstrated that throughout the first and second steps, MG muscle fascicles shortened, with shortening occurring earlier during the first step [53]. However, the simulation study estimated that MG fascicle length operated at relatively consistent regions of the F–L relationship at foot strike and peak force development [57]. Simulation studies are potentially limited as sprinter-specific properties of the muscle–tendon unit are not feasible to include. Gastrocnemius medialis fascicle length changes and shortening velocities showed no significant difference between the first and second steps [53] or across the acceleration phase [57]. This supports the hypothesis of positive work by muscle fascicles in the first and second steps of maximum acceleration sprinting. MG muscle fascicle lengths were estimated using ultrasonography [53]. MG fascicle behavior is consistent with a simulation study investigating the whole acceleration phase, showing higher positive fascicle activity during acceleration than constant-speed sprinting [57]. The biarticular nature of MG facilitated energy transfer across both the knee and ankle joints. For early acceleration, SOL muscle fascicles demonstrated relatively isometric and shortening behavior during stance (i.e., first 7-foot contacts; [57]). During initial acceleration, longer SOL muscle fascicle lengths at foot strike and at the time of peak force development appear favorable, enabling the muscle fascicles to operate on the descending region of the F–L curve. This allows SOL muscle fascicles to shorten throughout stance without reaching unfavorable portions of the ascending region of the F–L curve [57]. During the latter stages of the maximal sprint, SOL muscle fascicles displayed an SSC action.

4 Ankle Joint and Plantar Flexor Muscle–Tendon Unit Function: Maximum Velocity Phase

At maximum velocity, reduced ground contact times impose greater rates of shortening on the plantar flexors, decreasing the power output from these muscles [58, 59]. Despite this,

Table 3 Studies that have investigated plantar flexor or ankle joint function across the maximum velocity phase of sprinting

Study details			Participants		Ankle variables of interest
Study	Phase of sprint	Design	Sample	Ability level[a]	Ankle parameters examined
Bezodis et al. [3]	Maximum velocity phase (foot contact @ 45 m)	Multiple single-subject comparison	4 M	P1: 9.98 s (100 m) P2: 10.91 s (100 m) P3: 23.67 s (200 m) P4: 21.25 s (200 m]	Kinematics, kinetics
Zhong et al. [61]	Acceleration/maximum velocity phase (~35–45 m)	Cross-sectional analysis	8 M	10.27–10.80 s	Kinematics, kinetics
Johnson and Buckley [42]	Acceleration phase (data collected @14 m)	Group-based description	6 M	10.75 ± 0.26 s	Kinematics, kinetics
Yu et al. [62]	Acceleration/maximum velocity phase (Accel—12 m point; Maximum velocity—40 m point)	Cross-sectional analysis	20 M	10.94 ± 0.32 s	Kinematics, kinetics
Kuitinen et al. [1]	Acceleration/maximum velocity (participants accelerated preferred distance and maintained % of their maximal speeds)	Cross-sectional analysis	10 M	10.91 ± 0.39 s	Kinematics, kinetics, EMG
Lai et al. [57]	Acceleration phase (first 19 foot contacts)	Simulation model and cross-sectional analysis	5 M, 3 F	National level 100- to 400-m sprinters	Kinematics, kinetics, EMG + modelling
Lai et al. [8]	Prescribed running speeds: jogging (2.1 m s^{-1}); slow running (3.5 m s^{-1}); medium-paced running (5 m s^{-1}); fast running (7 m s^{-1}); sprinting (8 m s^{-1} or greater)	Simulation model and cross-sectional analysis	5 M, 4 F	Experienced runners	Kinematics, kinetics, EMG + modelling
Dorn et al. [63]	Prescribed running speeds: slow running (3.5 m s^{-1}); medium-paced running (5 m s^{-1}); fast running (7 m s^{-1}); sprinting (8 m s^{-1} or greater)	Simulation model and cross-sectional analysis	5 M, 4 F	Experienced runners	Kinematics, kinetics, EMG + modelling

The study design, participant sample, ability level, and ankle variables of interest are provided

Gp group, *mH* meter hurdles, *M* male, *F* female, *PB* personal best

[a] Ability level of the participants are reported as 100-m PB times (when reported in the studies) or the athletes' main sprint event PB times. All other descriptors are verbatim from the methods section of the cited study

faster sprinters are capable of applying greater mass-specific ground forces with smaller ground contact times [60]. The sprinters' ability levels for the examined sprinting studies are reported in Table 3.

4.1 Joint and External Kinetics/Kinematics

Ankle joint movement patterns during the maximum velocity phase are similar to acceleration, with an initial ankle DF observed during ground contact followed by a PF, and an ankle PF moment throughout the majority of stance to resist the contact torque that induced ankle DF at touchdown. A small DF moment has also been observed before take-off for a minority of a sprinter sample [3]. During maximum velocity sprinting the ankle joint is a net dissipater of energy [3], with the magnitude of the peak powers of the plantar flexor muscles greater during the performance of negative work (− 4930 ± 933 W) than the subsequent positive work (3954 ± 673 W) phase [61]. The ankle joint and plantar flexor MTU dissipate power during the first half of stance and generate power for the remainder of the stance phase [3, 61]. Comparing plantar flexor MTU power dissipation during maximum velocity [3] and acceleration [42], substantially greater power dissipation is observed for maximum velocity. Compared to the acceleration phase, the maximum velocity phase of sprinting has a reduced proportion of horizontal relative to vertical force production. The greater vertical loading placed on the plantar flexor MTU during maximum velocity sprinting potentially explains the greater plantar flexor MTU power dissipation [3]. The ability of the muscle–tendon units to generate rapid, forceful contractions and subsequent high joint power outputs is critical for maintaining velocity [5]. During the swing phase of maximum velocity sprinting, the torque contribution of the ankle joint is negligible compared to the hip and knee joints [62]. However, during stance, peak angular velocity (PF: 16.20 ± 1.97 rad s^{-1}, DF: 11.51 ± 0.96 rad s^{-1}) of the ankle is greater than the hip (extension: 9.32 ± 1.15 rad s^{-1}, flexion: 9.95 ± 1.02 rad s^{-1}) and knee (extension: 11.64 ± 1.11 rad s^{-1}, flexion: 9.57 ± 0.95 rad s^{-1}) joints [61]. The work done by larger monoarticular muscles of the hip is transferred to the ankle and the ground, which enables higher power outputs at the distal joints, critical for maintaining velocity [5]. Negative correlations with ground contact time at maximal effort suggest higher ankle joint stiffness may shorten the ground contact time but this has not been shown to be a limiting factor in sprint performance [1]. Ankle joint stiffness in sprinters is determined by inherent mechanical properties of the ankle MTUs, alongside neural activation patterns.

For the maximum velocity phase, the net energy generation of the ankle joint decreases from positive values during the initial steps following block exit and early acceleration, to negative values. Despite this, the ankle joint and plantar flexor MTU plays an important role in proximal-to-distal energy transfer which aims to maintain maximum velocity for as long as possible.

4.2 Muscle Contributions

Muscle fascicles of both SOL and MG absorb and generate equivocal amounts of power approaching maximal sprinting velocity (sub-elite sprinters [57]). Fascicle-shortening velocities of active muscles do not necessarily change with increases in sprinting velocity, potentially due to the contribution of the tendon, with evidence demonstrating small muscle fiber length changes in the SOL and GAS while sprinting at ≥ 8 m s^{-1} (experienced runners [8]). Minimization of muscle fiber length changes during maximal sprinting [8, 57] is attributed to increased utilization of tendon stretch and recoil due to the tendon's capacity to recoil at high velocities. This contributes to generating the rapid MTU shortening velocities required at high velocities, reducing the shortening velocity requirement from muscle fibers [8]. Longer plantar flexor muscle fascicles, coupled with the contributions of tendon stretch and recoil, enable plantar flexor muscle fibers to operate more effectively along the force–velocity (F–V) curve during sprinting [8]. While increased stretch and recoil of tendon strain energy is optimal for muscle fiber F–V relationship, this occurs at the expense of favorable muscle fiber operating lengths (F–L relationship [8]). At increased sprinting velocities, plantar flexor muscle fibers operate on the ascending limb of the F–L curve. Despite this, shorter muscle fiber lengths enabled higher tendon stretch and recoil during sprinting, facilitating increased contributions of tendon elastic strain energy to MTU positive work [8]. While peak forces of the SOL and GAS decrease with increased running speed, the contribution to vertical ground force remains similar [63]. These muscle and tendon properties were calculated using musculoskeletal modelling [8, 57], which does introduce limitations due to the assumptions of the model.

The limiting factor of these muscles in generating forces at maximal velocity is the limited ground contact time for force development, imosing increased shortening demands on the plantar flexors at higher velocities [8, 63]. The maximum speeds attained by the population in this study (maximal velocity < 10 m s^{-1}) are significantly lower than those achieved by world-class male (11.5–12.0 m s^{-1} [34]) and female sprinters (10.5–11.0 m s^{-1} [35]). Given the previous observations of Weyand et al. [60] that higher ground reaction forces are observed during faster running speeds, and the location of the center of pressure is unlikely to move significantly, it is reasonable to assume that in world-class athletes the muscular demands imposed are even greater.

5 Musculotendinous Factors Influencing Plantar Flexor Performance in Sprinters

Research on this question has investigated the contribution of various musculotendinous factors, focusing on the ankle joint and plantar flexor MTU role in maximal sprinting. A plantar flexor MTU with architecturally more favorable and rapid contractile kinetics can enable greater ground forces to be applied during the progressively shorter periods of ground contact as sprinting speed increases [9, 10]. Understanding the contribution of these factors helps in contextualizing the importance of the ankle joint and plantar flexor MTU to sprint performance. The sprinters' ability level for the studies examining plantar flexor MTU variables are reported in Table 4. The sprinters' ability level for the studies examining the Achilles tendon variables and also the ankle/foot anthropometrics are reported in Table 5.

5.1 Anthropometric Differences

Comparative functional morphology research suggests that skeletal structures of the foot and ankle, combined with plantar flexor musculotendinous factors, are determinants of locomotor speed. Sprinters of differing abilities have foot morphological differences [64], as well as compared to other populations [65, 67, 68]. Forefoot bone lengths are similar between faster and slower sprinters [69], but longer in sprinters compared with non-sprinters [65–68]. Forefoot bones have demonstrated associations with sprint performance, with weak correlations with the first toe [64] and moderate correlations with second toe bones [64, 67, 68]. These morphologies were measured using magnetic resonance imaging (MRI [64, 66–68]) or manual measurement [65, 69]; however, the results appear consistent regardless of measurement method. Simulation research suggests that similar to decreasing the moment arm, increasing toe length [and the gear ratio] can increase forward impulse [66].

Additional foot morphologies that may contribute to plantar flexor performance during sprinting is arch height, with suggestions that it can assist in utilizing MTP joint stored elastic energy during the stance phase of sprinting [70–72]. Foot arch height could assist in producing larger plantar flexor torques due to the increased metatarsophalangeal joint torques using the elastic energy during stance phase push off [65, 66, 70]. Foot arch height appears to be independent of foot length in sprinters and appears to be linked with improved sprint performance. A higher foot arch is related to an increased calcaneal inclination angle (i.e., angle between the inferior calcaneal surface and the supporting surface), which can contribute to modelling a taller calcaneus [73]. Therefore, a taller calcaneus could be a positive factor for an increased height of the foot arch. Foot arch height (faster vs. slower: 52.3 vs. 48.1 mm) and calcaneus height (faster vs. slower: 55.7 vs. 52.5 mm) measured with MRI are greater in faster vs. slower sprinters with both morphologies negatively moderately correlated with 100-m PB [64]. Relative calcaneus length (normalized to foot length) was also greater in faster sprinters and negatively moderately correlated with 100-m PB while talus length was similar between sprinter performance levels but displayed a negative moderate correlation with 100-m PB [64]. Limited research investigating foot morphologies and sprint performance is available, with Japanese male sprinters the sole participants of the available research. Further investigation is needed incorporating a wider selection of ethnicities and inclusion of both sexes. Other lower leg morphologies demonstrating moderate correlations with 100-m PB are shank length, with sprinters demonstrating significantly smaller shank lengths compared to non-sprinters (sprinters vs. non-sprinters: 41.1 vs. 44.1 cm [65]). However, no significant differences were observed between faster and slower sprinters (faster vs. slower: 39.9 vs. 41.2 cm [69]), or sprinters and endurance athletes (sprinters vs. endurance: 39.6 vs. 40.0 cm [74]). The differing measurement methods of manual measurement [65, 69] and MRI [74] across studies may contribute to the inconsistency in shank length differences across populations.

5.2 Muscle Strength

Increased plantar flexor torque is important in shortening ground contact times and increasing ground reaction forces during the stance phase, both of which are determinants of sprint performance [75]. Recognizing the importance of plantar flexor strength capabilities for sprint performance, numerous studies have examined this parameter during isometric or isokinetic plantar flexor maximal contractions, comparing sprinters with control populations. Plantar flexor isometric torque did not differ between elite versus sub-elite sprinters [76], a faster versus a slower group of sub-elite sprinters [77], and sub-elite sprinters versus untrained participants [78]. Isokinetic torque measures revealed greater torque generation in sprinters (elite and sub-elite) compared to untrained participants (sprinters vs. untrained: 16.0 vs. 8.1 N m), but only at the highest angular velocity tested (6.61 rad s^{-1} [79]). Plantar flexor strength discrepancies between sprinters and untrained participants at high angular velocities suggest that the task/contraction specificity may

Table 4 Studies that have investigated plantar flexor musculoskeletal factors in relation to sprint performance

Study details				Participants	
Study	Muscle studied	Variables examined	Design	Sample	Ability level[a]
Abe et al. [98]	LG, MG	MT, FL, PA	Between-group comparison/cross-sectional analysis	71 M	10.0–10.9 s (Gp 1) Distance runners (Gp 2) Untrained (Gp 3)
Abe et al. [95]	LG, MG	MT, FL, PA	Between-group comparison/cross-sectional analysis	48 F	12.21±0.70 s (Gp 1) Untrained (Gp 2)
Arampatzis et al. [116]	–	Isometric torque	Between-group comparison/cross-sectional analysis	66 M	Trained sprinters (Gp 1) Endurance runners (Gp 2) Untrained (Gp 3)
Costill et al. [104]	LG	Muscle fiber type	Between-group comparison/cross-sectional analysis	27 F, 34 M	11.4–11.4 s (F), 10.3–10.5 s (M) (Gp1) Middle-distance runners (Gp 2) Distance runners (Gp 3) Long/high jumpers (Gp 4) Javelin throwers (Gp 5) Shot-put/discus throwers (Gp 6) Untrained (Gp 7)
Dowson et al. [80]	–	Isokinetic torque	Cross-sectional analysis	24 M	Rugby players (8), Track sprinters (8), active (8)
Fukutani et al. [89]	LG, MG, SOL	MV	Between-group comparison	126 participants	11.1±0.4 s (Gp 1) Long-distance runners (Gp 2) Untrained (Gp 3)
Harridge and White [79]	–	Isokinetic torque	Between-group comparison/cross-sectional analysis	26 M	Senior UK club to Olympic Standard sprinters (100 m–400 mH; Gp 1) Untrained (Gp 2) Elderly (Gp 3)
Kubo et al. [78]	LG, MG, SOL	Isometric torque, MT	Between-group comparison/cross-sectional analysis	30 M	10.79±0.13 s (Gp 1) Untrained (Gp 2)
Kubo et al. [118]	LG, MG, SOL	Isometric torque, MT, FL (MG only), PA (MG only)	Between-group comparison	38 M	11.37±0.41 (Gp 1) Untrained (Gp 2)
Kumagai et al. [94]	LG, MG	MT, FL, PA	Between-group comparison/cross-sectional analysis	37 M	10.00–10.90 s (Gp 1) 11.00–11.70 s (Gp 2)
Lai et al. [8]	GAS (analyzed together), SOL	Muscle fascicle shortening velocity	Cross-sectional analysis based on musculoskeletal modelling	5 M, 4 F	Experienced runners
Lee and Piazza [65]	LG	MT, FL, PA,	Between-group comparison/simulation model	24 participants	10.7–12.3 s (100 m), 23.3–24.0 s (200 m) (Gp 1) Non-athletes (Gp 2)
Miller et al. [76]	LG, MG, SOL	Isometric torque, MV	Between-group comparison/cross-sectional analysis	45 M	10.10±0.07 s (Gp 1) 10.80±0.30 s (Gp 2) Untrained (Gp 3)
Miyake et al. [87]	LG, MG, SOL	MV, CSA	Between-group comparison/cross-sectional analysis	78 M	10.41±0.10 s (Gp 1) 10.81±0.10 s (Gp 2) 11.17±0.09 s (Gp 3) 11.56±0.16 s (Gp 4) Recreationally active (Gp 5)

Table 4 (continued)

Study details				Participants	
Study	Muscle studied	Variables examined	Design	Sample	Ability level[a]
Monte and Zamparo [82]	LG, MG, SOL	MT, FL, PA	Cross-sectional analysis	18 M	10.66 ± 0.51 s
Stafilidis and Arampatzis [77]	MG	Isometric torque, FL, PA, MT	Between-group comparison/cross-sectional analysis	28 M	11.04 ± 0.17 s (Gp 1) 11.64 ± 0.23 s (Gp 2)
Sugisaki et al. [86]	GAS (analyzed together), SOL	MV, CSA	Cross-sectional analysis	31 M	10.94 ± 0.39 s
Tanaka et al. [83]	LG, MG	MT	Between-group comparison/cross-sectional analysis	52 M	10.99 ± 0.39 s (Gp 1) Recreationally active (Gp 2)
Tottori et al. [84]	PF (not subdivided into 3 muscles)	CSA	Cross-sectional analysis	15 M	15.12 ± 1.04 s (Preadolescent: 11.6 ± 0.4 years old)
Tottori et al. [85]	PF (not subdivided)	CSA	Between-group comparison/cross-sectional analysis	96 M	11.12 ± 0.36 s (Gp 1) Recreationally active (Gp 2)

The muscle(s) and variables examined alongside the study design, participant sample and ability level are provided

Gp group, *M* male, *F* female, *MT* muscle thickness, *MV* muscle volume, *CSA* cross-sectional area, *FL* fascicle length, *PA* pennation angle, *PB* personal best

[a] Ability level of the participants are reported as 100-m PB times (when reported in the studies) or the athletes' main sprint event PB times. All other descriptors are verbatim from the methods section of the cited study

be an influencing factor, with isokinetic plantar flexor torque correlated with sprint performance (sprint velocities during acceleration and maximum velocity phases), albeit in a mixed population of elite sprinters, elite rugby players, and physically-active participants [80]. Similarities in isometric strength between sprinters and other populations may be attributed to the lack of specificity of the isometric strength measures versus the dynamic nature of maximal sprinting [81] Dynamic plantar flexor torque production appears to be most critical for sprinting, linked to the fact that faster sprinters exhibit a clear capability of applying greater propulsive forces in a limited time frame, applied through the ankle joint, compared with slower sprinters [18]. Dynamic plantar flexor torque generation is dependent on the magnitude and interactions between different architectural parameters, (i.e. muscle fascicle length, pennation angle, muscle size, and moment arms).

5.3 Muscle Architecture (Muscle Size, Fascicle Length, Pennation Angle)

5.3.1 Muscle Size

Muscle architecture alongside the fiber composition and biochemical properties influence the force-generating capacity of a muscle. Muscle size is one of these factors, with larger muscles expected to exert greater forces, and therefore possibly advantageous for sprinters. Plantar flexor muscle thickness (LG, MG, and SOL) measured using ultrasonography positively correlated with peak power production during the acceleration phase ($r = 0.82$–0.92) in an elite/sub-elite sample of sprinters [82]. Contrasting evidence reported a lack of association between plantar flexor muscle thickness [78, 83], cross-sectional area ((CSA) [84, 85]), and muscle volume [86, 87] with 100-m PB in sub-elite sprinters. The differing measurement methods of ultrasound [78, 82, 83] and MRI [76, 84–87] across studies may contribute to the inconsistency in the association between muscle size measures and 100-m PB.

Findings from elite sprinters confirmed the absence of a relationship between plantar flexor muscle volume and sprint performance measured using MRI, with no correlation observed between normalized muscle volumes of the total and individual plantar flexor muscles and 100-m performance [76]. The lack of association between plantar flexor muscle size and sprint performance is further observed when comparing muscle size between performance levels of sprinters. While elite sprinters have greater proximal muscle volumes (i.e., hip extensors) compared to sub-elite (hip extensor absolute muscle volume elite vs. sub-elite: 4002 vs. 3029 cm^3), absolute plantar flexor total muscle volume (elite vs. sub-elite: 1112 vs. 943 cm^3) and relative plantar flexor total muscle volume (elite vs. sub-elite: 12.92 vs. 12.48 $cm^3\ kg^{-1}$) are similar [76]. Comparable results have been observed, with no total plantar flexor muscle volume differences (absolute or relative) between

Table 5 Studies that have investigated Achilles tendon and ankle anatomical factors in relation to sprint performance

Study details			Participants	
Study	Parameter	Design	Sample	Ability level[a]
Arampatzis et al. [116]	Stiffness/compliance, elongation, strain, force	Between-group comparison/cross-sectional analysis	66 M	Trained sprinters (Gp 1) Endurance runners (Gp 2) Untrained (Gp 3)
Baxter et al. [66]	Moment arm, foot bone lengths	Between-group comparison/cross-sectional analysis	16 M	10.5–11.1 s (100 m), 21.4–24.1 s (200 m) (Gp 1) Non-sprinters (Gp 2)
Bex et al. [74]	Shank length	Between-group comparison/cross-sectional analysis	19 M	6.95–7.07 s (60 m), 10.68–10.99 s (100 m) (Gp 1) Endurance runners (Gp 2)
Karamanidis et al. [69]	FL: Moment arm, foot length, toe length, shank length	Between-group comparison/cross-sectional analysis	18 M	10.27 ± 0.07 s (Gp 1) 10.67 ± 0.08 s (Gp 2)
Kubo et al. [117]	Stiffness/compliance, elongation, force	Between-group comparison/cross-sectional analysis	24 M	11.01 ± 0.17 s (Gp 1) Untrained (Gp 2)
Kubo et al. [78]	Elongation, stiffness, force, thickness	Between-group comparison	30 M	10.79 ± 0.13 s (Gp 1) Untrained (Gp 2)
Kubo et al. [118]	Elongation, stiffness, force, CSA	Between-group comparison	38 M	11.37 ± 0.41 (Gp 1) Untrained (Gp 2)
Kubo et al. [119]	Elongation, strain, hysteresis, CSA	Between-group comparison/cross-sectional analysis	33 M	11.17 ± 0.24 s (Gp 1) Untrained (Gp 2)
Lai et al. [57][b]	Tendon elastic strain energy, muscle fascicle power	Cross-sectional analysis based on musculoskeletal modelling	5 M, 3 F	National 100- to 400-m sprinters
Lee and Piazza [65]	Moment arm, FL: Moment arm, toe lengths, foot lengths, shank length	Between-group comparison/simulation model	24 participants	10.7–12.3 s (100 m), 23.3–24.0 s (200 m) (Gp 1) Non-athletes (Gp 2)
Monte and Zamparo [82]	CSA, length	Cross-sectional analysis	18 M	10.66 ± 0.51 s
Stafilidis and Arampatzis [77]	Elongation, strain, force, Tibia length, FL: Tibia length	Between-group comparison	28 M	11.04 ± 0.17 s (Gp 1) 11.64 ± 0.23 s (Gp 2)
Suga et al. [64]	Foot bone lengths, foot arch (height/length), calcaneus (height/length)	Cross-sectional analysis	56 M	11.10 ± 0.41 s
Tanaka et al. [67]	Foot bone lengths, moment arm	Between-group comparison/cross-sectional analysis	72 M	11.07 ± 0.45 s (Gp 1) Recreationally active (Gp 2)
Tomita et al. [68]	Foot bone lengths	Between-group comparison/cross-sectional analysis	50 M	49.23 ± 1.46 s (400 m) (Gp 1) Non-sprinters (Gp 2)
Tomita et al. [122]	CSA, length	Cross-sectional analysis	48 M	11.12 ± 0.43 s

The parameter(s) examined alongside the study design, participant sample and ability level are provided

Gp group, *mH* meter hurdles, *M* male, *F* female, *CSA* cross-sectional area, *FL* fascicle length, *PB* personal best

[a] Ability level of the participants are reported as 100-m PB times (when reported in the studies) or the athletes' main sprint event PB times. All other descriptors are verbatim from the methods section of the cited study

[b] Lai et al. [53] examined tendon properties during sprint running, whereas the other studies measured these properties statically

four groups of sprinters of differing performance levels [87].

In comparison to other populations, relative plantar flexor total muscle volume measured using MRI is greater in male sprinters [76, 87] than previously reported values for physically active male participants [88]. Sprinters demonstrated greater relative LG and MG muscle volumes compared to endurance and untrained participants (MRI measured [89]), and greater relative plantar flexor CSA compared to untrained participants (MRI measured [85]). Additionally, sprinters' plantar flexor muscle thickness is also greater compared to untrained participants (ultrasound measured [78, 83]). However, muscle size differences across populations are inconsistent, with research also reporting similarities in muscle size across these groups (MRI measured [74, 90]), and even smaller muscle volumes of SOL for sprinters compared with endurance and untrained participants [89]. Additionally, junior-level sprinters (18–20 years old) have demonstrated similar muscle volumes in plantar flexor muscles compared with recreationally active individuals, with the tibialis posterior the only ankle-crossing muscle to be significantly larger in the sprinter population [90]. While larger muscles would be advantageous for force production during sprinting, additional muscle volume increases limb mass, which introduces a trade-off in terms of speed optimization. Sprinting requires optimal muscle volumes of the lower leg for power generation [91, 92] but requires it to be not too heavy for leg swing [93].

5.3.2 Fascicle Length

Sprinters' plantar flexor muscles are required to generate high shortening velocities to accelerate rapidly and attain high sprinting velocities [65, 94, 95]. Amongst sprinters, longer and less pennate GAS muscle fascicles have been associated with faster sprint times [94, 95]. Longer fascicles are advantageous due to the greater number of sarcomeres in series [95]. For a given MTU shortening velocity, each individual sarcomere can shorten more slowly, and due to the F-V relationship, can develop a higher force [96, 97]. These longer fascicles can produce greater power, and at the high shortening velocities experienced during sprinting, enable an increased rate of ground force application. Comparing faster to slower sprinters, MG (faster vs. slower: 6.62 vs. 5.70 cm) and LG (faster vs. slower: 8.07 vs. 6.55 cm) fascicle length was greater in faster sprinters [94]. More recently, MG fascicle length has been observed to be similar across groups of faster and slower sprinters (faster vs. slower: 7.54 vs. 8.59 cm); however, both of these groups could be classified as sub-elite [77]. Longer muscle fascicles in the MG/LG of sprinters compared to endurance athletes [98] and untrained participants [66, 95, 98] have been reported. Increased GAS fascicle lengths in sprinter populations compared to other populations has been demonstrated in previous research, and while longer muscle fascicles can be genetically conferred, they can also derive from specific adaptations to sprint training. Fascicle length increases in response to 5 weeks of sprint and jump training have been observed in the vastus lateralis and rectus femoris muscles [99]. Longer muscle fascicles have demonstrated negative correlations (absolute LG fascicle length: $r = -0.44$ to -0.54; absolute MG fascicle length: $r = -0.40$; relative LG fascicle length: $r = -0.29$ to -0.57; relative MG fascicle length: $r = -0.44$) with 100-m PB performance [94, 95], and positive correlations with peak values of velocity ($r = 0.65$–0.75), force ($r = 0.77$–0.80) and power ($r = 0.87$–0.90) across LG, MG, and SOL muscles [82]. The observed link between longer plantar flexor fascicle lengths and sprint performance may relate to the higher shortening velocities and mechanical powers they generate compared to shorter fascicles. An additional consideration for muscle fascicle length is the length of the muscle fascicles in relation to tendon moment arm size. This is because the amount of change in muscle fascicle length that occurs as a joint rotates (i.e., during sprinting) depends on the muscle moment arm [96]. Greater ratios have been observed in sub-elite sprinters with smaller tendon moment arms and longer LG muscle fascicles reported, compared to non-sprinters [65]. While greater ratios are observed in sprinters vs. non-sprinters, no differences were reported between faster and slower sprinters [69].

5.3.3 Pennation Angle

Muscle fascicle length explains more of the variation in plantar flexor kinetics than pennation angle [100]. However, both fascicle length and pennation angle govern absolute muscle shortening velocity [101]. An increased muscle pennation angle increases the fascicle shortening demands for a muscle shortening contraction and is associated with slower velocities, which can negatively impact sprinting velocity. Less pennate GAS fascicles have been correlated with faster sprint times [94, 95], and greater peak force, power, and velocity of LG, MG, and SOL during sprinting [82]. Faster sprinters compared with slower sprinters have been shown to have smaller LG (faster vs. slower: 14.0 vs. 15.2°) and MG (faster vs. slower: 21.4 vs. 23.5°) pennation angles [94]; however, extensive evidence confirming differences in pennation angle between performance level of sprinters is limited. Comparing sprinters with endurance-trained athletes revealed a smaller MG pennation angle for sprinters (sprinters vs. endurance: 21.5 vs. 23.3°), but similar LG pennation angles between groups (sprinters vs. endurance: 14.1 vs. 16.1° [98]). Compared with untrained controls, no differences in MG [95, 98] or LG [65, 95, 98] pennation were observed with sprinters.

5.3.4 Measurement Considerations

Plantar flexor muscle fascicle length, pennation angle, and muscle thickness parameters change during dynamic contractions such as sprinting [8, 102, 103]. Numerous studies have analyzed parameters such as fascicle length during dynamic movements of walking, running, and jumping. Limited sprinting studies have examined these parameters in a dynamic condition [53]. Many sprinting studies use resting values of these measures which do not necessarily reflect behavior during maximal sprinting and may explain the inconsistencies in results and relationships of these parameters across studies. Muscle structure measures at rest are crucial for assessing intrinsic muscle properties. However, further studies employing dynamic measurement methods [53] may delineate the contribution of musculotendinous parameters at certain periods of the race (e.g. tendon recoil is more important in the maximum velocity stage than acceleration [57]).

5.4 Muscle Fiber Type and Contraction Speed and Operating Lengths

Alongside muscle architectural properties, biochemical characteristics (i.e., myosin ATPase activity) determines muscle shortening velocity. Human muscle fibers are typically classified by myosin heavy chain isoforms, characterized by slow (type I fibers) to fast (type IIA and IIB/IIX fibers) contractile speeds. A higher proportion of type IIb/X fibers appears advantageous for sprinting due to the increased maximal shortening velocity of a muscle, exemplified by the correlation between fast-twitch fibers and sprint performance [32]. Additionally, due to the rapid contractile kinetics associated with fast-twitch fibers, they may enable greater ground forces to be applied during progressively shorter periods of ground contact approaching maximum velocity [10]. Sprinters' LG muscle has demonstrated increased proportions of type II fast-twitch fibers (~ 73–76%) compared to endurance athletes (~ 39–48%), and untrained participants (~ 47–49% [104]). Cadaver studies highlighted differing fiber type proportions in the plantar flexor muscles, with the SOL demonstrating a higher proportion of slow-twitch fibers, compared to the GAS which includes equal proportions of slow and fast-twitch fibers [105]. Variations in plantar flexor muscles fiber type proportions suggest the GAS may be suited for generating force at higher velocities, aligning with the increased contribution of the GAS to propulsion approaching maximum velocity [87]. Plantar flexor muscle performance during sprinting is not only dependent on the muscle shortening velocity. The regions of the force–length–velocity curves in which muscle fibers operate during sprinting can influence muscle performance; however, limited research has examined this during maximal sprinting [8, 63].

5.5 Tendon Properties (Stiffness, Strain, Young's Modulus)

5.5.1 Tendon and Muscle: Working in Tandem

The efficiency of a muscle working in series with a tendon is task specific. Across different gait conditions and speeds, different muscle fascicle lengths and tendon compliance combinations are required to maximize efficiency [106]. Rapid MTU shortening velocities required during sprinting are largely achieved by the contribution of tendon recoil with the tendons capable of achieving significantly higher shortening velocities than muscle fibers. Due to the high velocities of stretching and shortening during maximum sprinting, without the contribution of the tendons, muscles would operate in a mechanically unfavorable scenario [107–109]. Contributions of the tendon to MTU length changes enable reduced shortening velocities of the muscle fibers, allowing them to operate under favorable F–V conditions. Tendon mechanics estimated using musculoskeletal modelling during maximal sprinting revealed that Achilles tendon elastic strain energy is as critical at the initial stages of a maximal sprint, as it is at the end [57]. For the start of a sprint, Achilles tendon strain energy contributes largely to enhancing MTU propulsion (start of sprint tendon strain: SOL—5.72%, MG—5.72%), while towards the end the contribution is reducing muscle fascicle energy expenditure (foot contact 19 tendon strain: SOL—5.72%, MG—5.15%). Demonstrating this, Achilles tendon elastic energy stored in the SOL and MG varied by only 0.12 ± 0.05 J kg^{-1} from the start of the sprint to foot contact 19 [57]. Tendon strain energy is therefore crucial to the plantar flexors in generating sufficient energy and power, which is essential for attaining maximal sprinting speed. Whether a compliant or a stiffer Achilles tendon is optimal for sprinting performance is debated.

5.5.2 Increased Tendon Stiffness for Sprinting?

During sprinting, increases in power requirements from the muscles require a stiffer tendon to produce optimal efficiency and generate the necessary power with the given muscle volume. With small muscle fascicle lengths and low stiffness values, the power output required by sprinters cannot be produced without increasing the muscle size substantially [106]. A stiffer tendon is negatively correlated with force development time/electromechanical delay [110, 111], and positively correlated with the RFD [112], demonstrating its suitability for increasing force production, particularly during explosive contractions. Focusing on the sprint start, force development time (a component of electromechanical delay) has been proposed as a contributing factor to sprint start response time. Electromechanical delay is mainly determined by the elastic properties of the MTU and its capability to remove inherent series elastic 'slack' [110, 113]. Higher MTU stiffness levels facilitate greater force per unit of length change, thereby removing series elastic 'slack' at a greater rate [114, 115]. Given the likely influence of tendon stiffness on the rate of force transmission, it is reasonable to expect tendon stiffness to influence force transmission delays (i.e., electromechanical delay, sprint start response time) during sprint performance. However, this relationship is yet to be established experimentally. The argument for a stiffer Achilles tendon in sprinters is supported by findings of increased normalized Achilles tendon stiffness, measured isometrically using ultrasonography, in sprinters compared to endurance athletes and untrained participants (sprinters vs. endurance vs. untrained: 37.2 vs. 26.9 vs. 21.9 kN/strain). Additionally, sprinters demonstrated increased tendon force (sprinters vs. endurance vs. untrained: 2352 vs. 1726 vs. 1467 N), and plantar flexor moment (sprinters vs. endurance vs. untrained: 156.4 vs. 126.3 vs. 109.9 N m) with increased muscle strength accounting for a significant portion of the variation ($r^2 = 0.67$) in tendon stiffness [116].

5.5.3 Increased Tendon Compliance for Sprinting?

In contrast, increased contributions of a compliant tendon to length changes in the MTU reduces muscle fiber-shortening velocity, enabling more favorable F–V conditions. Potentially, a compliant Achilles tendon decreases the effectiveness of force transmission from contractile elements to the skeleton during sprinting. Sprinters' Achilles tendon properties including stiffness (44.0 N mm^{-1} [117]), maximal elongation (18.1 mm [78], 18.6 mm [118]), maximal strain, and hysteresis (15.7% [119]) are similar compared to untrained participants, with sprinters' maximal elongation (sprinters vs. endurance: 19.0 vs. 17.8 mm) and strain (sprinters vs. endurance: 6.2 vs. 6.1%) properties also similar compared with endurance-trained athletes [116]. There does not appear to be a clear association between sprinters' Achilles tendon stiffness/compliance and 100-m performance [116, 119]. Additionally, sprinters of differing performance levels demonstrated no difference in Achilles tendon maximal elongation or strain [77]. Potentially, an optimal bandwidth between Achilles tendon compliance and stiffness exists for sprinting, with sufficient compliance to utilize the tendon strain energy and adequate stiffness for rapid force transmission.

5.5.4 Measurement Considerations

The broad inconsistency in results across studies of tendon stiffness is likely due to the multitude of methodological approaches adopted by various research groups, alongside potential measurement errors, contributing to the large variability in reported values [127]. Tendon stiffness is commonly measured in isometric conditions [77, 116–119]. Potential measurement errors that can be encountered include the choice of anatomical features to scan and to track, inaccurate tracking of tendon elongation, estimations of tendon force, and data synchronization [120]. When determining tendon stiffness in dynamic conditions, potential errors include the projection of the muscle–tendon junction in 3D, data synchronization, and inaccurate tracking of the calcaneus insertion position [121]. When all these sources of error are considered, errors in tendon length of up to 13.1 mm and in moment arm of up to 14.4 mm have been observed, both of which directly impact calculated stiffness values.

5.6 Tendon Architecture (Moment arm, CSA, Length)

5.6.1 Tendon Cross-Sectional Area (CSA) and Length

Achilles tendon morphological properties of CSA and length potentially impact plantar flexor performance during sprinting, with correlations observed between these properties and the velocity of sub-elite sprinters during a 20-m acceleration [82]. In particular, increased Achilles tendon CSA enables sprinters to withstand greater mechanical stress, allowing sprinters to reach higher maximum velocities. Faster sprinters were observed to have greater Achilles tendon CSA ($r = -0.59$ [82]); however, contrasting findings of no association between Achilles tendon length or CSA and sprint performance in well-trained sprinters have also been reported [122]. Additionally, similarities in Achilles tendon CSA have been observed between well-trained sprinters and untrained men [119]. Variations between studies may be due to differences in sprinter performance level (sub-elite vs. well-trained) or varying sprinter race across the studies (European vs. Japanese). The methodology of quantifying Achilles tendon properties may also account for differences with ultrasound employed in one study [82] and MRI in the other [122], with a lack of correlation between ultrasound and MRI measures of Achilles tendon CSA previously reported [60, 123].

5.6.2 Tendon Moment Arm

The Achilles tendon moment arm is another determinant of plantar flexor performance, as it is the link between the net ankle joint moment and forces transmitted through the Achilles tendon, and consequently the link to MTU function. Simulations of the sprint-start push-off observed that sprinters can generate an increased forward impulse with longer toes and shorter Achilles tendon moment arms [65]. A higher ratio between these two parameters allows muscle fibers to shorten less and reduces peak fiber-shortening velocity, enabling the development of large torques over a wide range of motion at fast joint angular velocities (i.e., sprinting [65]). Sprinters' Achilles tendon moment arms (resting and during contracting) are smaller compared with non-sprinters (sprinter vs. non-sprinter resting moment arm: 51.5 vs. 58.5 mm; sprinter vs. non-sprinter contracted moment arm: 52.9 vs. 58.7 mm [66]) but similar across faster and slower sprinters examined during a passive test (sprinter vs. non-sprinter: 42 mm vs. 42 mm [69]). Contrasting findings reported no moment arm difference between sprinters and recreationally active participants measured at rest (sprinters vs. recreationally active: 48.7 vs. 48.8 mm [67]); however, ethnicity, sprinter performance level, sample size, or measurement methods may account for the lack of differences across studies. The differing tendon moment arm measurement methods of MRI [66, 67] and tendon excursion method using ultrasound [65, 69] across studies may contribute to the inconsistency in results. In relation to the ground reaction force moment arm length, studies reported greater toe [65, 67] and forefoot bone lengths [66, 67] in sprinters compared to non-sprinters. Across faster and slower sprinters no difference in foot geometries was observed [69].

6 Conclusion

6.1 Ankle and Plantar Flexor Contributions Across the Sprint Phases

6.1.1 Sprint Start

The ankle joint appears to be an important contributor to sprint start performance, particularly the rear leg ankle joint. The SSC action of the plantar flexor MTU appears to contribute to increased block force generation and block power but is dependent on the inclination of the block footplate. Comparing elite and sub-elite sprinters identified that elite sprinters produced greater RFD and normalized average horizontal block power, transferred through the ankle joint to the block.

6.1.2 Acceleration

The ankle joint and plantar flexor MTU appears to be the most critical of the major lower limb joints/MTUs during the acceleration phase. The contribution of the ankle joint to power generation and positive work is minimal during the first stance compared to knee and hip joints, but an increased contribution is observed during the second stance, mid-acceleration, and late-acceleration. In terms of muscular contributions, the GAS and SOL appear to have distinct roles. The SOL acts mainly as a supporter, generating large portions of the upward impulse, whereas the GAS acts as both an accelerator and supporter, contributing significantly to propulsive and upward impulses.

6.1.3 Maximum Velocity

During maximum velocity sprinting the ankle joint is a net dissipater of energy, potentially due to the greater vertical loading placed on the plantar flexors. However, the ankle joint is critical for energy transfer from proximal joints (i.e., hip joint, knee joint) to ground force application to maintain velocity. The ankle joint may increase its reliance on elastic strain energy as forward acceleration magnitude decreases and the athlete approaches maximum velocity.

6.2 Musculotendinous Factors Influencing Plantar Flexor Performance in Sprinters

Most likely, an optimal plantar flexor MTU profile exists for maximal sprinting. Potentially, this is a combination of several musculoskeletal factors. Comparing elite and sub-elite sprinters can delineate the musculotendinous factors of the plantar flexor MTU that contribute to a higher level of sprint performance, and how individualized these factors may be. Certain plantar flexor morphological factors may be a necessity in attaining a high level of sprint performance and could be present in both elite and sub-elite sprinters. However, plantar flexor performance differences between elite and sub-elite sprinters could rely on other factors such as technical ability. In other words, while both elite and sub-elite level sprinters may possess these superior properties (strength/morphologies/anthropometrics), the technical ability to maximize the performance of these properties may be the differentiating factor. Comparing sprinters with untrained athletes may better delineate the important musculotendinous factors of the plantar flexor MTU that contribute to superior PF performance during sprinting.

6.3 Future Research

In the completion of this review a distinct lack of research on female athletes, truly world-class athletes, bend running, and the stratification of variables with respect to athlete level was observed. Additionally, the majority of research on sprinters' ankle and plantar flexor function has examined the association between musculotendinous measures and 60/100/200/400-m personal best. Future research should, where possible, investigate the relationship of these musculotendinous measures with maximal sprinting kinetic/kinematic measures that determine sprint performance (i.e., velocity, force, power) or performance metrics (10/20/60-m splits). These measures may provide a better insight into the relationship of musculotendinous measures to maximal sprint performance, as personal bests at the time of testing may not be indicative of the athlete's current condition/performance ability. Additionally, this can further delineate the contribution of musculotendinous parameters at certain periods of the race (i.e., tendon recoil is more important in the maximum velocity stage than in acceleration [53]). With the continued emergence of sprinting 'super spikes', and the suggested influence of these on Achilles tendon and metatarsophalangeal joint performance, research on the force-producing demands placed on the ankle and plantar flexor MTU across the multiple versions of 'super spikes' available is required. Future research should aim to address the aforementioned areas to establish a comprehensive understanding of the influence of ankle and plantar flexor performance on maximal sprint performance.

Declarations

Funding This work was supported by the Irish Research Council under Project number GOIPG/2017/378.

Conflict of interest The authors declare that they have no competing interests.

Ethics approval Not applicable.

Informed consent Not applicable.

Consent for publication Not applicable.

Code availability Not applicable.

Author contributions EC, LAF, and DH contributed to the study conception and design. EC performed the literature search, interpreted the data, and wrote the original draft of the manuscript. EC, LAF, and DH contributed to the data interpretation and revised the manuscript. EC, LAF, and DH read and approved the final version of the manuscript.

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