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Myotonometric Assessment of Achilles Tendon and Gastrocnemius Stiffness in Recreationally Active Young Adults: Reliability, Impact of Sex, and Links to Linear Sprint

Matic Sašek[1], Petra Brnelić[1], Žiga Kozinc[1,2]

Affiliations: [1]University of Primorska, Faculty of Health Sciences, Izola, Slovenia, [2]Ludwig Boltzmann Institute for Rehabilitation Research, A-1140 Vienna, Austria

Correspondence: Žiga Kozinc. University of Primorska, Faculty of Health Sciences, Livade 6, 6310, Izola, Slovenia. E-mail: ziga.kozinc@fvz.upr.si

Abstract

This study examined the relationship between passive Achilles tendon (AT) and gastrocnemius (GAS) stiffness, measured by myotonometry, and 40-m sprint performance across acceleration and maximal velocity phases, while accounting for sex differences. Twenty-one student athletes (10 males, 11 females) underwent bilateral passive stiffness assessments of the AT and GAS using MyotonPRO, followed by 40-m sprint testing with 10, 20, 30, and 40 m splits. Reliability was assessed using the intraclass correlation coefficient (ICC) and coefficient of variation (CV). Sex differences were examined with independent t-tests. Partial correlations controlling for sex were used to assess associations between passive stiffness and sprint performance. Passive stiffness and sprint variables demonstrated excellent within-session reliability (ICC = 0.95–0.99; CV < 5%). Males showed significantly greater passive GAS stiffness bilaterally ($p = 0.006–0.049$) and faster sprint times at 30 m ($p = 0.040$) and 40 m ($p < 0.001$), while passive AT stiffness did not differ significantly between sexes. Partial correlations indicated that greater passive AT stiffness in both legs was associated with faster sprint times at 10 m ($r = -0.46$ and -0.58, $p = 0.008$ and 0.043) and 20 m ($r = -0.49$ and -0.58, $p = 0.008$ and 0.029). No associations were observed at 30 m or 40 m, nor between passive GAS stiffness and sprint performance. Myotonometry provides reliable measures of AT and GAS stiffness. Greater passive AT stiffness is associated with faster acceleration sprint performance independent of sex.

Keywords: *Achilles tendon; gastrocnemius; stiffness; myotonometry; sprint performance; sex differences*

@MJSSMontenegro
ACHILLES STIFFNESS AND SPRINT PERFORMANCE
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Introduction

The plantar flexor muscle-tendon unit (MTU), combining the triceps surae muscles and Achilles tendon (AT), plays a central role in ensuring efficient force transmission and body propulsion during all phases of linear sprinting. Its contribution begins at the start of the sprint, with the highest muscle

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activity occurring in the final phase of the push-off (Mero & Komi, 1990), during which plantar flexor MTU transfers power generated in the proximal joints to the ground and simultaneously generates force. A high force-producing capacity of the plantar flexor muscles is therefore particularly desirable when the goal is a fast start (Crotty et al., 2024). After the initiation of the sprint, the acceleration phase aims to increase the forward momentum of the body's centre of mass. Previous research has shown that a significant portion of this momentum is provided by the plantar flexor MTU (Macchi et al., 2025), with the gastrocnemius muscle (GAS) serving as the primary propulsor (Pandy et al., 2021). Due to changing biomechanical demands, the role of the plantar flexor MTU shifts during the acceleration phase and takes on a very specific role during the maximum velocity phase (Willer et al., 2024). In this phase, shorter ground contact times and higher vertical ground reaction forces require the plantar flexor MTU to act more as an energy absorber and transmitter (Crotty et al., 2024). Its primary role is to efficiently absorb energy during the initial stance phase (eccentric or decelerating) and then transfer it during the later stance phase (concentric or propulsive) to maintain maximum sprinting velocity for as long as possible (Willer et al., 2024).

Several plantar flexor MTU characteristics have been identified as factors contributing to linear sprint performance, including greater specific strength, a higher proportion of fast-twitch fibre types, a smaller pennation angle, longer fascicles, and optimal muscle volume (Crotty et al., 2024). In addition, MTU stiffness, defined as "the ability of a muscle or tendon to resist deformation in response to the application of force" (Latash & Zatsiorsky, 1993), has attracted particular attention in recent decades. Increased stiffness of the AT and triceps surae is desirable for explosive contractions such as the sprint start and allows for more efficient use of the stretch-shortening cycle by improving force transmission and minimising energy loss, thus enhancing sprint performance (Bojsen-Møller et al., 2005; Mero et al., 1992). This is supported by studies showing that sprinters with stiffer GAS perform better in the 100 m sprint [9] and have higher AT stiffness than endurance runners (Arampatzis et al., 2007). Therefore, plantar flexor MTU stiffness appears to be an important factor in sports where sprinting speed is of particular importance.

Despite its relevance to speed, stiffness is rarely measured in practice as standard procedures are based on expensive and time-consuming ultrasound assessments (Pinel et al., 2021; Yamazaki et al., 2022). In recent years, myotonometry has become established as a practical alternative. This method assesses palpable muscle and tendon stiffness by recording the magnitude of radial tissue displacement in response to a perpendicularly applied mechanical impulse from the device (i.e., the myotonometer) (McGowen et al., 2023). Compared to conventional methods, myotonometry is faster and more accessible. Moreover, several studies have confirmed its reliability and validity for the assessment of AT and GAS stiffness (Pruyn et al., 2016; Schneebeli et al., 2020; Taş & Salkın, 2019; Volesky et al., 2025). However, there is limited evidence on the relationship between plantar flexor stiffness measured by myotonometry and linear sprint performance, which limits its application in an athletic performance context.

To address this gap, the present study investigated the relationship between AT and GAS stiffness, measured by myotonometry, and 40 m sprint performance. Given previous reports of sex-related differences in triceps surae and tendon properties (Taş & Salkın, 2019)[15], and the fact that sprint performance also differs between men and women, we additionally investigated sex differences and whether these relationships persist when controlling for sex. We hypothesised that males would demonstrate greater AT and GAS stiffness and faster sprint performance compared with females, and that greater AT and GAS stiffness would be associated with faster sprint performance across all phases.

Materials and methods

Design and Participants

A cross-sectional study with two visits was conducted. At the first visit the stiffness of the AT, and the medial and lateral part of the GAS (GAS_M and GAS_L, respectively) was assessed. The second visit included 40-m sprints and the assessment of 10-, 20-, 30- and 40-metre split times.

Ten male (23.3 ± 1.3 years; 180.9 ± 6.9 cm body height, and 82.9 ± 3.5 kg body mass) and 11 female (23.5 ± 1.6 years; 166.5 ± 5.4 cm body height, and 61.1 ± 6.5 kg body mass) student athletes volunteered to participate in the study (21 participants in total). They were classified as Tier 2 individuals, who train to compete in different sports at local-level approximately 3 times per week (McKay et al., 2022). Only participants that were free of acute or chronic lower limb injuries, musculoskeletal disorders, or other health limitations in the previous six months were included in the procedures. Participants were instructed to refrain from strenuous physical activity for at least 24 h prior to each testing session. Participants were informed about the procedures and gave informed consent to participate in the study. The methods and interventions were reviewed and approved by the University of Primorska's Commission for Ethics in Human Subjects Research (approval number: 4264-19-6/23).

Muscle and Tendon Stiffness Assessment

Stiffness was assessed by the same investigator using a non-invasive handheld myotonometer (MyotonPRO, Myoton AS, Estonia), which quantifies the mechanical properties of palpable soft tissue. The MyotonPRO delivers a short mechanical impulse to the tissue, which causes a natural, damped oscillation. The resistance of the tissue to this deformation, known as stiffness, is calculated from the resulting acceleration curve. Specifically, the tissue stiffness (expressed in $N \cdot m^{-1}$) is calculated by multiplying the maximum acceleration of the oscillation waveform by the mass of the probe and dividing by the maximum displacement of the tissue. Higher values therefore indicate a greater stiffness of the tissue (Schneider et al., 2015).

The AS and GAS stiffness of the left and right leg was assessed under passive conditions, with the order of leg testing randomized between participants. Throughout the manuscript, stiffness assessed under these conditions is referred to as "passive stiffness". Participants were barefoot and lay prone on a table. The knees were extended, the ankles relaxed, and hanging slightly over the edge to maintain a neutral foot position. They were instructed to remain completely relaxed to minimise active muscle contraction. Measurements were performed on GAS_M, GAS_L and AT (Figure 1). GAS passive stiffness was measured at the centre of the muscle belly (i.e., one third of the distance between the me-

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dial femoral condyle and the lateral malleolus and between the lateral femoral condyle and the medial malleolus, respectively). AT passive stiffness was measured 2 cm proximal to the superior aspect of the calcaneus (Taş & Salkın, 2019). The MyotonPRO probe was placed perpendicular to the tissue surface, and each site was measured with five mechanical impulses. If the variation between five pulses exceeded 8%, the measurement was repeated. Each site and leg were measured three times and the mean value was used for subsequent analysis.

Linear Sprint Performance Testing

To assess sprint performance, three linear 40-m sprints were performed in an athletics stadium under dry windless environmental conditions. Prior to the test, a standardised warm-up was performed, including 10 minutes of jogging and dynamic stretching, 10 repetitions of squats, push-ups, crunches, and vertical jumps, followed by two submaximal 40-m sprint trials. Three maximal sprint attempts were then performed with at least three-minute breaks in between. The distances of 10 m, 20 m, 30 m, and 40 m were precisely determined using a GWM 32 measuring tape (Bosch, Gerlingen, Germany) and marked with cones. A pair of single-beam laser timing gates (Brower, TCi-System B13283, Utah, USA) were positioned at the start and at each marked distance to ensure accurate timing. The first set of timing gates was placed 0.5 metres in front of the start line to prevent premature triggering of the start (Haugen & Buchheit, 2016). The start line was marked with the tape to standardise the start position in the two-point stance. The split times at distances 0–10 m (T_{10}), 0–20 m (T_{20}), 0–30 m (T_{30}), and 0–40 m (T_{40}) of the fastest 40 m sprint were recorded. Analysing the sprint performance over the 40 m distance made it possible to evaluate the phases of early acceleration (T_{10}), late acceleration (T_{20}), and maximum velocity (T_{30} and T_{40}) of the linear sprint.

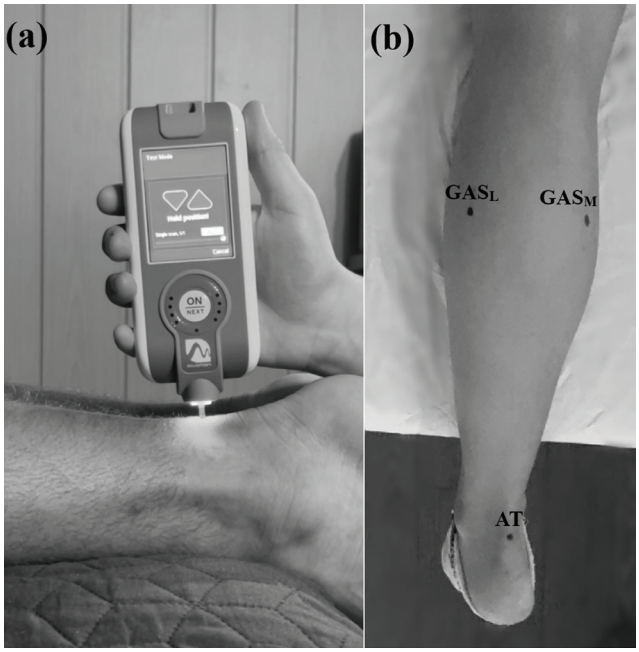

Figure 1. Myotonometry assessment (a) and anatomical measurement sites (b) for passive stiffness of the gastrocnemius muscle (GAS_L, GAS_M) and Achilles tendon (AT).

Statistical Analysis

The statistical analysis was performed with IBM SPSS Statistics (version 26). The descriptive data of the outcome variables are presented as mean ± standard deviation (SD). To assess the relative and absolute reliability of the outcome variables, the intraclass correlation coefficient (ICC; model 2.1) and the coefficient of variation (CV; as SD divided by mean and multiplied by 100) were calculated with 95% confidence intervals. The Shapiro-Wilk test was used to assess the normal distribution of the variables, whereas linearity and homoscedasticity were assessed via scatterplots. Differences between men and women were analysed using an independent samples t-test, with Levene's test used to check the assumption of homogeneity of variances between the sexes. To control for the influence of sex on the relationships between GAS_M, GAS_L, AT passive stiffness, and linear sprint split times, partial correlations were calculated. The correlations were interpreted as negligible ($r < 0.1$), weak ($r = 0.1–0.4$), moderate ($r = 0.4–0.7$), strong ($r = 0.7–0.9$) and very strong ($r = 0.9$) according to Akoglu (2018). All statistical tests were two-tailed, and statistical significance was set at $p < 0.05$.

Results

Table 1 presents the descriptive statistics and within-session reliability for passive stiffness and linear sprint performance variables. The ICC and CV confirmed excellent relative (95% CI lower bound ≥ 0.89) and absolute reliability (95% CI upper bound ≤ 5.49%) across all outcome variables.

Sex comparisons are presented in Table 2. Men demonstrated significantly higher passive stiffness of the GAS_L and GAS_M on both legs ($p = 0.006–0.049$). No significant differences were observed in AT passive stiffness, although values tended to be higher in men ($p = 0.106–0.211$). In sprint performance, men were significantly faster in the maximum velocity phase (T_{30}: $p = 0.040$; T_{40}: $p < 0.001$), whereas differences in early and late acceleration did not reach statistical significance (T_{10}: $p = 0.099$; T_{20}: $p = 0.085$).

Table 1. Descriptive statistics of each repetition and the results of relative and absolute within-session reliability for the outcome variables on total sample.

Variable	Rep 1	Rep 2	Rep 3	ICC (95 CI)	CV in % (95 CI)
Left GAS_L stiffness ($N \cdot m^{-1}$)	300.7 ± 77.2	304.9 ± 78.1	304 ± 75.3	0.99 (0.99, 1.00)	2.19 (1.76, 2.92)
Left GAS_M stiffness ($N \cdot m^{-1}$)	285.4 ± 69.9	285.1 ± 70.5	284.4 ± 70.2	0.99 (0.99, 1.00)	2.11 (1.69, 2.81)
Left AT stiffness ($N \cdot m^{-1}$)	949 ± 145.7	967.4 ± 167.2	967.3 ± 167.6	0.95 (0.89, 0.98)	4.12 (3.31, 5.49)
Right GAS_L stiffness ($N \cdot m^{-1}$)	307 ± 90.6	310.1 ± 88.8	310.0 ± 87.0	0.99 (0.98, 1.00)	2.91 (2.34, 3.88)
Right GAS_M stiffness ($N \cdot m^{-1}$)	290 ± 74.2	290.3 ± 77.4	290.8 ± 80.5	0.99 (0.99, 1.00)	2.26 (1.82, 3.02)
Right AT stiffness ($N \cdot m^{-1}$)	915.9 ± 177.5	917.1 ± 178	918.4 ± 183.6	0.98 (0.96, 0.99)	2.82 (2.27, 3.76)
T_{10} (s)	2.13 ± 0.3	2.14 ± 0.3	2.15 ± 0.3	0.97 (0.94, 0.99)	2.52 (2.03, 3.37)
T_{20} (s)	3.43 ± 0.23	3.42 ± 0.23	3.45 ± 0.25	0.95 (0.89, 0.98)	1.70 (1.37, 2.27)
T_{30} (s)	4.74 ± 0.34	4.76 ± 0.35	4.76 ± 0.35	0.98 (0.96, 0.99)	1.00 (0.80, 1.33)
T_{40} (s)	6.06 ± 0.44	6.04 ± 0.45	6.05 ± 0.45	0.99 (0.97, 0.99)	0.93 (0.74, 1.23)

Note. GASL: lateral gastrocnemius; GASM: medial gastrocnemius; AT: Achilles tendon; T_{10}: 0 to 10 m split time; T_{20}: 0 to 20 m split time; T_{30}: 0 to 30 m split time; T_{40}: 0 to 40 m split time; N: Newtons; m: meters; s: seconds; ICC: intraclass correlation coefficient; 95CI = 95 % confidence interval; CV = coefficient of variation.

Table 2. Results of a t-test comparing outcomes between male and female athletes.

Variable	Female (n = 11)	Male (n = 10)	t-test	
			t	p
Left GAS_L stiffness ($N \cdot m^{-1}$)	262.5 ± 44.2	347.9 ± 81.5	-3.02	0.007
Left GAS_M stiffness ($N \cdot m^{-1}$)	247.5 ± 42.5	326.2 ± 72.8	-3.07	0.006
Left AT stiffness ($N \cdot m^{-1}$)	919.6 ± 131.2	1007 ± 176.4	-1.30	0.211
Right GAS_L stiffness ($N \cdot m^{-1}$)	268.4 ± 62.4	353.8 ± 94.1	-2.47	0.023
Right GAS_M stiffness ($N \cdot m^{-1}$)	259.1 ± 60.1	324.7 ± 82.0	-2.11	0.049
Right AT stiffness ($N \cdot m^{-1}$)	856.9 ± 99.4	983.4 ± 224.9	-1.70	0.106
T_{10} (s)	2.24 ± 0.33	2.03 ± 0.21	1.74	0.099
T_{20} (s)	3.51 ± 0.18	3.34 ± 0.25	1.81	0.085
T_{30} (s)	4.90 ± 0.31	4.59 ± 0.32	2.21	0.040
T_{40} (s)	6.35 ± 0.35	5.72 ± 0.26	4.57	<0.001

Note. p-values reported in the table are not adjusted for multiple testing across variables. GASL: lateral gastrocnemius; GASM: medial gastrocnemius; AT: Achilles tendon; T_{10}: 0 to 10 m split time; T_{20}: 0 to 20 m split time; T_{30}: 0 to 30 m split time; T_{40}: 0 to 40 m split time; N: Newtons; m: meters; s: seconds.

Partial correlations between passive stiffness and linear sprint performance are shown in Table 3. Significant moderate negative correlations were found between left AT passive stiffness and both T_{10} (r = -0.58; p = 0.008), and T_{20} (r = -0.58; p = 0.008). Similarly, significant moderate negative correlations were observed between right AT passive stiffness and T_{10} (r = -0.46; p = 0.043) and T_{20} (r = -0.49; p = 0.029). Correlations between AT passive stiffness and sprint performance during the maximum velocity phase were weaker and not significant. Moreover, no significant correlations were observed between GAS passive stiffness and sprint performance.

Table 3. Correlation between stiffness and linear sprint performance variables.

	Left leg			Right leg		
	GAS_L	GAS_M	AT	GAS_L	GAS_M	AT
T_{10}	-0.12 (-0.58, 0.25)	-0.11 (-0.51, 0.34)	-0.58 (-0.81, -0.19)**	0.06 (-0.39, 0.48)	-0.12 (-0.52, 0.33)	-0.46 (-0.74, -0.03)*
T_{20}	-0.09 (-0.50, 0.35)	0.03 (-0.41, 0.45)	-0.58 (-0.81, -0.19)**	0.08 (-0.36, 0.50)	0.01 (-0.42, 0.44)	-0.49 (-0.76, -0.07)*
T_{30}	-0.10 (-0.51, 0.35)	-0.02 (-0.45, 0.42)	-0.37 (-0.69, 0.08)	-0.01 (-0.44, 0.42)	-0.05 (-0.47, 0.39)	-0.40 (-0.71, 0.04)
T_{40}	0.08 (-0.37, 0.49)	0.17 (-0.29, 0.56)	-0.25 (-0.61, 0.21)	0.18 (-0.27, 0.57)	0.14 (-0.31, 0.54)	-0.13 (-0.53, 0.32)

Note. Values are partial correlation coefficients with 95 % confidence intervals controlling for sex. GAS_L: lateral gastrocnemius; GAS_M: medial gastrocnemius; AT: Achilles tendon; T_{10}: 0 to 10 m split time; T_{20}: 0 to 20 m split time; T_{30}: 0 to 30 m split time; T_{40}: 0 to 40 m split time. * p < 0.05, ** p < 0.01

Discussion

The present study investigated the reliability of myotonometry to assess plantar flexor MTU passive stiffness, sex differences in GAS and AT passive stiffness, and their relationship with linear sprint performance. The main findings were that (i) myotonometry showed excellent within-session reliability for both GAS and AT passive stiffness, (ii) males had greater GAS passive stiffness, while no sex differences were observed for AT passive stiffness, and (iii) after controlling for sex, greater AT passive stiffness was significant-

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ly correlated with faster performance in the early and late acceleration phases (10 and 20 m), but not in the maximal speed phase of the sprint.

Our results showed excellent relative and absolute reliability (ICC = 0.95–0.99; CV < 5%), confirming previous studies that reported excellent within-session reliability of myotonometry to quantify passive stiffness of left and right leg AT and GAS (McGowen et al., 2023). This emphasises the applicability of the method in sports practice as a viable alternative to ultrasound-based examinations, which are often costly and time-consuming.

Passive stiffness in our sample was similar to previously reported values, with GAS for females and males of ~240 to 270 and ~320 to 360 $N \cdot m^{-1}$, respectively, and AT of ~850 to 900 and ~850 to 1000 $N \cdot m^{-1}$, respectively (Pruyn et al., 2016; Schneebeli et al., 2020; Volesky et al., 2025). We found that males exhibited significantly higher GAS_L and GAS_M passive stiffness, whereas AT passive stiffness did not differ significantly between sexes. This is in partial agreement with previous work by Taş and Salkin (Taş & Salkın, 2019), who reported sex-specific differences in GAS and also AT passive stiffness. The lack of significant differences in AT stiffness in our sample may be explained by the relatively small sample size or the heterogeneous athletic background of the participants. Nonetheless, the significant differences in GAS passive stiffness and sprint performance emphasise the importance of considering sex as a confounding factor when examining stiffness using myotonometry. Furthermore, as males showed higher AT passive stiffness and also faster sprint performance, it could be hypothesised that the specific mechanical properties of the plantar flexor MTU are partly responsible for the already known differences in linear sprint performance between sexes (Galantine et al., 2023).

Taking sex into account, AT but not GAS passive stiffness, was associated with T_{10} and T_{20}. In particular, the early and late sprint acceleration phases were associated with higher AT passive stiffness, which is consistent with the biomechanical role of the AT as a key structure for efficient force transmission and energy storage-return during explosive push-off actions (Monte & Zamparoi, 2019). During the steps of the acceleration phase, a change in length of the plantar flexor MTU is primarily due to the changes in length of the soleus and GAS muscle fascicles (Lai et al., 2016), which may require a stiffer AT to enable efficient force transmission within the MTU. However, at higher sprint velocities, the change in muscle fascicle lengths of the plantar flexors is minimal (Lai et al., 2016), forcing the muscles to contract under lower velocity, which is biomechanically more optimal for generating high vertical ground reaction forces (Farris & Sawicki, 2011; Weyand et al., 2000). Thus, most of the change in MTU length of the plantar flexors is related to the change in AT, such that it must act as a more compliant spring, to utilise elastic strain energy (Kubo et al., 2011; Lichtwark & Wilson, 2007). The specificity of the associations with the acceleration phase in our study emphasises the functional importance of AT stiffness for sprint acceleration and not for maximal sprint velocity. However, it should be emphasised that this interpretation is speculative and cannot be directly inferred from the present cross-sectional results, therefore, further studies are needed to clarify whether a stiffer or more compliant AT is more desirable for sprint performance across distinct sprint phases.

From a practical perspective, this study provides several important applications. Firstly, myotonometry provides a reliable field-ready tool for monitoring tendon and muscle passive stiffness in athletes. For this purpose, it could be used to assess the mechanical properties of the plantar flexor MTU in the field, especially in sports where sprint performance plays a crucial role. Secondly, as higher AT passive stiffness has been associated with better acceleration performance, practitioners might consider utilising training modalities known to improve it, such as plyometric training (Ramírez et al., 2022), eccentric loading, or heavy resistance (Geremia et al., 2018) training. Given the observed sex differences in GAS passive stiffness and sprint performance, practitioners and researchers should consider sex when assessing athletes.

The results of this study should be interpreted with several limitations in mind. Firstly, the relatively small and heterogeneous sample of Tier 2 student athletes (McKay et al., 2022) limits the generalisability of the results to elite athletes and those active in sports disciplines with a high sprint density. Secondly, the cross-sectional design prevents causal conclusions from the results of our study. Third, only passive stiffness was measured, whereas stiffness during active muscle contractions could provide more biologically valid insights. To address these gaps, we suggest that future studies examine larger, more homogeneous samples, include elite-level athletes, and use a longitudinal design to determine whether exercise-induced changes in AT stiffness measured by myotonometry directly improve sprint performance.

Conclusion

Myotonometry is a reliable method for assessing AT and GAS passive stiffness in Tier 2 athletes (McKay et al., 2022). Regardless of sex, higher AT passive stiffness is associated with faster 10 and 20 m sprint performance, emphasising its functional importance for sprint acceleration. These findings support the use of AT passive stiffness in monitoring athletes and emphasise the potential value of stiffness-focused training interventions for sprint acceleration development.

Conflicts of Interest

The authors declare no conflict of interest.

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