

Ger J Exerc Sport Res
<https://doi.org/10.1007/s12662-026-01092-x>
 Received: 12 September 2025
 Accepted: 29 December 2025

© The Author(s) 2026



Diego Jaén-Carrillo¹ · Alberto Rubio-Peirotn² · Luis Santos³ ·
 Antonio Cartón-Llorente²

¹ Department of Sport Science, University Innsbruck, Innsbruck, Austria

² Universidad San Jorge, Zaragoza, Spain

³ Universidad de Oviedo, Oviedo, Spain

Influence of strength and musculotendinous properties on running biomechanics on different terrains in highly trained trail runners

Introduction

Trail running differs from standardized running in terms of both duration and environment, often lasting for several hours or even days and covering diverse terrains, extreme temperatures, and high altitudes (ITRA, 2024). These demanding conditions require trail runners to develop specific biomechanical and neuromuscular adaptations, particularly in the lower limb extensor muscles and tendons, which are essential for propulsion during uphill segments (Padulo, Powell, Milia, & Ardigo, 2013; Rubio-Peirotn, Cartón-Llorente, Mugele, & Jaén-Carrillo, 2024). Conversely, downhill sections impose high eccentric loads, negatively affecting muscle function (Ehrström et al., 2018; Giandolini et al., 2016).

In order to endure the prolonged effort and optimize performance while minimizing muscle damage, runners subconsciously fine-tune their mechanics to minimize metabolic cost (Khassetarash, Vernillo, Krüger, Edwards, & Millet, 2022). In this self-optimization process, leg stiffness plays a crucial role (Moore, 2016; Moore et al., 2019). The combination of increased leg stiffness and shorter ground contact time (GCT) seems to favor a greater reliance on elastic energy storage and return (Moore

et al., 2019) by optimizing the stretch-shortening cycle (Vogt & Hoppeler, 2014). However, on inclined terrain, the reutilization of elastic energy is notably reduced. Previous studies have shown that maximal elastic energy use is ~20% lower when running uphill and ~12% lower when running downhill compared to level running (Snyder & Farley, 2011). This decrease in energy efficiency is associated with greater muscle activation, especially in the vastus group, which is activated ~23% more during uphill and downhill running compared to flat terrain (Sloniger, Cureton, Prior, & Evans, 1997).

In this context, strength and muscular endurance emerge as key factors in trail running, as they must compensate for the reduced reutilization of elastic energy on inclines (Lemire et al., 2021; Sabater-Pastor et al., 2022; Vernillo et al., 2017). Despite engaging in less strength training compared to road runners, trail runners have shown greater force and power production, suggesting that incline training induces beneficial neuromuscular adaptations (Sabater-Pastor et al., 2023). Notably, knee extensor strength has been associated with trail running performance (Balducci, Cléménçon, Trama, Blache, & Hautier, 2017). Furthermore, quadriceps strength has been positively correlated with the stiffness and thickness of

the patellar tendon ($r = 0.45$ and $r = 0.44$, respectively; Taş et al., 2017), highlighting the importance of both the morphological and functional characteristics of myotendinous units in athletic performance. However, the specific strength demands of trail running remain largely unexplored, particularly regarding how different resistance training loads (i.e., low, moderate, or high) influence performance.

One approach to addressing this gap is to examine the relationship between neuromuscular behavior during different percentages of one-repetition maximum (1RM) in a particular strength exercise (i.e., half squat [HSQ]) and biomechanical variables affecting running economy and performance under submaximal effort. Additionally, comparing these associations on the athletic track and

Abbreviations

CSA	Cross-sectional area
GCT	Ground contact time
HSQ	Half-squat
MPV	Mean propulsive velocity
PF	Peak force
SDef	Strength deficit
1RM	One-repetition maximum

Table 1 Demographic description of the participants.

Variable	Mean \pm SD
Age (years)	31.7 \pm 5.3
Height (cm)	179.9 \pm 6.0
Weight (kg)	70.9 \pm 4.9
BMI (kg/m ²)	21.9 \pm 1.1
TR experience (years) [^]	7 (6.50)
ITRA performance Index	759 \pm 99
Weekly volume (km)	93.67 \pm 33.01
Weekly elevation gain (m)	2553.33 \pm 1101.21
ST sessions per week [^]	2 (1)
1 RM for half-squat (kg)	138.08 \pm 14,074
1 RM for half-squat (kg/BW)	1.96 \pm 0.202

BMI body mass index, TR trail running, 1 RM one-repetition maximum, ITRA International Trail Running Association, ST strength training, BW bodyweight, SD standard deviation

[^]Reported as median (interquartile range) given a violation of the normality test (Shapiro–Wilk test)

in the trail runners' natural environment (i.e., trails) may help to identify the optimal strength training intensity to specifically enhance trail running performance. In this sense, assessing the strength deficit (SDef)—the relative difference between the force produced against a given percentage of 1 RM and that produced against the maximal load (González-Badillo, Yañez-García, Mora-Custodio, & Rodríguez-Rosell, 2017; Loturco et al., 2021; McGuigan, Wright, & Fleck, 2012; Suchomel, Nimphius, & Stone, 2016)—may help to further bridge the gap between strength training and trail running performance. A higher SDef suggests an athlete's inability to fully exploit maximal strength capacity during rapid unloaded tasks like running (Loturco et al., 2021; McGuigan et al., 2012; Suchomel et al., 2016). For instance, Loturco and colleagues (Loturco et al., 2021) found that elite sprinters exhibit lower SDef than professional rugby players, with SDef significantly associated with speed and power measures, making it a valuable indicator of athletic performance. Similarly, Zabaloy et al. (Zabaloy et al., 2022) demonstrated that in young rugby players, lower SDef and higher 1 RM squat performance were significantly linked to superior sprint speed. Despite SDef being derived from maximal velocity tasks, its relevance extends to submaximal efforts that involve brief force application times, such as endurance running. Low SDef ensures the runner can fully ac-

cess available strength capacity within this limited time, whereas a high SDef may force excessive reliance on elastic recoil. Thus, assessing SDef may help to identify the individual neuromuscular limitation impacting the efficiency and fatigue resistance necessary for varied terrain. To date, no studies have investigated these relationships in trail running, highlighting a crucial area for future research.

Given the multifactorial nature of trail running performance and the fact that the specific strength demands of trail running remain unidentified, examining strength variables in trail athletes may provide valuable insights. Therefore, this study aimed to determine the relationship between running biomechanical variables on two flat running surfaces, i.e., the athletic track and well-groomed trails, and SDef at different percentages of 1 RM in the HSQ. A secondary objective was to assess whether SDef at different 1 RM percentages in the HSQ is dependent on patellar tendon morphology in male highly trained trail runners. It was hypothesized that significant correlations would exist between the SDef at different 1 RM percentages of the HSQ and both the trail running biomechanical variables and patellar tendon morphology.

Methods

Study design

The study was experimental, constituting a crossover study with a repeated-measures design.

Participants

Fifteen male trail runners participated in this study (Table 1). All were free from musculoskeletal injuries as well as cardiopulmonary and metabolic disorders. Before enrolment, participants provided written informed consent after receiving detailed verbal and written explanations of the experimental procedures and potential risks. The sample size for this study was determined based on Cohen's statistical power analysis for correlation coefficient designs (Cohen, 1992). Calculations were conducted using R software (version 3.3.1, www.r-project.org). To estimate statistical power, the software requires input parameters, including the expected correlation coefficient (r), sample size (n), significance level (α), and the alternative hypothesis type ("one-sided" or "two-sided"). For this study, the parameters were set as follows: $r = 0.7$, $n = 15$, $\alpha = 0.05$, and a two-sided alternative hypothesis. The resulting statistical power was 0.87. The study protocol was approved by the ethics committee at the local university (approval no. 109/2024) and adhered to the principles of the Declaration of Helsinki. Participants were recruited through convenience and snowball non-probability sampling methods.

Experimental design

Day 1—maximum strength assessment

Upon entering the fitness room, participants began a warm-up consisting of 5 min of pedaling on a stationary bike at 60 rpm and 60 W, followed by dynamic mobility exercises including dynamic stretching and air squats. This was followed by a strength test using a velocity-based training approach (Pareja-Blanco et al., 2017). Participants were instructed to always keep the barbell

in contact with the upper trapezius and their feet grounded (i.e., jumping was not allowed; Conceição, Fernandes, Lewis, González-Badillo, & Jimenez-Reyes, 2016). The eccentric phase of the squat was controlled, with the concentric phase performed as quickly as possible once knee flexion reached 90 degrees (Banyard, Nosaka, & Haff, 2017; Conceição et al., 2016). Mean propulsive velocity (MPV) and peak force (PF) were continuously recorded throughout all HSQ attempts at a sampling frequency of 1000 Hz using a linear position transducer attached to the barbell (Chronojump Boscossystem, Barcelona, Spain). The load progression began at 20 kg and increased in steps of 10 kg until an MPV of 0.5 m/s was reached. Subsequently, increments of 1–5 kg were applied until 1 RM was achieved. For loads resulting in an MPV up to 1.15 m/s, four repetitions were performed with a 3- to 4-minute rest interval. For medium loads ($0.5 \text{ m/s} \leq \text{MPV} \leq 1.15 \text{ m/s}$), two repetitions were performed with a 5-min rest, and for maximum loads ($\text{MPV} < 0.5 \text{ m/s}$), one repetition was performed with a 6-min recovery. During the 1 RM tests, participants were allowed to complete five attempts. After each successful lift, the barbell load was adjusted by 0.5 to 2.5 kg in consultation with the participant. Only the last successful lift with proper technique (i.e., knee flexion at 90 degrees) and fastest MPV was recorded as the 1 RM and considered for further analysis (Sanchez-Medina, Perez, & Gonzalez-Badillo, 2010). The 90-degree knee angle was individually determined for each participant during familiarization. Reproducibility across trials was assured by employing a band secured to tripods positioned at the established half-squat depth, providing the participant with consistent tactile feedback for the required range of motion (Perez-Castilla, Garcia-Ramos, Padiá, Morales-Artacho, & Feriche, 2020). All repetitions were performed in a power cage (Star Trac Max Rack, Star Trac, Irvine, CA, USA) under the supervision of the same researcher and assisted by two trained spotters for safety.

Ger J Exerc Sport Res <https://doi.org/10.1007/s12662-026-01092-x>
© The Author(s) 2026

D. Jaén-Carrillo · A. Rubio-Peiotén · L. Santos · A. Cartón-Llorente

Influence of strength and musculotendinous properties on running biomechanics on different terrains in highly trained trail runners

Abstract

Background. This study aimed to explore the relationship between running biomechanics on two flat surfaces—athletic track and trail—and strength deficit (SDef) at various percentages of one-repetition maximum (1 RM) in the half-squat (HSQ). Additionally, it sought to examine whether SDef at these loads is influenced by patellar tendon morphology in highly trained trail runners. **Methods.** Fifteen trail runners performed an HSQ 1 RM test following a velocity-based approach and two running time trials (9 and 3 min) on two different surfaces. Mean propulsive velocity and peak force were recorded using a linear position transducer and used to calculate SDef from 30 to 90% of 1 RM. The Stryd power meter (Stryd Next Gen, Boulder, CO, USA) was used to assess leg stiffness, speed, ground contact time, and cadence during the four running bouts. Patellar tendon thickness and cross-sectional area were also measured with a high-definition ultrasound device.

Results. Large negative associations were found between SDef at 40–70% 1 RM and shorter ground contact time and higher leg stiffness, particularly in the 3-min trial on trail terrain. Furthermore, patellar tendon thickness was also negatively associated with SDef at low-to-moderate loads (40–60% 1 RM).

Conclusion. These findings suggest that runners with greater SDef compensate via enhanced musculotendinous elastic properties, highlighting the functional role of patellar tendon thickness. Assessment of SDef provides a valuable basis for individualized training prescription in trail runners, guiding practitioners to focus either on increasing the rate of force development at low-to-moderate loads to reduce SDef or on plyometric training to maximize elastic efficiency.

Keywords

Half-squat · Leg stiffness · Patellar tendon · Trail running · Strength deficit

Day 2—strength assessment protocol

Between 48 and 72 h after the 1 RM determination and following the warm-up procedure described above, participants completed two repetitions at 40%, 50%, 60%, 70%, 80%, and 90% of their 1 RM using the same squat technique as previously described. The Chronojump system, attached to the barbell of the power cage, was used to determine the MPV and PF of each repetition. The relationships between load and PF, between percentages of 1 RM and the corresponding PF values, and between percentages of 1 RM and corresponding loads were analyzed using either linear or second-degree polynomial models, depending on the best fit for each dataset. First, the load percentage for each value relative to the 1 RM (considered as 100%) was

determined using the following formula (Eq. 1):

$$\text{Load percentage} = \left(\frac{\text{Load}}{\text{Load at 1RM}} \right) \times 100 \quad (1)$$

Then, a linear or second-degree polynomial equation was selected based on the coefficient of determination ($R^2 \geq 0.8$), the p -value ($p\text{-value} < 0.05$), and the Akaike information criterion (AIC). If both equations met the criteria for R^2 and p -value, the model with the lower AIC was selected to minimize uncertainty in the predictions. This process balanced model accuracy (goodness of fit) with simplicity. If an equation did not meet the criteria, it was discarded, and another was chosen. The selected equation was then used to estimate the loads at 30%, 40%, 50%, 60%, 70%, 80%, and 90% of 1 RM, which were not directly measured during the load test. The SDef at 30%, 40%, 50%, 60%, 70%,

80%, and 90% of 1 RM for each athlete in the HSQ was calculated through the following steps:

- **Model selection.** A linear or second-degree polynomial equation was selected to model the relationship between loads and their respective PF values, following the process described above.
- **Load percentage calculation.** The load percentages relative to 1 RM were estimated as shown above (Eq. 1).
- **PF estimation.** A second linear or polynomial equation was selected to estimate the PF values at 30%, 40%, 50%, 60%, 70%, 80%, and 90% of 1 RM, which were not directly measured during the load test.
- **SDef calculation.** The SDef was calculated as the percentage difference between the PF values at each load percentage and the PF value at 1 RM. The formula used (Eq. 2) is as follows:

$$SDef \text{ at } X\%1RM = \left(\frac{PF \text{ at } 1RM - PF \text{ at } X\%1RM}{PF \text{ at } 1RM} \right) \times 100 \quad (2)$$

Day 3—running variables protocol

Between 24 and 48 h after the strength assessment protocol, participants completed the first running test of two testing sessions aimed at assessing running performance on two distinct flat surfaces: track and trail. The order of surface testing was randomized. The second running test (for either track or trail) was conducted 48 h later to allow for adequate recovery. To control for external variables, all tests were performed at the same time of day (± 1 h), and participants wore the same running shoes for both surfaces. Each running test session began with a standardized warm-up comprising 10 min of low-to-moderate intensity running, equivalent to that of an easy long-distance run. This was followed by dynamic mobility exercises and concluded with three progressively faster 100-m runs. The main test included a 9- and a 3-min maximal effort run, separated by a 30-min active recovery period consisting of very easy running (Ruiz-Alias, Olaya-Cuartero, Nancupil-

Andrade, & García-Pinillos, 2022). During both time trials, participants were instructed to cover the greatest possible distance, and their perceived exertion was assessed using the Borg CR-10 scale (Borg, 1998). To minimize potential fatigue effects, participants were advised to refrain from high-intensity exercise, such as interval training, during the 24 h prior to testing. All sessions were conducted at the same time of day (± 1 h) under controlled environmental conditions: $21 \pm 1^\circ\text{C}$ and $55 \pm 5\%$ humidity, with air velocity maintained below 2 m/s.

The Stryd power meter (Stryd Next Gen, Boulder, CO, USA), clipped to the laces of the right shoe and paired to a Garmin Forerunner 735 XT sport watch (Garmin Ltd., Olathe, Kansas, USA) was used to collect leg stiffness, speed, GCT, and cadence during the 9- and 3-min running bouts (Imbach, Candau, Chailan, & Perrey, 2020).

Measurements

Patellar tendon morphology

B-mode ultrasound images of the patellar tendon were obtained using a high-resolution ultrasonic device (Vscan AirTM CL, General Electric Healthcare, Germany, 2013) with the participant lying in supine position on a medical stretcher with both knees flexed at a 30° angle (Del Bano-Aledo et al., 2017). To assess tendon thickness, the probe was aligned longitudinally at a reference point located 1 cm distal to the inferior pole of the patella, marked on the skin for identification. The cross-sectional area (CSA) was then measured by positioning the probe transversely at the same location. Ultrasound images were captured with a depth setting of 3 cm and a gain of 100 dB. Each measurement was recorded twice by an experienced researcher with over 10 years of expertise in diagnostic ultrasound imaging. Before statistical analysis, tendon thickness and CSA were measured using ImageJ software (NIH, Baltimore, MD, USA; Kernozek, Knaus, Rademaker, & Almonroeder, 2018).

Statistical analyses

All data are presented as mean \pm standard deviation (SD), with 95% confidence intervals (CIs). The assumption of normality was assessed using the Shapiro–Wilk test, while homogeneity of variances was evaluated with Levene’s test. Mauchly’s test was applied to assess sphericity. Relationships between intensity loads (30–90% 1 RM), SDef at different percentages of 1 RM in the HSQ, and running variables on both terrains (track and trail) were analyzed using Pearson’s correlation coefficient when data followed a normal distribution and Spearman’s correlation coefficient otherwise. The magnitudes of the correlation coefficients were interpreted based on the following criteria: <0.1 (trivial), 0.1 – 0.3 (small), 0.3 – 0.5 (moderate), 0.5 – 0.7 (large), 0.7 – 0.9 (very large), and 0.9 – 1.0 (almost perfect; Hopkins, Marshall, Batterham, & Hanin, 2009). Statistical analyses were performed using R (version 3.3.1, www.r-project.org) and GraphPad Prism (version 10.4.1, GraphPad Software, Inc., Boston, MA, USA), with significance set at $p < 0.05$.

Results

Strength assessment

The absolute 1 RM in HSQ exercise was 138 ± 14 kg, while the 1 RM relative to bodyweight was 1.96 ± 0.20 . Additionally, the calculated values for strength deficit at loads ranging from 40% to 90% of 1 RM are shown in **Fig. 1**.

Running variables for the 9- and 3-min time trials on both surfaces

The running biomechanics of trail runners during the 9- and 3-min tests are summarized in **Fig. 2**. The performance analyses during both time trials revealed that the total distance covered in the 9-min test was 2798 ± 282 m and 2657 ± 202 m on the athletic track and the groomed trail, respectively. The distance reached in the 3-min track test was 1011 ± 82 m, while 965 ± 61 m were achieved while running over the trail.

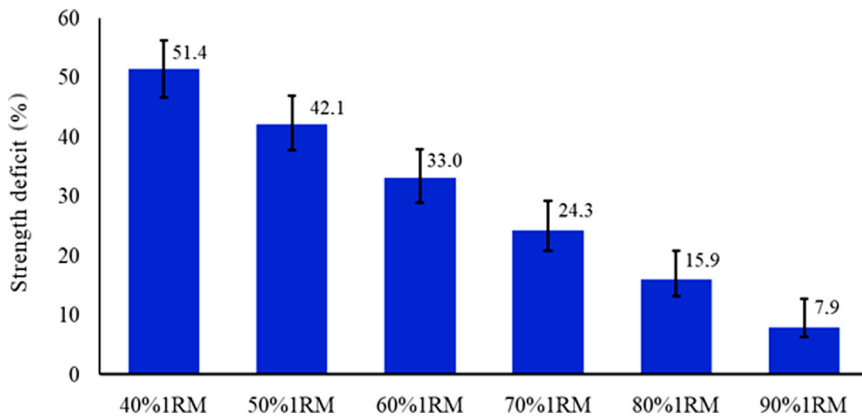


Fig. 1 ▲ Strength deficit in half-squat exercise at different load intensities. *1RM* one-repetition maximum

Relationship between strength deficit and running variables

The correlation analyses between strength deficit at different load intensities and the studied running biomechanical variables are displayed in [Table 2](#).

Relationship between strength deficit and patellar tendon morphology

[Table 3](#) summarizes the correlations between strength deficit and patellar tendon thickness and CSA.

Discussion

This study aimed to examine the relationship between strength deficit at different load intensities and performance-related biomechanical variables in highly trained trail runners on two different flat surfaces—the athletic track and a well-groomed trail. Additionally, correlations between strength deficit and patellar tendon morphology were also assessed. As hypothesized, the findings revealed significant associations between strength deficits at different training loads (40–70% of 1RM) and key neuromuscular characteristics, particularly leg stiffness, across different running efforts. Large negative correlations were also found between patellar tendon thickness and strength deficits at low loads ($\leq 60\%$ 1RM), showing that the thicker the tendon, the lower the strength deficit.

Enhancing an athlete's strength has been shown to positively impact several

key physiological and biomechanical factors related to running. Strength gains allow athletes to produce the same level of force with reduced motor unit recruitment (Barnes & Kilding, 2015), reflecting improved neuromuscular efficiency. Despite the fact that these adaptations may lead to more refined biomechanical patterns and muscle coordination, ultimately supporting better overall running performance, the 1RM values in HSQ of trail runners involved in this study showed no significant correlation with performance in either the 3- or the 9-min time trial. In this sense, the ability to rapidly generate and apply substantial force seems to play a critical role in sprint running (Zabaloy et al., 2022). However, the endurance of distance and trail runners may be more closely related to their ability to maintain a high running economy, allowing for better utilization of elastic capacities at moderate and low loads. Thus, a comparison between the mesomorphic somatotype of sprinters and the ectomorphic profile of endurance runners helps to explain the lack of correlation observed at submaximal speeds.

Strength gains in distance runners have previously been associated with greater muscle stiffness and shorter GCT (Paavolainen, Hakkinen, Hamalainen, Nummela, & Rusko, 1999), which in turn contributes to more effective force transmission during running and highlights the importance of addressing strength deficit rather than absolute maximum strength for this population. Strength deficit refers to the inability to fully

express maximal strength when lifting submaximal loads (González-Badillo et al., 2017). That is, the further the working load is from an athlete's 1RM, the greater the force that remains unexpressed ([Fig. 2](#)). In the present study, large correlations were found between strength deficits at 40–70% of 1RM and GCT (negative correlation) and leg stiffness (positive correlation). Specifically, athletes with a greater strength deficit at moderate and low loads exhibited shorter GCT and higher leg stiffness, indicating reduced time available to generate force in a specific task such as running at a sustained pace. Moreover, these correlations were stronger during the 3-min time trial compared to the 9-min trial. This indicates that at higher running velocities, the inability to produce maximal force at moderate and low loads is more pronounced, further supporting the link between neuromuscular performance in resistance exercises and running mechanics. Of note, the correlations observed in the present study between strength deficit at low-to-moderate loads (40–70% 1RM) and both GCT and leg stiffness were more pronounced during the trail surface running bouts than on the athletic track. This finding suggests that on the trail, the runners with a greater strength deficit would compensate by relying even more on neuromuscular mechanisms, as shorter GCT and greater leg stiffness enhance elastic energy storage and return, thus improving their stretch-shortening cycle. Therefore, the current results reinforce the notion of an interplay between muscle activation and leg stiffness, whereby these variables appear to compensate for one another depending on contextual factors (Lemire et al., 2021; Sabater-Pastor et al., 2022; Vernillo et al., 2017) and underscore the relevance of assessing strength deficit to better understand how trail runners optimize their running mechanics when encountering their usual environment, i.e., trails.

In order to shed light on the role of functional and morphological characteristics of the muscle-tendon units in rapid force production, as occurs during running, this study also examined the re-

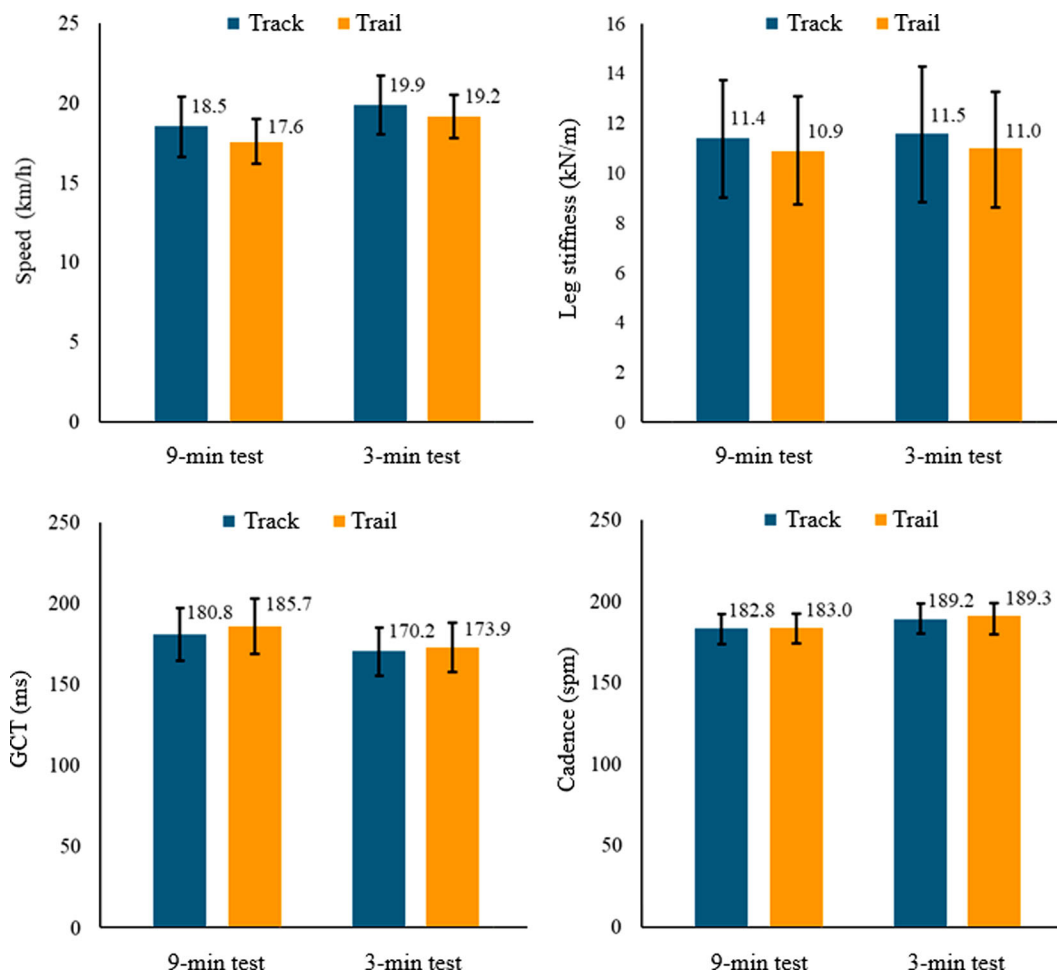


Fig. 2 ◀ Descriptive values of running variables evaluated during the 9- and 3-min time trials on the athletic track and the trail. GCT ground contact time

relationships between strength deficits in HSQ and patellar morphology. Large negative correlations were found between patellar tendon thickness and strength deficit at 40, 50, and 60% ($r = -0.518$, $r = -0.530$, and $r = -0.515$, respectively). In line with this, previous studies (Taş et al., 2017; Westh et al., 2008; Yamamoto & Ota, 2009) have reported significant associations between quadriceps strength and patellar tendon properties. Taş and colleagues found moderate correlations between isokinetic quadriceps strength and patellar tendon thickness ($r = 0.45$) and stiffness ($r = 0.44$), while Yamamoto and Ota reported high correlations between isometric leg extension strength and patellar tendon CSA ($r = 0.78$) and stiffness ($r = 0.65$). Despite the fact that the current study did not find a significant association between maximum strength and tendon morphological variables, our results seem to follow the same trend, and the discrepancy may be related to

the protocol selected to evaluate maximum strength in a more ecological setting (i.e., HSQ). The strong negative correlations found in the present study between patellar tendon thickness and strength deficit at low-to-moderate loads (40–60% 1 RM) suggest a relevant link between tendon morphology and neuromuscular efficiency during submaximal force production. These findings align with previous studies indicating that strength deficit is a valuable indicator of athletic performance. However, this association has been studied primarily in power-based sports, showing that athletes with lower strength deficits tend to exhibit superior sprinting performance and higher 1 RM squat values (Loturco et al., 2021; Zabaloy et al., 2022).

In contrast, the relationship between strength deficit and endurance performance remains largely unexplored. To date, no studies have directly examined this link in endurance or trail running

populations, marking a significant gap in the literature. Nevertheless, some evidence suggests that tendon morphology may play an important role in endurance performance. Specifically, Kovács et al. (2020) found that Achilles tendon thickness was strongly correlated with marathon performance ($r = 0.65$), highlighting the relevance of muscle–tendon unit characteristics in sustained running contexts. The present findings, showing significant negative correlations between strength deficit at moderate loads and patellar tendon thickness, contribute to addressing this gap by suggesting that neuromuscular efficiency and tendon morphology may be interconnected and relevant not only to explosive tasks but also to performance in trail running.

As previously discussed, trail runners tend to exhibit higher peaks of strength and power compared to road runners (Pastor et al., 2022). Never-

Table 2 Pearson's correlation coefficients between strength deficit and the running variables during the 3- and 9-min time trials on the athletic track and the trail.

	Sdef30	Sdef40	Sdef50	Sdef60	Sdef70	Sdef80	Sdef90
Track							
<i>9-min running bout</i>							
Speed (km/h)	-0.090	-0.139	-0.167	-0.195	-0.191	-0.207	-0.149
GCT (ms)	-0.307	-0.397	-0.414	-0.421	-0.414	-0.372	-0.320
Cadence (spm)	0.114	0.106	0.086	0.067	0.057	0.024	0.005
Leg stiffness (kN/m)	0.268	0.369	0.404	0.427	0.408	0.364	0.193
<i>3-min running bout</i>							
Speed (km/h)	-0.110	-0.153	-0.177	-0.198	-0.189	-0.203	-0.142
GCT (ms)	-0.423	-0.520*	-0.525*	-0.517*	-0.495	-0.435	-0.362
Cadence (spm)	0.170	0.162	0.142	0.116	0.104	0.071	0.058
Leg stiffness (kN/m)	0.306	0.437	0.479	0.516*	0.497	0.454	0.274
Trail							
<i>9-min running bout</i>							
Speed (km/h)	-0.033	-0.047	-0.066	-0.081	-0.072	-0.087	-0.027
GCT (ms)	-0.406	-0.492	-0.490	-0.485	-0.457	-0.400	-0.306
Cadence (spm)	0.183	0.176	0.152	0.128	0.113	0.078	0.056
Leg stiffness (kN/m)	0.384	0.493	0.539*	0.560*	0.535*	0.491	0.301
<i>3-min running bout</i>							
Speed (km/h)	-0.028	-0.061	-0.095	-0.122	-0.126	-0.157	-0.136
GCT (ms)	-0.463	-0.559*	-0.570*	-0.565*	-0.527*	-0.457	-0.319
Cadence (spm)	0.252	0.249	0.224	0.194	0.171	0.127	0.084
Leg stiffness (kN/m)	0.299	0.440	0.494	0.544*	0.525*	0.486	0.277

GCT ground contact time, *spm* steps per minute, *Sdef30–90* strength deficit in percentage of one repetition maximum for half-squat from 30–90 %

* $p < 0.05$

Table 3 Pearson's correlation coefficients between strength deficit and patellar tendon morphology.

	Sdef30	Sdef40	Sdef50	Sdef60	Sdef70	Sdef80	Sdef90
Thickness (mm)	-0.454	-0.518*	-0.530*	-0.515*	-0.488	-0.452	-0.388
CSA (mm ²)	-0.225	-0.132	-0.089	-0.005	-0.013	-0.040	-0.003

Sdef30–90 strength deficit in percentage of one repetition maximum for half-squat from 30–90 %, *CSA* cross-sectional area

* $p < 0.05$

theless, the present findings highlight a particular limitation in their ability to produce maximal power at moderate loads—potentially representing a weak link in performance. This inefficiency in force expression aligns with previous findings on power output in the HSQ, where Cormie et al. (Cormie, McCaulley, Triplett, & McBride, 2007) demonstrated a load-dependent decrease in energy efficiency. Similarly, Izquierdo et al. (Izquierdo, Häkkinen, Gonzalez-Badillo, Ibáñez, & Gorostiaga, 2002) identified 60% 1 RM as the optimal load for concentric-only HSQ performance in middle-distance runners, supporting the

relevance of submaximal loading zones for power development in endurance athletes.

In this context, both strength and resistance to strength emerge as critical factors for trail running performance, where muscle power production appears to be highly constrained by terrain-specific demands. Therefore, assessing both the morphological and neuromuscular characteristics of the muscle–tendon units in trail runners becomes essential. The observed strength deficits may reflect a compensatory mechanism within the stretch–shortening cycle (SSC), whereby muscle power generation must offset the reduced

reutilization of elastic energy under the unstable or irregular surfaces typical of trail environments. Taken together, these findings suggest a complex interplay between muscular strength, tendon morphology, and SSC dynamics that may underlie performance in trail running and thus warrant further investigation.

Conclusion

The results of the current study establish a critical link between an athlete's submaximal neuromuscular capacity and their running mechanics, particularly under the demanding conditions of trail terrain. Our findings demonstrate that a greater SDef is strongly associated with a shorter ground contact time and higher leg stiffness. This functional coupling suggests that runners with a defined neuromuscular weakness (i.e., an inability to rapidly express force) compensate by augmenting their reliance on the musculotendinous unit's elastic properties. This strategy is further supported by the observed relationship between lower SDef and increased patellar tendon thickness.

Practitioners should consider utilizing SDef assessment for neuromuscular profiling in trail runners and to guide individualized resistance training prescription. Athletes with a high SDef may focus on improving their rate of force development at 40–70% 1 RM, while those with a low SDef might benefit from targeted plyometric training to optimize elastic efficiency.

Corresponding address



Alberto Rubio-Peiratón, PhD
Universidad San Jorge
Zaragoza, Spain
arubio@usj.es

Acknowledgements. The researchers thank all the volunteers for their participation in the study.

Author Contribution. D. Jaén-Carrillo: conceptualization, methodology, data curation, formal analysis, writing—original draft preparation, writing—review & editing. L. Santos: data curation, writing—review & editing. A. Cartón-Llorente: conceptualization, methodology, writing—review & editing, supervision. A. Rubio-Peiratón: conceptualization, method-

ology, data curation, writing—original draft preparation, writing—review & editing.

Funding. Open Access funding provided thanks to the CRUE-CSIC agreement with Springer Nature.

Availability of data and materials. The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest. D. Jaén-Carrillo, A. Rubio-Peironán, L. Santos, and A. Cartón-Llorente declare that they have no competing interests.

All procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. The study was approved by the Bioethics Committee of the University of Innsbruck (approval no. 109/2024). All participants provided written informed consent after receiving detailed verbal and written explanations of the experimental procedures and potential risks.

Open Access. This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Balducci, P., Cléménçon, M., Trama, R., Blache, Y., & Hautier, C. (2017). Performance factors in a mountain ultramarathon. *International Journal of Sports Medicine*, 38(11), 819–826.
- Banyard, H., Nosaka, K., & Haff, G. (2017). Reliability and validity of the load—velocity relationship to predict the 1 RM back squat. *J Strength Cond Res*, 31, 1897–1904. <https://doi.org/10.1519/jsc.0000000000001657>.
- Barnes, K. R., & Kilding, A. E. (2015). Running economy: measurement, norms, and determining factors. *Sports Med Open*, 1(1), 8. <https://doi.org/10.1186/s40798-015-0007-y>.
- Borg, G. (1998). Borg's perceived exertion and pain scales. *Human kinetics*, .
- Cohen, J. (1992). Statistical power analysis. *Current directions in psychological science*, 1(3), 98–101.
- Conceição, F., Fernandes, J., Lewis, M., González-Badillo, J. J., & Jimenez-Reyes, P. (2016). Movement velocity as a measure of exercise intensity in three lower limb exercises. *Journal of sports sciences*, 34(12), 1099–1106.
- Cormie, P., McCaulley, G. O., Triplett, N. T., & McBride, J. M. (2007). Optimal loading for maximal power output during lower-body resistance exercises. *Med Sci Sports Exerc*, 39(2), 340–349. <https://doi.org/10.1249/01.mss.0000246993.71599.bf>.
- Del Bano-Aledo, M. E., Martínez-Paya, J. J., Rios-Díaz, J., Mejías-Suarez, S., Serrano-Carmona, S., & de Groot-Ferrando, A. (2017). Ultrasound measures of tendon thickness: Intra-rater, Inter-rater and Inter-machine reliability. *Muscles Ligaments Tendons J*, 7(1), 192–199. <https://doi.org/10.11138/mltj/2017.7.1.192>.
- Ehrström, S., Tartaruga, M. P., Easthope, C. S., Brisswalter, J., Morin, J.-B., & Vercauteren, F. (2018). Short trail running race: beyond the classic model for endurance running performance. *Medicine and science in sports and exercise*, 50(3), 580–588.
- Giandolini, M., Horvais, N., Rossi, J., Millet, G., Morin, J. B., & Samozino, P. (2016). Acute and delayed peripheral and central neuromuscular alterations induced by a short and intense downhill trail run. *Scandinavian Journal of Medicine & Science in Sports*, 26(11), 1321–1333.
- González-Badillo, J. J., Yañez-García, J. M., Mora-Custodio, R., & Rodríguez-Rosell, D. (2017). Velocity loss as a variable for monitoring resistance exercise. *Int J Sports Med*, 38(3), 217–225. <https://doi.org/10.1055/s-0042-120324>.
- Hopkins, W. G., Marshall, S. W., Batterham, A. M., & Hanin, J. (2009). Progressive statistics for studies in sports medicine and exercise science. *Med Sci Sports Exerc*, 41(1), 3–13. <https://doi.org/10.1249/MSS.0b013e31818cb278>.
- Imbach, F., Candau, R., Chailan, R., & Perrey, S. (2020). Validity of the Stryd power meter in measuring running parameters at submaximal speeds. *Sports*, 8(7), 103.
- ITRA (Producer) (2024). *Discover Trail Running*. <https://itra.run/About/DiscoverTrailRunning>
- Izquierdo, M., Häkkinen, K., Gonzalez-Badillo, J. J., Ibáñez, J., & Gorostiaga, E. M. (2002). Effects of long-term training specificity on maximal strength and power of the upper and lower extremities in athletes from different sports. *Eur J Appl Physiol*, 87(3), 264–271. <https://doi.org/10.1007/s00421-002-0628-y>.
- Kernozek, T. W., Knaus, A., Rademaker, T., & Almonroeder, T. G. (2018). The effects of habitual foot strike patterns on Achilles tendon loading in female runners. *Gait Posture*, 66, 283–287. <https://doi.org/10.1016/j.gaitpost.2018.09.016>.
- Khassetarash, A., Vernillo, G., Krüger, R. L., Edwards, W. B., & Millet, G. Y. (2022). Neuromuscular, biomechanical, and energetic adjustments following repeated bouts of downhill running. *Journal of sport and health science*, 11(3), 319–329. <https://doi.org/10.1016/j.jshs.2021.06.001>.
- Kovács, B., Kóbor, I., Gyimes, Z., Sebestyén, Ö., Tihanyi, J. (2020) Lower leg muscle–tendon unit characteristics are related to marathon running performance. *Abstract Scientific Reports* 10(1). <https://doi.org/10.1038/s41598-020-73742-5>
- Lemire, M., Hureau, T. J., Favret, F., Geny, B., Kouassi, B. Y., Boukhari, M., & Dufour, S. P. (2021). Physiological factors determining downhill vs uphill running endurance performance. *Journal of Science and Medicine in Sport*, 24(1), 85–91.
- Loturco, I., Pereira, L. A., Freitas, T. T., Bishop, C., Pareja-Blanco, F., & McGuigan, M. R. (2021). Maximum strength, relative strength, and strength deficit: relationships with performance and differences between elite sprinters and professional rugby union players. *Int J Sports Physiol Perform*, 16(8), 1148–1153. <https://doi.org/10.1123/ijspp.2020-0342>.
- McGuigan, M. R., Wright, G. A., & Fleck, S. J. (2012). Strength training for athletes: does it really help sports performance? *International journal of sports physiology and performance*, 7(1), 2–5.
- Moore, I. S. (2016). Is there an economical running technique? A review of modifiable biomechanical factors affecting running economy. *Sports Med*, 46(6), 793–807. <https://doi.org/10.1007/s40279-016-0474-4>.
- Moore, I. S., Ashford, K. J., Cross, C., Hope, J., Jones, H. S., & McCarthy-Ryan, M. (2019). Humans optimize ground contact time and leg stiffness to minimize the metabolic cost of running. *Frontiers in sports and active living*, 1, 53.
- Paavolainen, L., Häkkinen, K., Hamalainen, I., Nummela, A., & Rusko, H. (1999). Explosive-strength training improves 5-km running time by improving running economy and muscle power. *J Appl Physiol*, 86(5), 1527–1533. <https://doi.org/10.1152/jap.1999.86.5.1527>.
- Padulo, J., Powell, D., Milia, R., & Ardigo, L. P. (2013). A paradigm of uphill running. *PLoS One*, 8(7), e69006.
- Pareja-Blanco, F., Rodríguez-Rosell, D., Sánchez-Medina, L., Sanchis-Moysi, J., Dorado, C., Mora-Custodio, R., & Calbet, J. (2017). Effects of velocity loss during resistance training on athletic performance, strength gains and muscle adaptations. *Scandinavian Journal of Medicine & Science in Sports*, 27(7), 724–735.
- Pastor, F. S., Besson, T., Varesco, G., Parent, A., Fanget, M., Koral, J., & Millet, G. Y. (2022). Performance determinants in trail-running races of different distances. *International Journal of Sports Physiology and Performance*, 17(6), 844–851. <https://doi.org/10.1123/ijspp.2021-0362>.
- Perez-Castilla, A., García-Ramos, A., Padial, P., Morales-Artacho, A. J., & Feriche, B. (2020). Load-velocity relationship in variations of the half-squat exercise: influence of execution technique. *J Strength Cond Res*, 34(4), 1024–1031. <https://doi.org/10.1519/JSC.0000000000002072>.
- Rubio-Peironán, A., Cartón-Llorente, A., Mugele, H., & Jaén-Carrillo, D. (2024). The trail runners' tendon—how do weekly mileage and elevation gain affect Achilles and patellar tendon morphology? *Journal of Functional Morphology and Kinesiology*, 10(1), 1.
- Ruiz-Alias, S. A., Olaya-Cuartero, J., Nancupil-Andrade, A. A., & García-Pinillos, F. (2022). 9/3-minute running critical power test: mechanical threshold location with respect to ventilatory thresholds and maximum oxygen uptake. *International journal of sports physiology and performance*, 17(7), 1111–1118. <https://doi.org/10.1123/ijspp.2022-0069>.
- Sabater-Pastor, F., Besson, T., Varesco, G., Parent, A., Fanget, M., Koral, J., & Millet, G. Y. (2022). Performance determinants in trail-running races of different distances. *International journal of sports physiology and performance*, 17(6), 844–851. <https://doi.org/10.1123/ijspp.2021-0362>.
- Sabater-Pastor, F., Besson, T., Berthet, M., Varesco, G., Kennouche, D., Dandrieux, P.-E., & Millet, G. Y. (2023). Elite road vs. Trail runners: comparing economy, biomechanics, strength, and power. *The Journal of Strength & Conditioning Research*, 37(1), 181–186.
- Sanchez-Medina, L., Perez, C., & Gonzalez-Badillo, J. (2010). Importance of the propulsive phase in strength assessment. *International Journal of Sports Medicine*, 31(02), 123–129.

-
- Sloniger, M. A., Cureton, K. J., Prior, B. M., & Evans, E. M. (1997). Lower extremity muscle activation during horizontal and uphill running. *J Appl Physiol*, 83(6), 2073–2079. <https://doi.org/10.1152/jap.1997.83.6.2073>.
- Snyder, K. L., & Farley, C. T. (2011). Energetically optimal stride frequency in running: the effects of incline and decline. *J Exp Biol*, 214(Pt 12), 2089–2095. <https://doi.org/10.1242/jeb.053157>.
- Suchomel, T. J., Nimphius, S., & Stone, M. H. (2016). The importance of muscular strength in athletic performance. *Sports Med*, 46(10), 1419–1449. <https://doi.org/10.1007/s40279-016-0486-0>.
- Taş, S., Yılmaz, S., Onur, M. R., Soylu, A. R., Altuntaş, O., & Korkusuz, F. (2017). Patellar tendon mechanical properties change with gender, body mass index and quadriceps femoris muscle strength. *Acta Orthop Traumatol Turc*, 51(1), 54–59. <https://doi.org/10.1016/j.aott.2016.12.003>.
- Vernillo, G., Giandolini, M., Edwards, W. B., Morin, J.-B., Samozino, P., Horvais, N., & Millet, G. Y. (2017). Biomechanics and physiology of uphill and downhill running. *Sports Medicine*, 47, 615–629.
- Vogt, M., & Hoppeler, H. H. (2014). Eccentric exercise: mechanisms and effects when used as training regime or training adjunct. *Journal of applied physiology*, 116(11), 1446–1454.
- Westh, E., Kongsgaard, M., Bojsen-Møller, J., Aagaard, P., Hansen, M., Kjaer, M., & Magnusson, S. P. (2008). Effect of habitual exercise on the structural and mechanical properties of human tendon, in vivo, in men and women. *Scand J Med Sci Sports*, 18(1), 23–30. <https://doi.org/10.1111/j.1600-0838.2007.00638.x>.
- Yamamoto, N., & Ota, T. (2009). Relationships between the mechanical properties of patellar tendons and quadriceps strength in humans. *Journal of Biomechanical Science and Engineering*, 4, 530–538. <https://doi.org/10.1299/jbse.4.530>.
- Zabaloy, S., Giráldez, J., Fink, B., Alcaraz, P. E., Pereira, L. A., Freitas, T. T., & Loturco, I. (2022). Strength deficit in elite young rugby players: differences between playing positions and associations with sprint and jump performance. *The Journal of Strength & Conditioning Research*, 36(4), 920–926. <https://doi.org/10.1519/jsc.0000000000004234>.

Publisher's Note. Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.