Received: 20 February 2026 | Accepted: 25 March 2026

DOI: 10.1002/jeo2.70755

ORIGINAL PAPER

Journal of Experimental Orthopaedics WILEY

The association between GPS-derived external workload metrics and soleus muscle injuries in professional football (soccer) players

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Abstract

Purpose: To investigate the association between external GPS workload metrics and soleus muscle injuries (SMI) in elite professional football.

Methods: A retrospective cohort study was conducted across seven consecutive seasons (2017/2018–2023/2024) in a single Italian Serie A first-team squad. One hundred and sixty player-season observations were included (25.4 ± 3.2 years; goalkeepers excluded), with 4704 match-hours and 31,686 training-hours recorded. SMIs were defined as time-loss soleus muscle complaints (excluding contact injuries) diagnosed by the club medical staff in accordance with FIFA consensus definitions and classified as structural or non-structural. External loads were quantified using 50 Hz GPS (Stats Perform) and included total distance, high-intensity distance ($\geq 16\ km\cdot h^{-1}$), sprint distance ($\geq 25\ km\cdot h^{-1}$), and acceleration/deceleration distances ($\geq \pm 2.0\ m\cdot s^{-2}$). For injured players, workloads were averaged across the 7- and 28-day window preceding injury (excluding injury day) and compared to control periods of equal duration. Between-player comparisons contrasted injured players' injury periods with control periods in non-injured players.

Results: Twenty-nine SMIs (52% were nonstructural) occurred in 17 players. Injured players were older than noninjured players (29.2 ± 3.9 vs. 25.0 ± 3.2 years; $p = 0.041$). Most injuries occurred in training (83%); incidence was 0.76/1000 training-hours and 1.06/1000 match-hours; injury burden was 10.86 days/1000 hours. No within-player differences were observed between injury and control weeks for any workload metric ($p > 0.05$). Over 28 days, injured players demonstrated lower sprint distance versus their control month (−37%; $p = 0.014$; $d = -0.71$). For between-player analyses, deceleration distance was higher in the 7-day injury period versus noninjured controls (+17%; $p = 0.041$; $d = 0.44$), with no 28-day differences.

Conclusion: SMIs imposed a substantial burden in elite football and were not preceded by acute workload spikes relative to players' own control periods. Findings suggest SMIs may occur within a context of sustained

Abbreviations: a, alpha; ACC, accelerations; cm, centimetre; CMI, calf muscle injury; DEC, decelerations; ECIS, Elite Club Injury Study; FIFA, Fédération Internationale de Football Association; GPS, global positioning system; HID, high-intensity distance; Hz, hertz; KG, kilograms; Km, kilometre; M, metre; SD, sprint distance; SMI, soleus muscle injury; TD, total distance.

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high training volumes, with modest elevations in short-term deceleration exposure and reduced longer-term sprint distance observed prior to injury.

Level of Evidence: Level III.

KEYWORDS

calf, fatigue, injury epidemiology, injury prevention, muscle injury, training load

INTRODUCTION

Muscle injuries remain a significant cause of time-loss in professional football (soccer), with substantial consequences for team performance, player health and availability [27, 28, 39]. Muscle injuries account for around a third of all injuries [18, 19, 21] with a notable increase observed in relation to cumulative match exposure [4]. While most research has focused on hamstring muscle injuries, being the predominant muscle injury [21], calf muscle injuries (CMI) also represent a clinically important problem. CMIs account for ~13% of all muscle injuries in elite football [18], with the majority of these involving the Soleus (~70%) rather than the Gastrocnemius complex [30, 52]. These injuries often occur during critical periods of the season [40]. They are also associated with high recurrence rates [18, 52] and longer and more variable time-loss versus other lower limb muscle injuries [18, 21]. Despite their frequency and impact, research on CMIs and specifically soleus muscle injury (SMIs) is limited.

Understanding injury aetiology is fundamental to both the prevention and management of injuries in sport [2, 53]. Musculoskeletal injury ultimately represents mechanical failure, occurring either when a single high-magnitude load exceeds tissue capacity or when repetitive submaximal loading surpasses the tissue's fatigue tolerance [38]. Within this framework, appropriate management of training load is required to optimise fitness while minimising injury risk [3, 23, 57]. Both insufficient chronic loading and excessive loading, particularly when acute demands exceed a player's underlying fitness, have been associated with elevated injury risk in football and other team sports [6, 7, 37, 41, 42, 56]. A substantial body of literature has examined associations between training load and lower-limb injury across team sports, including football. However, the effectiveness of workload monitoring as an injury prevention strategy remains debated, with inconsistent associations reported between workload metrics and injury occurrence [35]. A major limitation of this literature is that most studies aggregate all lower-limb non-contact or soft-tissue injuries into a single category when examining workload–injury relationships [6, 7, 37, 41, 42, 56]. Given the complex, multifactorial nature of sports injury [5], and the clear evidence that different injuries exhibit distinct biomechanical mechanisms and risk profiles [8–14, 24], such aggregation is likely to obscure clinically meaningful associations between specific workload metrics (e.g., running volume vs. sprint exposure) and specific injury pathologies.

The soleus muscle is particularly relevant in this context. As the primary contributor to propulsive force during running, it generates more mechanical work at sub-maximal running velocities than any other lower-limb muscle [15]. Unlike the knee flexors or hip extensors, soleus activation and force output remain consistently high across a wide range of running velocities [15]. The soleus muscle plays a critical role in ankle joint stability, postural control, braking, and regulation of leg stiffness during dynamic sporting tasks [15, 29, 46]. SMIs are disproportionately common versus gastrocnemius injuries in running-based sports such as football [30, 52] and are frequently considered fatigue-related injuries [18], likely reflecting sensitivity to cumulative running volume, particularly total distance (TD) and submaximal running load. This contrasts with other muscle groups in football and other sports, which tend to be more sensitive to high-speed running or sprint exposure, such as hamstring injuries [47, 51]. Research exploring workload–injury relationships in CMI is extremely limited [52], with no study to date specifically examining the association between external workload and SMIs in football. An understanding of the soleus-specific workload and injury relationship may enable more targeted injury prevention and rehabilitation and return-to-play strategies in football.

As such, the present study aimed to investigate the association between external training load metrics and the incidence of SMIs in professional football players. The hypothesis was formulated that an increased risk of SMIs would be associated with greater training loads, particularly when accumulated rapidly over short periods.

METHODS

Study design

This was a retrospective study conducted over seven consecutive seasons (2017/2018 to 2023/2024), involving the first team players of a single professional football club, competing in the Italian Serie A. Injury and training load data were collected as part of routine team monitoring procedures. SMIs were diagnosed and classified by the club's medical staff, while training and match loads were recorded via GPS technology.

Participants

The study population comprised 160 player-season observations of professional football players. Some players were included across multiple seasons if they remained in the squad; however, each player-season was treated as an independent data point (age, 25.4 ± 3.2 years; range: 19–34 years). Player positions were: 64 defenders (40%), 56 midfielders (35%) and 40 forwards (25%). Goalkeepers were excluded. Total exposure during the study period was 4704 h for matches and 31,686 h for training. The following exclusion criteria were applied: (1) transfer to another club during the season; (2) absence of a first-team contract and (3) presence of a medical complaint during the selected control periods.

Data were collected prospectively as part of routine medical and performance monitoring within the club across multiple seasons (2017/2018–2023/2024), and the present analyses were conducted retrospectively. Ethical approval was obtained from the Bioethical Committee of the University of Bologna (n° 0007503 of 08/01/2025), which specifically covered the retrospective use of anonymised routine monitoring data for research purposes. As part of their professional contractual agreements, players provided consent for the collection and use of anonymised medical and performance data for research and audit purposes in accordance with standard practice in elite professional sport.

Injury and exposure data collection

The team's medical staff conducted a thorough diagnostic evaluation and recorded all injuries in accordance with the FIFA consensus statement for football injury studies [22]. A SMI was defined as any muscle-related complaint involving the soleus muscle that resulted in time-loss, defined as the player being unable to fully participate in at least one subsequent training session or match. The categorisation of injuries was based on the underlying cause, with acute injuries being attributed to a specific, identifiable event, and overuse injuries resulting from cumulative microtrauma without a discernible inciting incident, as defined by the consensus statement on injury definitions and data collection procedures in football [22]. These were categorised as either structural or non-structural based on clinical assessment and imaging, in accordance with internal medical protocols [20]. Structural injuries were defined as those demonstrating macroscopic fibre disruption on MRI, whereas non-structural injuries were defined as clinical soleus-related time-loss injuries without clear fibre disruption on imaging. MRI diagnoses were made by experienced sports medicine radiologists in collaboration with team physicians according to standard clinical practice. Formal inter-rater reliability was not assessed. Direct contact injuries (e.g., contusions) were excluded from the analysis. Severity was defined by the number of days of absence: minimal (1–3 days), mild (4–7 days), moderate (8–28 days) and severe (>28 days).

The team's athletic trainers were responsible for recording exposure data, which included only on-pitch training and match hours. Off-pitch activities such as gym-based strength sessions, recovery modalities, and preactivation exercises were not tracked using GPS and were therefore excluded from exposure time calculations. The incidence of injury was calculated as the number of SMIs per 1000 h of exposure. The functional impact was then quantified by calculating the number of days lost per 1000 h of exposure, thus providing a key indicator for evaluating the seasonal impact of soleus injuries on player availability and team management. Training exposure was defined as the total duration of on-field training sessions, from the beginning of the warm-up to the end of the final drill, excluding gym-based or rehabilitation activities.

Weekly external load monitoring

The external loads experienced by the athletes during training sessions and competitive matches were monitored via 50 Hz portable GPS units with integrated inertial sensors (K-SPORT; Stats Perform). The validity and reliability of this K 50 model, which features sensor fusion between GPS and inertial technologies has been confirmed in a validation study [36], which reported a typical error of 1.9% and a coefficient of variation of 2.1% for distance measurement during dynamic movements. To minimise inter-unit variability, each player consistently wore the same device across all sessions. Units were positioned between the scapulae at the level of the thoracic spine using a tight-fitting vest to reduce movement artefacts. In accordance with manufacturer guidelines, devices were activated at least 15 min before the start of each training session and official match to ensure proper satellite lock and data reliability. Following the conclusion of the training practice or match, the GPS accelerometer data were downloaded to a personal computer and analysed using a customised software package (K-Fitness; Stats-Perform).

The physical performance variables selected for analysis included TD, high-intensity distance [HID, defined as distance covered at speeds ≥16 km·h^{-1}, including sprint distance (SD)], SD (defined as distance covered at speeds ≥ 25 km·h^{-1}), as well as distances covered during moderate-to-high intensity accelerations (ACC, ≥2.0 m·s²) and decelerations (DEC, ≤–2.0 m·s²). GPS-accelerometer data were also used to derive training and match durations (in minutes), which were summed to calculate total weekly on-pitch exposure [52]. Only field-based activities were included in this analysis. In cases of missing external load data (e.g., GPS dropout, device malfunction), individual values were estimated using the player's own recent data (e.g., same-day session average or rolling weekly average), when available. If individual data were not available, team averages for the same position group and session type (training or match) were used as a substitute. This approach was applied consistently across both training sessions and official matches, and concerned fewer than 5% of the total data points. Similar strategies to handle GPS-related missing data are commonly adopted in team-sport monitoring research to minimize bias and preserve dataset validity [25, 43].

Statistics

Descriptive statistics were presented as mean ± standard deviation for continuous variables, and as counts and percentages for categorical variables. Normality of continuous data was assessed using the Shapiro–Wilk test and Q–Q plots.

Workload metrics (TD, HID, SD, ACC and DEC) for the injured players were averaged across the injury week (the 7 days immediately preceding the injury, excluding the day of injury) and injury month (the 28 days immediately preceding the injury, excluding the day of injury).

These were compared to corresponding control periods of equal duration (7- and 28-day windows). Control periods were selected from the same player within the same season where possible and were required to be free from injury, rehabilitation, and return-to-play phases. Periods were selected based on data completeness and availability from timeframes outside the injury window. Equivalent control periods were also extracted for noninjured players.

Paired-samples *t*-tests were used to compare injury and control periods within injured players, while independent-samples *t*-tests were used to compare injury periods in injured players with control periods in non-injured players. Results were reported as mean difference and percentage change (Δ%). Cohen's *d* effect sizes were calculated and interpreted as trivial (<0.2), small (0.2–0.49), moderate (0.5–0.79), and large (≥0.8). All analyses were conducted using R (version 4.3.3), with statistical significance set at $p < 0.05$.

A power analysis was conducted using G*Power (version 3.1.9.7) based on a previous study with similar rationale [52]. The TD metric with a difference of 18% (21,586.60 ± 4100.48 m vs. 25,117.41 ± 4884.93 m) between injured and noninjured players, an effect size Cohen's $d = 1.01$, and an allocation ratio of 3:1 (noninjured:injured) were retrieved from the study [52]. To keep the sample size calculation more conservative, an allocation ration of 4:1 with an effect size = 0.6 were adopted. Considering $\alpha = 0.05$, and power = 0.8, the total sample size was estimated in 140 players-season observations.

RESULTS

Injury incidence and characteristics

Within the overall cohort, 29 SMIs were recorded across 17 players, corresponding to 18% of the 160 player-season observations. Of these, nine players sustained a single injury, six sustained two injuries, and two players experienced four SMIs over the observation period. Injured players were significantly older (29.2 ± 3.9 years) than noninjured players (25.0 ± 3.2 years) ($p = 0.04$) (Table 1). Of the 29 injuries, 15 were classified as structural and 14 as nonstructural.

The distribution of injuries by position was as follows: defenders accounted for 31% of injuries, midfielders 31% and forwards 37%. When considering the proportion of players injured within each position, approximately 1 in 4 forwards sustained an injury, compared with fewer than 1 in 6 defenders and midfielders.

Of the injuries sustained, 24 (82.8%) occurred during training and 5 (17.2%) during matches. The

TABLE 1 Descriptive statistics of demographic, anthropometric and physiological variables in injured and noninjured players.

	All	Injured ($N = 29$)	Noninjured ($N = 131$)	*p*-value
Age (years)	27.1 ± 3.6	29.2 ± 3.9	25.0 ± 3.2	**0.041**
Height (cm)	183.9 ± 6.4	183.3 ± 5.9	184.4 ± 6.9	0.565
Body mass (kg)	83.5 ± 7.2	82.5 ± 6.8	84.5 ± 7.5	0.632
Position				
Defender	59	9 (15%)	50 (85%)	
Midfielder	57	9 (16%)	48 (84%)	
Forward	44	11 (25%)	33 (75%)	0.244
Overall	160			

Note: Values are presented as mean ± standard deviation for continuous variables and as number (percentage) for categorical variables. $p < 0.05$ indicates statistical significance.

overall incidence was 0.76 injuries per 1000 h of training exposure and 1.06 injuries per 1000 match hours. The total injury burden, measured in terms of the number of days of absence per 1000 h of exposure, was 10.86 days per 1000 h. The mean time of absence per injury was 12.9 ± 13.3 days.

Injury versus control period workload in injured players

During the 7-days period, no differences in workload metrics were found between injury and control period for the injured players ($p > 0.05$, Table 2). During the 28-days period, players sustaining a SMI showed lower SD in relation to their own control period ($\Delta = 37\%$, $p = 0.014$, Table 3).

Injured versus noninjured players workload

During the 7-days period prior to injury, players reported higher DEC distance than noninjured players ($\Delta = 17\%$, $p = 0.041$, Table 2). No differences were noted during the 28-days period ($p > 0.05$).

DISCUSSION

This is the first study to specifically examine the association of external workload metrics during training and matches and SMIs in elite male football. The main findings were that SMIs imposed a substantial injury burden on the squad, with an average of approximately four injuries per season. Injuries were more common in training than matches and were more common in older players and those with a history of SMIs. In the week preceding injury, injured players displayed similar total workloads to their own control week, although DEC workloads were moderately higher, with trends for greater TD, ACC and HID compared to non-injured players. Over the 4-week period prior to injury, workload exposure was largely comparable to control periods, except for lower SD relative to players own 4-week control period.

Epidemiology

The incidence and burden of SMIs observed in the present cohort were markedly higher than those reported in the UEFA Elite Club Injury Study (ECIS) for CMIs [18, 26], although they were comparable to more recent data from Spanish professional football [52]. Across the seven-season observation period, 29 SMIs were recorded, equating to ~4 SMIs per season, and an injury burden of 10.86 days per 1000 h. In contrast, Ekstrand et al. [18] reported that elite European teams typical sustain approximately two CMIs per season, with a burden of 4.6 days per 1000 h. This represents a more than two-fold greater injury burden in the present cohort, despite our analysis being restricted specifically to SMIs, rather than all CMIs.

The majority of SMIs occurred during training (83%), with few (17%) sustained during matches. This corresponds to only a moderately higher risk (~40%) in matches versus training (0.74 vs. 1.06 injuries per 1000 h). This contrasts with previous reports on CMIs, which suggests a five-to-six-fold greater match risk versus training, with ~70%–75% of injuries occurring during matches [18, 52]. This discrepancy may reflect the present study's exclusive focus on SMIs, in contrast to broader classification of CMIs in prior surveillance studies. Recent work has demonstrated that SMIs account for around 70% of calf injuries in professional football [30, 52]. The higher proportion of training-related SMIs observed in the present cohort therefore supports the premise that SMIs pathology may be more closely linked to cumulative training exposure than

TABLE 2 Comparison of the workload metrics of players sustaining a soleus muscle injury between the injury week and a control week and between injured and noninjured players (7-day period).

	Injured players		Noninjured players	Injured: injury vs. control week			Injured vs. noninjured players		
7-days	Injury week	Control week	Control week	Δ%	*p*-value	ES	Δ%	*p*-value	ES
TD	35,245 ± 8124	36,973 ± 9069	32,496 ± 7767	−5%	0.485	−0.20	8%	0.098	0.35
HID	5652 ± 1964	6275 ± 2094	5081 ± 1639	−11%	0.251	−0.31	10%	0.122	0.32
SD	261 ± 199	357 ± 233	223 ± 207	−37%	0.110	−0.45	14%	0.397	0.18
ACC	1841 ± 691	1758 ± 930	1592 ± 701	5%	0.576	0.10	14%	0.105	0.36
DEC	1657 ± 663	1593 ± 774	1375 ± 613	4%	0.599	0.09	**17%**	**0.041**	**0.44**

Note: values are presented as mean ± standard deviation; bold *p*-values indicate statistical significance.

Abbreviations: ACC, acceleration distance (≥2.0 m·s²); DEC, deceleration distance (≥2.0 m·s²), ES, Cohen's *d* effect size; HID, high intensity distance (distance covered in metres at speeds ≥16 $km \cdot h^{-1}$, including sprint distance); SD, sprint distance (distance in metres covered at speeds ≥25 $km \cdot h^{-1}$); TD, total distance (m). Bold values indicate significant findings.

TABLE 3 Comparison of the workload metrics of players sustaining a soleus muscle injury between the injury month and a control month and between injured and noninjured players (28-day period).

28-days	Injured players		Noninjured players	Injured: injury vs. control month			Injured vs. noninjured players		
	Injury month	Control month	Control month	Δ%	*p*-value	ES	Δ%	*p*-value	ES
TD	136,168 ± 29,622	147,377 ± 20,943	133,789 ± 26,023	−8%	0.080	−0.44	2%	0.685	0.09
HID	21,457 ± 5486	24,562 ± 4959	21,959 ± 6737	−14%	0.100	−0.59	−2%	0.724	−0.08
SD	1009 ± 600	1381 ± 443	1105 ± 800	**−37%**	**0.014**	**−0.71**	−10%	0.558	−0.14
ACC	7043 ± 2526	7105 ± 3046	6465 ± 2775	−1%	0.851	−0.02	8%	0.346	0.22
DEC	6328 ± 2416	6574 ± 2728	5557 ± 2392	−4%	0.932	−0.10	12%	0.157	0.32

Note: values are presented as mean ± standard deviation; bold *p*-values indicate statistical significance.

Abbreviations: ACC, acceleration distance (≥2.0 m·s²); DEC, deceleration distance (≥2.0 m·s²); ES, Cohen's *d* effect size; HID, high intensity distance (distance covered in metres at speeds ≥16 km·h^{-1}, including sprint distance), SD, sprint distance (distance in metres covered at speeds ≥25 km·h^{-1}), TD, total distance (m). Bold values indicate significant findings.

acute match demands. This supports research showing that CMIs in elite football (ECIS) are not impacted by congested match play, like other lower limb muscle injuries [4].

More than half of all injuries were classified as non-structural with relatively short time-loss, suggesting that functional SMIs may have been under-reported in earlier surveillance studies. The mean absence per injury (12.9 days) was slightly lower than that reported previously for CMIs (~15 days) [18, 52]. Improvements in diagnostic awareness of soleus-specific pathology likely contribute to the higher incidence observed.

Injured players were significantly older than non-injured players, consistent with previous research [18, 26, 52]. No differences were observed for height, body mass, or playing position. Re-injury was common, with nearly half of injured players sustaining multiple SMIs. Prior injury is a well-established risk factor for calf and soleus injuries [24], likely reflecting persistent deficits in tissue capacity, neuromuscular control, and load tolerance.

Workload and SMIs

This is the first study to specifically examine the relationship between external workload and SMIs, in elite football, rather than grouping these injuries under CMIs or lower limb muscle categories. A recent pilot study in Spanish professional football examining CMIs reported an acute increase in workload (16%–37%) during the 7-day period preceding injury [52]. In contrast, the present pathology-specific analysis of SMIs did not demonstrate comparable acute workload elevations in the week preceding injury, with workload values largely similar to players' own control periods. Differences in injury classification (CMIs vs. SMIs), cohort characteristics, and analytic approach (within-player comparisons in the present study versus aggregated injury analyses in prior work) may partly explain these contrasting findings. These observations suggest that workload patterns associated with soleus-specific pathology may differ from those reported for broader calf muscle injury groupings, although direct comparisons between studies should be interpreted cautiously. As such, injured players did not experience an acute increase in workload immediately prior to injury. This contrasts with several studies on lower-limb soft-tissue injury that have linked acute workload spikes and elevated acute: chronic workload ratios to increased injury risk in football [6, 7, 17, 37] and other team sports [16, 31–33, 42], suggesting that the mechanisms underpinning SMIs may differ from those proposed for other muscle injuries in football.

Similarly, minimal change and in some cases a slight reduction was observed in the 4-week workload preceding injury compared with players' control 4-week period. To our knowledge this is the first study to document 4-week workload exposure prior to CMIs/SMIs specifically. Previous work examining longer-term loading patterns for aggregated lower-limb injuries has generally reported both increased [6, 7] and decreased injury risk with high 3-to-4-week training loads [17] highlighting the complexity of more chronic workload-injury relationships. Together, these findings indicate that SMIs in this cohort were not preceded by acute (7-day) or more sustained (4-week) elevations in external workload metrics. Bowen et al. [7] reported that a low amount of TD accumulated over 4-weeks increased the risk of sustaining non-contact injury, particularly when low chronic loading was followed by an acute spike prior to injury.

Between player comparison further supported the observation that changes in workload were not associated with injury. Injured players demonstrated only modestly higher 7-day DEC workloads than un-injured players (+17%, ES, 0.40) with similarly small-to-moderate effect sizes for TD, ACC and HID. This is the first study to contrast workload exposure specifically between players sustaining SMI and un-injured players. Most previous investigations have pooled all lower-limb soft-tissue or non-contact injuries into a single category, limiting the ability to draw pathology-specific inferences.

While acute workload change was minimal, the absolute workload values in this cohort, specifically TD were notably high when compared with those reported previously. Seven-day TD values in the present cohort (35–37 km) were approximately 40%–70% greater than those reported in the Spanish cohort studied by Soler et al. [52]. Based on published classifications, where <24 km is considered low, 24–30 km low-to-moderate, >30–31 km high and >37 km very high [7, 37], all 7-day TD workloads in the present study would be classified as high-to-very-high. A similar pattern was evident for 4-week workloads, where both injured and uninjured players accumulated very high chronic TD exposures (>134 km across 28 days). Therefore, despite the absence of acute workload spikes, players in this cohort were consistently exposed to very high cumulative TD/running volumes. Four-week loads are typically conceptualised as markers of chronic loading and physical preparedness (i.e., "fitness") and are often considered protective against injury when appropriately progressed [23]. It is therefore plausible that in some players these loads were protective, whereas in others, particularly those with prior injury or age-related reductions in tissue capacity, they may have exceeded individual tissue load-tolerance capacity. Collectively, these contrasting findings suggest that different workload patterns may be associated with CMIs versus soleus-specific injuries, although direct comparisons between studies should be made cautiously.

These findings have important mechanistic implications for SMIs. Jogging and submaximal running impose substantial repetitive loads on the plantar-flexor muscle–tendon complex, with the soleus acting as the primary contributor to propulsive force during these activities [15]. Unlike the hamstrings or hip extensors, which experience their greatest mechanical demands at high running speeds, soleus activation remains high across a wide range of running velocities, including low- and moderate-speed running [15]. During submaximal running, athletes typically experience vertical ground reaction forces of approximately 2–3 times body mass per step [15, 45, 48] with a large proportion of this force generated by the ankle plantar flexors [15]. At faster speeds, soleus force contribution decreases due to reduced ground contact time and increased reliance on proximal musculature [15]. Consequently, TD may reflect a proxy of cumulative plantar-flexor exposure rather than peak mechanical demand. From this perspective, the consistently high TD exposure observed in the present cohort may represent a contributing mechanical context within which SMIs occurred in this cohort.

The biomechanical specificity of soleus loading also helps explain the discrepancy between the present findings and the sprint-dominated workload–injury relationships commonly reported for hamstring injuries [47, 51]. Whereas hamstring strain risk is strongly linked to high-speed running and sprint exposure, SMIs appear to be more sensitive to prolonged submaximal loading and fatigue accumulation. In this context, the significantly lower 4-week SD observed prior to injury could reflect reduced exposure to high-velocity loading, potentially leading to a loss of load variability and a greater relative contribution of submaximal running to overall mechanical stress.

Finally, the fact that many SMIs occurred in older players and as re-injuries suggests that workload effects are likely moderated by intrinsic risk factors such as age-related reductions in tissue capacity and residual deficits following prior injury. Previous injury is a well-established risk factor for CMIs and SMIs [24, 26], and it is plausible that given the same absolute workload exposure, previously injured or older players may operate closer to their individual tissue tolerance limits. Although the present study was not sufficiently powered to stratify workload–injury relationships by injury history, future research should examine how workload interacts with intrinsic risk modifiers such as age, prior SMI, plantar-flexor strength, and ankle dorsiflexion range of motion, to name a few.

Methodological considerations

The present study has several important methodological strengths and limitations that should be considered when interpreting the findings. Key strengths include the seven consecutive seasons of data collection within a consistent elite professional football environment, the homogeneous cohort of first-team players, and the prospective recording of both injury and external workload data as part of routine club monitoring. Workload associations were examined using both within-player (injury vs. control periods) and between-player (injured vs. noninjured players) comparisons across defined 7- and 28-day time windows. The extended observation period enabled a pathology-specific investigation focused exclusively on SMIs, rather than grouping all calf or lower limb muscle injuries together, thereby improving biomechanical and clinical specificity.

Despite these strengths, several methodological considerations warrant careful interpretation. Although injury and workload data were prospectively collected, the present study employed a retrospective analytical design. Accordingly, the findings should be interpreted as exploratory associations rather than evidence of causality. The relatively small number of SMIs available for analysis ($n = 29$) limits statistical power and restricts the ability to detect small-to-moderate exposure-injury relationships [1–3]. While comparable to many single-club longitudinal workload studies in elite football [7, 37, 42, 52], substantially larger datasets are required to examine interaction effects and multifactorial injury models [38, 50]. The limited number of injuries also precluded multivariate modelling and analysis was therefore restricted to univariable comparisons. Contemporary theoretical models conceptualise sports injury as the result of dynamic, non-linear interactions between multiple intrinsic and extrinsic risk factors, including age, strength, fatigue, movement strategy, and workload [2, 5, 57]. Future research should therefore examine workload–SMI relationships within larger cohorts that allow for multivariable and interaction-based modelling.

Potential sources of bias should also be acknowledged. Selection bias may arise from the single-club cohort design, and survivorship bias may have occurred across seasons due to player transfers, differences in squad status, or variable exposure time. Information bias is possible given the reliance on GPS-derived workload metrics as external proxies of mechanical demand. Although injury diagnoses were made by experienced medical staff in accordance with consensus definitions, misclassification cannot be entirely excluded. In addition, injured players were significantly older than noninjured players, and prior injury history was not formally adjusted for in the analyses. Residual confounding by age, prior injury, or other intrinsic factors (e.g., strength or neuromuscular capacity) is therefore possible and limits causal interpretation.

The unit of analysis also warrants clarification. Some players contributed data across multiple seasons, and a small number sustained more than one SMI. Analyses treated player-season observations as independent and clustering within players was not formally modelled. This approach may underestimate variance and overstate statistical precision. Given the modest number of injuries, more complex mixed-effects or cluster-adjusted models were not considered feasible without risking model instability; results should therefore be interpreted with appropriate caution.

Missing GPS data (<5%) were imputed using recent individual values or, when unavailable, team or positional averages. While this approach preserved sample size and analytic stability, it may attenuate variance and influence effect estimates. Sensitivity analyses were not performed due to the limited number of events, and the potential impact of imputation should be considered when interpreting the findings.

Finally, multiple workload variables were examined across two time windows using both within- and between-player comparisons. No formal adjustment for multiple comparisons was applied. Accordingly, the analyses should be interpreted as exploratory, and statistically significant findings should be considered in light of potential type I error inflation.

To enhance analytic stability and reduce collinearity between workload metrics, primary variables were limited to TD, HID, SD and moderate-to-high intensity acceleration and deceleration ($\geq\pm 2.0\,m\cdot s^{-2}$), capturing key dimensions of volume, intensity, and change-of-velocity demands. It is possible that using higher thresholds for ACC and DEC may have revealed different associations with SMIs [44, 49, 55]. Although GPS technology provides practical estimates of external workload in elite football, it cannot directly quantify internal tissue loading, joint moments, muscle–tendon forces, or fatigue state [34, 54]. Workload metrics should therefore be interpreted as external proxies of mechanical demand rather than direct measures of soleus muscle loading.

Future research integrating larger multi-club cohorts, multivariable modelling, biomechanical assessment, and neuromuscular profiling would further advance understanding of SMI mechanisms and workload interactions.

Practical implications

SMIs appear to represent a meaningful injury burden in elite football, greater than previously recognised, with the present cohort sustaining ~4 SMIs per season and exhibiting a substantially greater injury burden than typically reported in the literature. Most injuries were classified as minor to moderate, with a high proportion of nonstructural (functional) injuries. This pattern is consistent with a fatigue-related aetiology and likely reflects the exceptionally high chronic TD workloads observed in this cohort.

Given the unique functional role of the soleus as the primary contributor to propulsion during jogging and running, TD and submaximal running volume may represent relevant indicators of cumulative plantarflexor exposure in football, acknowledging that GPS-derived metrics provide indirect estimates of internal tissue loading. From a practical perspective, these findings indicate that monitoring and regulating chronic TD and/or running loads rather than focusing solely on sprint and change of velocity (ACC, DEC) exposure should form a central component of SMI risk management strategies. Sustained exposure to high running volumes, even in the absence of acute workload spikes, is likely to exert a meaningful and cumulative injury risk for SMIs in elite football players.

CONCLUSION

SMIs exert a meaningful injury burden in elite football, with this cohort sustaining approximately four SMIs per season. Injuries were not associated with acute increases in training load prior to injury but occurred in the context of consistently high chronic training volumes, particularly TD and running loads. These findings suggest that sustained high running volumes may characterise the workload context in which SMIs occurred in this cohort and warrant consideration within monitoring strategies in elite football.

AUTHOR CONTRIBUTIONS

Gianni Nanni and Luca Benedetti conceived the idea for the study and oversaw the longitudinal data collection and/or data management. Gianni Nanni oversaw the medical team prised with injury diagnosis. Luca Benedetti oversaw collection of GPS workload and training exposure data. Luca Benedetti, Matthew Buckthorpe and Stefano Di Paolo performed the data analysis, interpreted results and wrote the manuscript, with all other authors providing intellectual input on draughts versions of the manuscript. All authors approved the final version of the manuscript.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

FUNDING INFORMATION

The authors have no funding to report.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are not publicly available due to privacy and contractual restrictions with the participating club(s), but may be available from the corresponding author upon reasonable request and with permission of the participating organisation.

ETHICS STATEMENT

The study received ethical approval from the Bioethical Committee of the University of Bologna (n° 0007503 of 08/01/2025).

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How to cite this article: Benedetti L, Buckthorpe M, Di Paolo S, Della Villa F, Nanni G. The association between GPS-derived external workload metrics and soleus muscle injuries in professional football (soccer) players. J Exp Orthop. 2026;13:e70755. https://doi.org/10.1002/jeo2.70755