Jump Height Lies: Force–Time CMJ Metrics Reveal Hidden Neuromuscular Responses in Elite Football

Joao B Marques, [1] **Vasileios Sideris**, [1] **Felipe Rabelo**, [2] **Thiago S Maria**, [2] **Lucas Marques**, [2] **Martin Buchheit** [1 3 4 5 6 7]

[1]Aspetar, Orthopaedic Sports Medicine Hospital, FIFA Medical Center, Doha, Qatar
[2]Red Bull Bragantino Futebol LTDA, Sao Paulo, Brazil
[3]Type 3.2 Performance, Montvalezan, France
[4]Optimo Performance Center, Estepona, Spain
[5]INSEP, Paris, France
[6]HIIT Science, Revelstoke, Canada
[7]Athletica, Revelstoke, Canada

Monitoring | Jump height | Jump strategy | Time-based metrics | Fatigue | Match response | Seasonal changes | Playing time

Headline

The countermovement jump (CMJ) is widely used to monitor neuromuscular status in elite football (Marques & Chamari, 2023; Buchheit & Hader, 2025), yet uncertainty remains about which CMJ metrics best reflect post-match changes. While GPS-derived measures quantify external locomotor exposure, they provide only indirect proxies of internal neuromuscular strain and cannot fully capture the biological response to training and match load (Buchheit et al., 2026a). This study examined the sensitivity of CMJ-derived variables across different levels of match exposure, rolling 7-day accumulated external load, and seasonal fluctuations. These findings challenge reliance on jump height alone and highlight the importance of monitoring how performance is achieved.

Aim of the study

The aim of this study was to identify the CMJ-derived variables most sensitive to neuromuscular responses in professional football players by examining their associations with match exposure, rolling 7-day accumulated GPS-derived load, and seasonal variation across the competitive season.

Design of the study

This longitudinal observational study assessed CMJ performance in elite football players 48 h after official matches across a competitive season, examining the effects of match exposure, rolling 7-day accumulated load, and seasonal fluctuations on CMJ-derived variables. The data analyzed in this study were retrospectively extracted from routine athlete monitoring procedures conducted by a Professional Football Club in Brazil as part of standard performance practice. No procedures were performed outside normal operational monitoring, and no experimental intervention was introduced for research purposes. All data were anonymized prior to analysis and processed in accordance with applicable Brazilian regulations and club data governance policies.

Methods

Participants

Twenty players (age: 24.3 ± 3.4 y, body weight: 79.5 ± 7.5 kg, height: 181.1 ± 6.8 cm) were included. CMJ testing was performed indoors 48 h after official matches (D+2) under the supervision of two experienced investigators. Participants wore standardized athletic clothing and footwear. Players unable to complete testing due to injury were excluded.

Procedures

CMJ Test

CMJ performance was assessed using dual force plates (ForceDecks Max; VALD Performance, Australia) sampling at 1000 Hz. Players performed standardized CMJs with hands on hips following a controlled warm-up (e.g. 5 min cycling, 6 bilateral squats, and 3 sub-maximal CMJ efforts). The best trial (highest jump height) was retained for analysis to reflect maximal performance capacity. Figure 1 illustrates the vertical ground reaction force-time curve and the phases of the CMJ.

CMJ-derived variables

Table 1 displays the variables selected for analysis based on their established relevance to neuromuscular function and stretch-shortening cycle performance (Bishop et al., 2023).

Locomotor-derived variables

Locomotor external load data were collected during all training sessions and matches using wearable microtechnology units (Catapult Vector S7 for outfield players and Vector G7 for goalkeepers; Catapult Sports, Melbourne, Australia). Variables derived from GPS included total distance, high-intensity running distance, sprint distance, peak running speed, sprint count, and acceleration/deceleration metrics. All variables were processed using Catapult OpenField software and aggregated using a rolling 7-day window to quantify short-term accumulated load. In line with recent conceptual advances, these GPS-derived metrics were interpreted as external locomotor load indicators rather than direct measures of internal neuromuscular load, reinforcing the need to combine them with internal response markers such as CMJ force-time variables (Buchheit et al., 2026a).

Seasonal distribution of Match, GPS, and CMJ observations

GPS observations represented the densest monitoring stream across the season, with 2,959 observations overall, compared with 749 game observations and 748 CMJ observations (Figure 2). On a weekly basis, this corresponded to an average of 59.2 GPS observations, versus 15.0 game and 15.0 CMJ observations, indicating substantially greater temporal coverage for GPS-derived load data compared with match exposure and neuromuscular testing.

Statistical analysis

Linear mixed-effects models were used to assess changes in CMJ-derived variables across match exposure levels, accounting for repeated measures within players. Player identity was included as a random effect, with match exposure (>70 min, 40–70 min, <40 min) included as a fixed effect. Effect sizes were calculated as standardized mean differences (Cohen's d) and interpreted using standard thresholds (small = 0.2, moderate = 0.5, large = 0.8).

Associations between rolling 7-day GPS-derived load metrics and CMJ variables were examined using linear mixed-effects models, with player identity included as a random effect and each GPS metric entered as a fixed-effect predictor. Standardized regression coefficients (β) were calculated to describe the magnitude and direction of associations and are presented as heatmaps. Negative coefficients indicate lower CMJ values with higher accumulated load, whereas positive coefficients indicate higher CMJ values.

To examine seasonal fluctuations, CMJ variables were expressed as percentage changes relative to the first quarter (Q1) baseline and summarized descriptively across subsequent quarters (Q2–Q4). Seasonal analyses were descriptive and intended to illustrate the magnitude and direction of change over time.

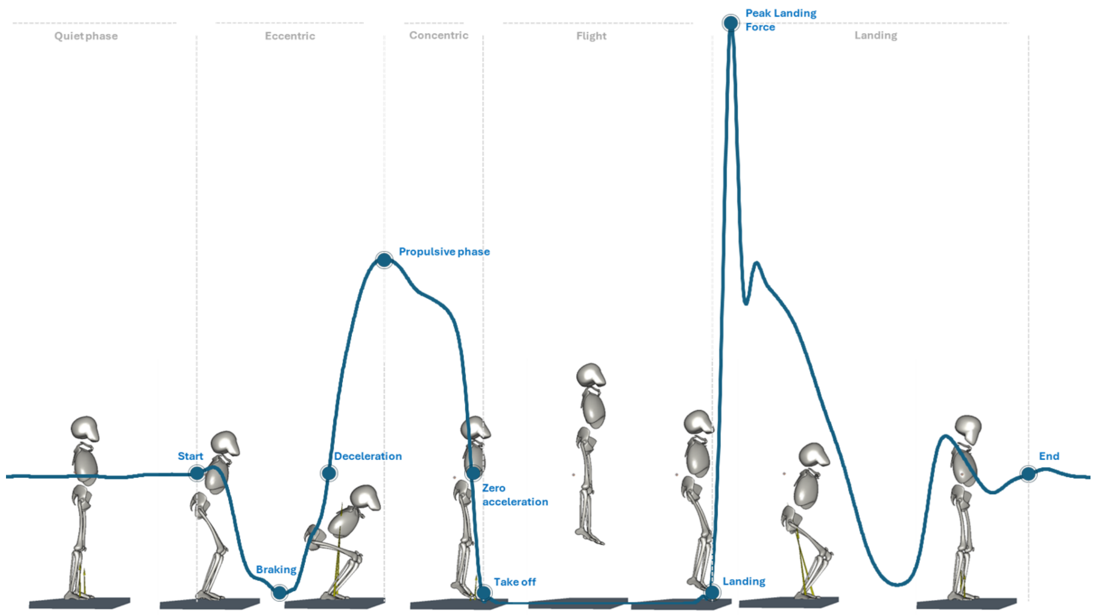

Fig. 1. **Representative vertical ground reaction force–time curve during a CMJ, showing the quiet standing, eccentric/braking, concentric/propulsive, flight, and landing phases. Key events (start, onset of braking, onset of deceleration, onset of propulsion, zero acceleration, take-off, and landing) are annotated alongside the corresponding movement sequence.**

Table 1. CMJ variables derived from force-time data selected for analysis.

Phase/ Domain	Variables	Description
Concentric	RSI modified	Reactive strength index modified (jump height / time to take-off)
	Concentric peak force	Maximum vertical force during the concentric phase
	Concentric impulse (0 – 100 ms)	Net impulse generated in the first 100 ms of the concentric phase
	Concentric mean force	Mean vertical force during the concentric phase
	Concentric impulse	Net impulse during propulsive force application
	Peak power / kg	Maximal concentric power normalized to body mass
Eccentric	Time to braking phase	Time from movement onset to peak eccentric braking
	Eccentric deceleration impulse	Net impulse during the eccentric braking phase
	Eccentric peak force	Maximum vertical force during the eccentric phase
	Eccentric mean force	Mean force produced during the eccentric phase
Flight	Jump height	Vertical displacement of center of mass

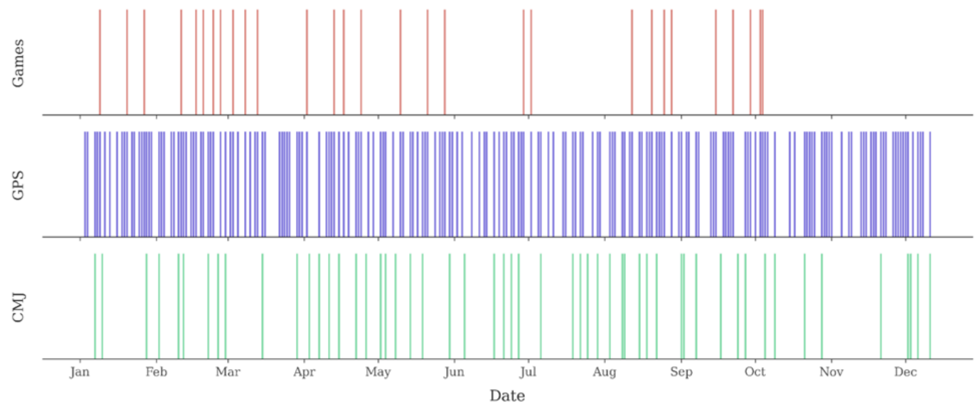

Fig. 2. Seasonal timeline of match, GPS, and CMJ observations for a representative player (P005). Each vertical line represents a recorded observation date across the competitive season. The figure highlights the substantially higher frequency and temporal density of GPS-derived load monitoring compared with match and CMJ assessments.

Results

Match exposure

CMJ force-time responses demonstrated a clear dose-response pattern according to match exposure duration, with the greatest impairments observed between players exposed to >70 min and those exposed to <40 min of match play (Figure 3). The most pronounced differences were seen in contraction time (+0.55), time to braking phase (+0.37), RSI modified (-0.39), concentric mean force (-0.44), concentric impulse (0 – 100 ms) (-0.42), and concentric peak force (-0.32), indicating progressively impaired rapid force production with increasing match exposure. Differences between >70 min and 40–70 min were smaller but directionally similar, while jump height remained largely unchanged across all comparisons (-0.12 to +0.11).

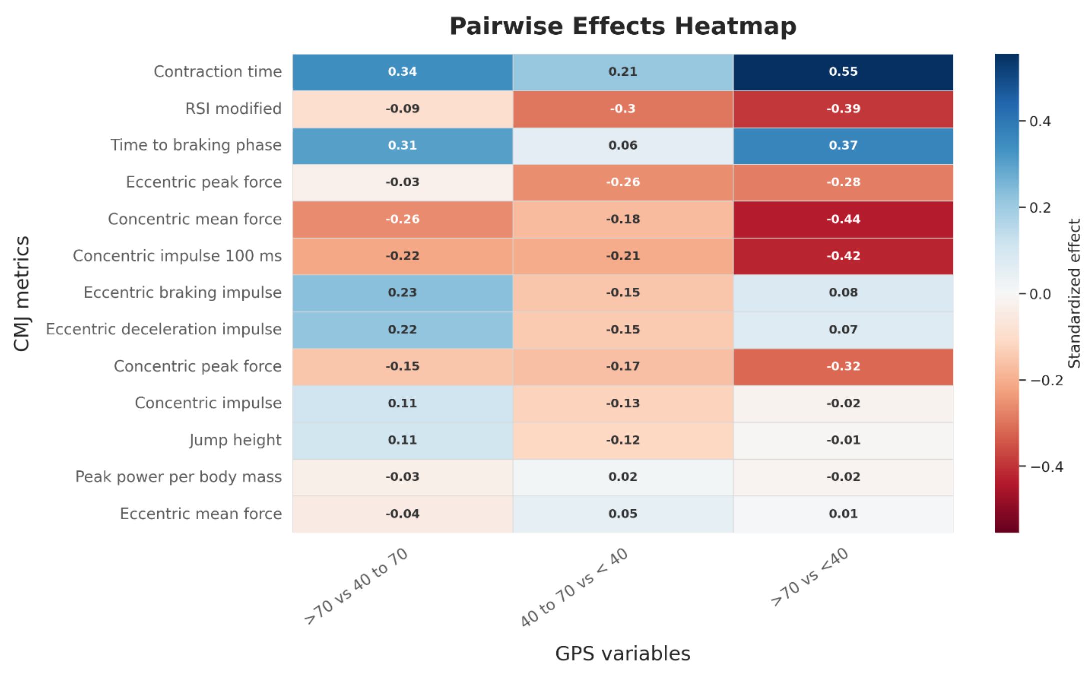

Fig. 3. Standardized mean differences in CMJ metrics according to level of match exposure.

GPS-derived accumulated load

Higher rolling 7-day accumulated external load was consistently associated with impairments in CMJ force-time characteristics (Figure 4). The strongest negative associations were observed between sprint-related load metrics and eccentric peak force (up to -0.21), concentric impulse (0 – 100 ms) (up to -0.19), eccentric braking impulse (up to -0.17), concentric peak force (up to -0.18), and concentric mean force (up to -0.15). In contrast, contraction time showed consistent positive associations with accumulated load (+0.11 to +0.18), indicating progressively slower force production under higher load exposure. RSI modified also declined systematically with increasing load (up to -0.14), whereas jump height showed only trivial and inconsistent associations (-0.05 to +0.12).

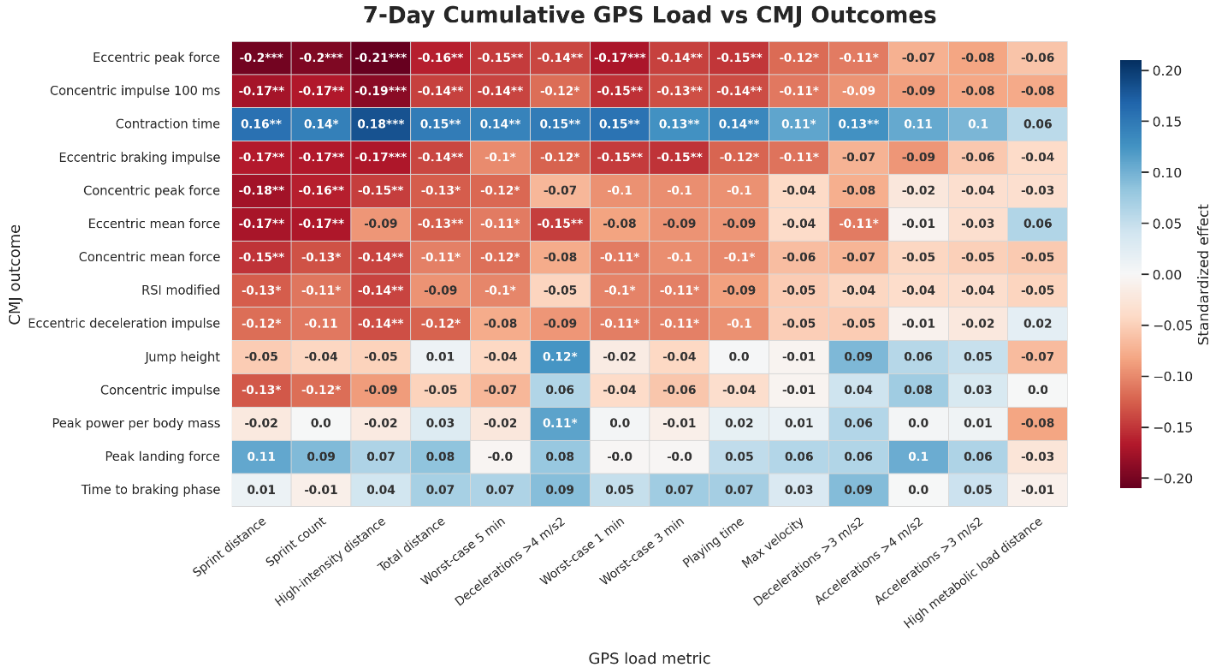

Fig. 4. Associations between rolling 7-day cumulative GPS-derived load metrics and CMJ force–time variables expressed as standardized regression coefficients (β). Negative values (red) indicate that higher accumulated load is associated with lower CMJ values, whereas positive values (blue) indicate higher CMJ values with increasing load. Note: Significant associations (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$).

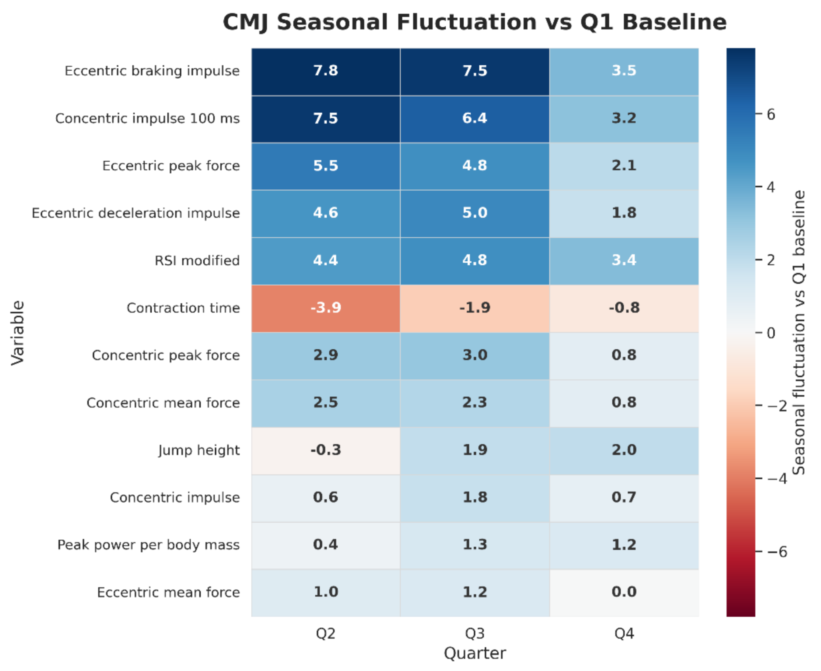

Fig. 5. Seasonal fluctuation in CMJ performance variables relative to the Q1 baseline. Heatmap cells display standardized change scores for each quarter. Positive deviations from Q1 are shown in blue and negative deviations in red, with color intensity indicating the magnitude of change. Legend: Q1 = First quarter, Q2 = Second quarter, Q3 = Third quarter, Q4 = Fourth quarter.

Seasonal fluctuations

Seasonal fluctuations in CMJ variables showed contrasting patterns between force-time characteristics and jump performance across the competitive season (Figure 5). Relative to the Q1 baseline, contraction time showed its most favorable change in Q2 (-3.9%), with the magnitude of improvement diminishing in Q3 (-1.9%) and Q4 (-0.8%). In contrast, several force-time variables showed positive deviations relative to Q1, particularly eccentric braking impulse (+7.8%, +7.5%, +3.5%), concentric impulse in the first 100 ms (+7.5%, +6.4%, +3.2%), eccentric peak force (+5.5%, +4.8%, +2.1%), eccentric deceleration impulse (+4.6%, +5.0%, +1.8%), and RSI-modified (+4.4%, +4.8%, +3.4%). These increases were most evident in Q2 and Q3 and were attenuated in Q4. By comparison, jump height remained relatively stable across the season (-0.3% to +2.0%), suggesting that force-time characteristics varied more than jump outcome.

Discussion

The main finding of this study is that CMJ force-time variables were more sensitive than jump height for detecting neuromuscular responses in elite football players. This pattern was consistent across match exposure, GPS-derived short-term accumulated load, and throughout the competitive season. Collectively, these results indicate that the neuromuscular cost of match play and training is more clearly reflected in the force-time characteristics of the jump than in the final performance outcome alone. This supports the growing recognition that external load and internal neuromuscular response represent distinct but complementary dimensions within athlete monitoring systems, requiring integrated interpretation rather than isolated analysis (Buchheit et al., 2026a; Buchheit et al., 2026b). A likely explanation is that football-related load primarily impairs stretch-shortening cycle efficiency, particularly the capacity to rapidly develop and transmit force following eccentric loading (Debenham et al., 2015; Blazevich & Babault, 2019).

Match exposure

The match exposure analysis demonstrated a clear dose-response relationship between match exposure duration and CMJ force-time responses. Elite match play imposes repeated eccentric braking actions, accelerations, decelerations, and high-intensity running demands, all of which are known to contribute to residual neuromuscular fatigue in the days after competition (Nedelec et al., 2012; Carling et al., 2018; Silva et al., 2018; Harper et al., 2019). The greatest impairments were observed between players exposed to >70 min and those exposed to <40 min of match play, characterized by prolonged contraction time and time to braking phase, alongside reductions in RSI modified, concentric mean force, early concentric impulse, and concentric peak force. These findings indicate that rapid force production is progressively impaired as playing time increases.

Importantly, the intermediate responses observed in the 40–70 min group further support a graded neuromuscular burden rather than a threshold effect occurring only after full-match exposure. Notably, jump height remained largely stable across all exposure comparisons despite substantial deterioration in force-time characteristics, indicating that performance outcome may be preserved even when underlying neuromuscular function is compromised.

GPS-derived accumulated load

The rolling 7-day load analysis adds an important mechanistic layer to this interpretation. Because this rolling 7-day window incorporated both training and match exposures, the observed associations likely reflect the combined neuromuscular cost of competition and subsequent training load. Greater rolling 7-day accumulated load, particularly higher sprint distance, sprint count, and high-intensity running exposure, was associated with reduced eccentric braking capacity, lower concentric force production, diminished early impulse generation, and prolonged contraction time. Together, these findings indicate impaired stretch-shortening cycle efficiency under sustained load accumulation, suggesting that players progressively lose the ability to rapidly absorb and generate force as weekly mechanical stress increases. In the present study, this was consistently reflected in reductions in RSI modified, early concentric impulse, concentric peak force, and eccentric braking impulse, whereas jump height remained comparatively unchanged.

A key observation is that contraction time increased consistently as cumulative load rose, indicating slower neuromuscular force production despite preserved jump outcome. This likely reflects residual neuromuscular strain resulting from repeated eccentric and high-speed locomotor demands across both training and match exposure. In contrast, jump height showed only trivial and inconsistent associations with load, reinforcing that it is a relatively insensitive marker of the true neuromuscular cost of weekly load accumulation.

These findings support the broader monitoring framework proposed by Marques and Chamari (2023) and Buchheit and Hader (2025), and further reinforced by Buchheit et al. (2026a), who emphasize that GPS-derived variables quantify external locomotor load rather than internal neuromuscular strain itself. In this context, the present findings demonstrate the importance of integrating GPS exposure metrics with CMJ force-time responses, as external load alone cannot fully explain the internal physiological strain imposed by training and match play.

Seasonal fluctuations

The seasonal heatmap demonstrates that CMJ force-time characteristics are substantially more responsive to longitudinal neuromuscular changes than jump height across the competitive season. Several force-time variables, particularly eccentric braking impulse, early concentric impulse, eccentric peak force, and RSI modified, showed marked positive elevations relative to Q1 baseline, especially during Q2 and Q3. These increases may reflect positive neuromuscular adaptation to repeated exposure to elite competition and training loads, potentially indicating improved stretch-shortening cycle efficiency and enhanced force transmission capacity during the middle phases of the season. Similarly, the reduction in contraction time may reflect altered force-production timing, potentially indicating improved movement efficiency or modified neuromuscular pacing as players adapt to repeated match demands.

An important finding is that these substantial seasonal fluctuations occurred despite jump height remaining largely unchanged. This reinforces the central concept of the study that athletes may maintain performance outcome while underlying movement strategies change considerably over time. From a monitoring perspective, this suggests that jump height alone is insufficient to detect the dynamic neuromuscular changes that occur throughout a season, whereas force-time variables provide a more sensitive reflection of both accumulated fatigue and adaptive responses to chronic training and competition demands.

Interpretation within current literature

The present findings align with previous literature showing that time- and strategy-related CMJ variables are more sensitive than jump height to detect neuromuscular fatigue (Gathercole et al., 2015; Lonergan et al., 2022; Bishop et al., 2023). Similar observations have been reported in elite Rugby Sevens players, where season-long exposure to training and competition resulted in substantial changes in kinetic and time-dependent CMJ variables, including contraction time, early impulse, and RSI modified, while jump height remained unchanged. These findings reinforce the concept that monitoring only traditional outcome measures may lead to misleading conclusions regarding neuromuscular status, whereas force-time analysis provides a more sensitive representation of both fatigue and adaptation. Metric selection should therefore depend on the purpose of testing, with force-time and timing-related variables being more appropriate for fatigue monitoring than outcome measures alone (Bishop et al., 2023). Although Mohr et al. (2025) reported post-match reductions in jump height in highly exposed players, the stable jump height observed in the present study, despite clear force-time alterations, suggests that jump height may inconsistently reflect underlying neuromuscular status.

A central concept emerging from these results is the dissociation between performance outcome and movement strategy. Jump height reflects what was achieved, whereas force-time metrics provide insight into how performance was produced. This distinction aligns with contemporary monitoring models in elite football, where external load measures describe imposed locomotor demand, while CMJ force-time variables reflect the athlete's internal neuromuscular response to that load (Buchheit et al., 2026a; Buchheit et al., 2026b). Together, these frameworks support the interpretation that force-time CMJ analysis provides a more biologically meaningful marker of neuromuscular status than performance outcome measures alone.

Applied implications

From an applied perspective, these findings support the use of CMJ force-time analysis as part of an integrated monitoring system in elite football. Metrics such as RSI modified, contraction time, early concentric impulse, concentric peak force, and eccentric braking impulse provide more meaningful information than jump height when the objective is to detect residual fatigue and guide recovery decisions. When interpreted alongside contextual information such as match exposure and external load, these variables can help practitioners make more informed decisions regarding readiness, loading, and return to high-intensity training. This integrated approach is consistent with recent neuromuscular monitoring frameworks emphasizing that internal response markers are essential because external load metrics alone cannot adequately characterize contractile fatigue or readiness status (Buchheit et al., 2026b).

A limitation of this study is that seasonal fluctuations were described descriptively relative to Q1 baseline and were not tested using inferential comparisons between quarters. These seasonal findings should therefore be interpreted as descriptive trends. Additionally, no biochemical or perceptual fatigue markers were included, limiting comparison between mechanical and physiological recovery responses.

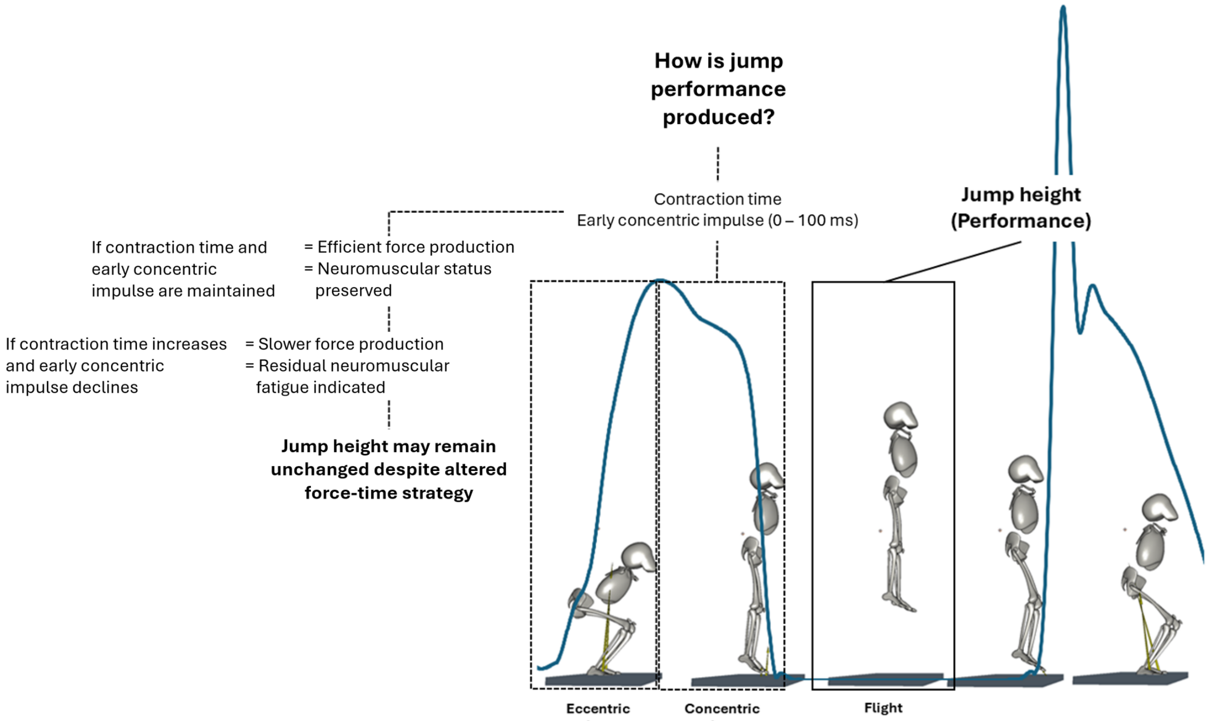

Fig. 6. Force-time pathway of CMJ performance, showing how early force production and concentric time determine jump outcome, and how compensatory strategies can maintain jump height despite neuromuscular fatigue.

Applied CMJ force-time interpretation framework

Figure 6 presents a simple, individualized framework that practitioners can use to interpret CMJ force-time responses beyond jump height alone when monitoring neuromuscular status. While jump height reflects the final performance outcome, force–time variables describe how performance is produced and are more sensitive to residual neuromuscular fatigue following match play. This framework can be used as a practical guide to support the identification of altered neuromuscular responses, even when performance outcome appears unchanged.

The left-hand side of the figure illustrates how jump performance is produced through the interaction of force-time variables that control rapid force generation. In the present study, contraction time, early concentric impulse, concentric peak force, and RSI modified were consistently sensitive to match exposure and accumulated load, indicating altered neuromuscular status even when jump height remained stable. From an applied perspective, this framework can be used to guide interpretation of CMJ monitoring data, helping practitioners identify slower force production and reduced impulse generation as indicators of residual neuromuscular fatigue. Importantly, it highlights that athletes may preserve jump height despite meaningful changes in the strategy used to generate performance, reinforcing the need to monitor how performance is achieved rather than relying on outcome alone.

Practical Applications

- Jump height alone is insufficient to detect residual neuromuscular fatigue 48 h post-match.
- RSI modified, early concentric impulse, and concentric peak force were approximately 2-4 times more sensitive than jump height, making them more suitable for detecting post-match neuromuscular changes.
- Greater match exposure (>70 min) induces the largest neuromuscular impairments and should prompt modified recovery and loading strategies within the subsequent 48-72 h.
- Rolling 7-day accumulated external load, particularly sprint-related metrics, should be interpreted alongside CMJ force-time variables to better identify residual neuromuscular strain.
- Monitoring how performance is achieved (force-time strategy) rather than relying on performance outcome alone provides a more accurate assessment of neuromuscular readiness.
- Integrating CMJ force-time analysis with locomotor load data provides a more complete picture of player status and may reduce the risk of false-negative readiness decisions.
- Individual force-time baselines may support more personalized interpretation of neuromuscular status in applied football settings.

Conflict of interest

The authors declare no competing interests.

References

1. Bishop C, Jordan M, Torres-Ronda L, Loturco I, Harry J, Virgile A, Mundy P, Turner A, Comfort P. Selecting Metrics That Matter: Comparing the Use of the Countermovement Jump for Performance Profiling, Neuromuscular Fatigue Monitoring, and Injury Rehabilitation Testing. Strength Cond J. 2023; 45:545-553.

2. Buchheit M, Hader K. Data everywhere, insight nowhere: a practical quadrant-based model for monitoring training load vs. response in elite football. Sport Perf & Science Reports. #258, May 2025.

3. Buchheit M, Lopez Sagarra A, Boskovic A, Komino P, Norman D, Hader K. GPS 3.0: from distance into zones toward better proxies of internal neuromuscular load in elite football. Sport Perf & Science Reports. #280, Feb 2026a.

4. Buchheit M, Barba Balda E, Lopez Sagarra A, Carruthers T, Ogden A, Marques J, Hader K, Millet GY. Monitoring low-frequency fatigue during return-to-play in elite football: physiological basis and a four-case series. Sport Perf & Science Reports. #289, Apr 2026b.

5. Blazevich AJ, Babault N. Post-activation Potentiation Versus Post-activation Performance Enhancement in Humans: Historical Perspective, Underlying Mechanisms, and Current Issues. Front Physiol. 2019; 10:1359.

6. Carling C, Lacome M, McCall A, Dupont G, Le Gall F, Simpson B, Buchheit M. Monitoring of Post-match Fatigue in Professional Soccer: Welcome to the Real World. Sports Med. 2018; 48:2695-2702.

7. Debenham J, Travers M, Gibson W, Campbell A, Allison G. Eccentric fatigue modulates stretch-shortening cycle effectiveness - a possible role in lower limb overuse injuries. Int J Sports Med. 2015; 37:50-55.

8. Gathercole R, Sporer B, Stellingwerff T. Countermovement Jump Performance with Increased Training Loads in Elite Female Rugby Athletes. Int J Sports Med. 2015; 36:722-8.

9. Harper DJ, Carling C, Kiely J. High-Intensity Acceleration and Deceleration Demands in Elite Team Sports Competitive Match Play: A Systematic Review and Meta-Analysis of Observational Studies. Sports Med. 2019; 49:1923-1947.

10. Lonergan B, Price P, Lazarczuk SL, Howarth DJ, & Cohen DD. A comparison of countermovement jump performance and kinetics at the start and end of an international Rugby Sevens season. The Journal of Sport and Exercise Science, 2022; 6:79–89.

11. Marques J, Chamari K. Performance Management in Elite Football: A Teamwork Modeling Approach. Int J Sports Physiol Perform. 2023; 18:371-1373.

12. Mohr P.A, Bishop C, Pupo J.D. Variation in countermovement jump metrics following competitive soccer matches throughout a season in professional players. Sport Sci Health. 2025; 21:3051-3059.

13. Nedelec M, McCall A, Carling C, Legall F, Berthoin S, Dupont G. Recovery in Soccer: Part I-post-match fatigue and time course of recovery. Sports Med. 2012; 42:997-1015.

14. Silva JR, Rumpf MC, Hertzog M, Castagna C, Farooq A, Girard O et al. Acute and residual soccer match-related fatigue: a systematic review and meta-analysis. Sports Med. 2018; 48:539-583.