Monitoring low-frequency fatigue during return-to-play in elite football: physiological basis and a four-case series

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Headline

Training monitoring practices in healthy and injured players often prioritize the quantification of training load, while biological responses and adaptations are less consistently assessed (Buchheit & Hader 2025). The four-quadrant framework proposed by Buchheit and Hader separates monitoring by purpose (load vs response/adaptation) and by biological system (metabolic vs neuromuscular), providing a practical structure to align monitoring tools with their intended function. Within this framework, low-frequency fatigue (LFF), also known as prolonged low-frequency force depression (PLFFD), is conceptualised as an internal neuromuscular response marker derived from electrical stimulation and force sensing (Ridard et al., 2022; Tito et al., 2025; Timbert et al., 2023; Reimann et al., 2024). This distinction is critical as internal neuromuscular load remains difficult to quantify directly, and decision-making during rehabilitation and return-to-play requires system-specific response markers that reflect contractile function rather than external outputs alone (e.g., work done on pitch, strength assessment).

Aim

This paper integrates a mechanistic understanding of LFF with applied monitoring during rehabilitation in elite football. It aims to describe how LFF develops across return-to-play programs and how its time course relates to variations in training content, including on-pitch exposure and gym-based sessions.

Conceptual framework for monitoring

The quadrant framework shown in Figure 1 differentiates between training load (the imposed stimulus) and the athlete's response and adaptation (the biological output). This separation is required to operationalise dose–response relationships and to inform programming decisions beyond simple exposure quantification. The second axis distinguishes metabolic from neuromuscular domains, with the later encompassing muscle and tendon activity or strain and overall structural load.

Within this framework, objective internal neuromuscular response options remain limited. Typical internal measures include creatine kinase and thermography (Buchheit & Hader, 2025). However, creatine kinase is invasive and cost-intensive, while thermography reflects surface temperature changes rather than contractile function per se. Consequently, the most common fatigue-relevant alternatives rely on external performance proxies, including jump tests on force plates (Cohen 2026, Tito et al. 2025) or barbell velocity during standardised resistance exercise (Reyes-Laredo 2024).

Although these approaches provide useful information, they require maximal effort, precise scheduling, and player buy-in, and they add task demands within already constrained training timelines. In contrast, LFF, provides a direct index of contractile impairment based on electrical stimulation and force measurements (Ridard et al., 2022; Tito et al., 2025; Timbert et al., 2023; Reimann et al., 2024; Buchheit & Laursen, 2026). It is described as a valid marker for short-term fatigue and longer-term adaptation (Ridard et al., 2022; Tito et al., 2025), with the practical advantage of being passive (Tito et al., 2025; Timbert et al., 2023; Buchheit & Laursen, 2026), i.e. not dependent on the player's motivation. Nonetheless, its current implementation remains limited by cost and by predominant validation in the quadriceps, highlighting both its applied potential and present methodological constraints (Buchheit & Hader, 2025).

Mechanisms and definition of low-frequency fatigue

The term fatigue is polymorphic and requires an operational definition because it can reflect subjective feelings as well as central, peripheral, metabolic, and mechanical processes (Enoka & Stuart, 1992; Gandevia, 2001; Enoka & Duchateau, 2016; Millet & Lepers, 2004; Millet, 2011; Millet et al., 2011). In applied physiology, neuromuscular fatigue, also known as objective or performance fatigability, is often defined as an exercise-induced reduction in maximal force or power generating capacity (Enoka & Stuart, 1992; Enoka & Duchateau, 2008; Millet & Lepers, 2004), although force and power decrement are not equivalent (Krüger et al. 2019). This reduction can originate from central mechanisms that reduce motor-unit recruitment or dischargrate, and from peripheral mechanisms within muscle fibres that reduce force for a given neural drive (Enoka & Stuart, 1992; Gandevia, 2001; Fitts, 1994; Millet & Lepers, 2004; Millet et al., 2011; Martin et al., 2010).

Low-frequency fatigue refers to a preferential loss of evoked force at low stimulation frequencies relative to higher frequencies, reflecting a rightward shift of the force–frequency relationship (Jones, 1996; Martin et al., 2004; Lattier et al., 2004).

This pattern is most consistently linked to impaired excitation–contraction coupling, primarily via reduced Ca^{2+} release from the sarcoplasmic reticulum, which reduces Ca^{2+} binding to troponin, limits cross-bridge formation, and depresses force production (Jones, 1996; Favero, 1999; Allen et al., 2008; Lattier et al., 2004; Millet et al., 2011). In certain occasions (i.e. following eccentric contractions), the long-lasting nature of this component, which can persist for hours to days, is of applied interest during return-to-play because it provides an objective marker of delayed recovery and residual peripheral contractile impairment as training content and intensity are progressively reintroduced, including gym-based strength work and on-pitch running exposures (Jones, 1996; Enoka & Duchateau, 2016; Millet & Lepers, 2004; Lattier et al., 2004).

In practice, LFF is typically assessed using electrically evoked contractions, either nerve or muscle stimulation, combined with mechanical output measurement (Tito et al., 2025; Timbert et al., 2023; Reimann et al., 2024; Strepp et al., 2024; Ridard et al., 2022). In this paper, we use an applied stimulation-based monitoring approach integrated within our environment to characterise the peripheral component of fatigue related to excitation–contraction coupling (Jones, 1996; Favero, 1999; Allen et al., 2008; Millet et al., 2011). A full description of the device, stimulation parameters, and testing procedure is provided in the following section. Here, the key point is that the approach captures a local, peripheral signature of knee extensors fatigue, derived from evoked responses rather than a direct measure of whole-body performance capacity (Enoka & Duchateau, 2016; Millet, 2011). Field data indicate that the magnitude and recovery kinetics of the low- versus high-frequency force ratio differ across strength, sprint, and endurance exposures, supporting a mechanism-specific expression of fatigue (Reimann et al., 2024; Buchheit & Laursen, 2026).

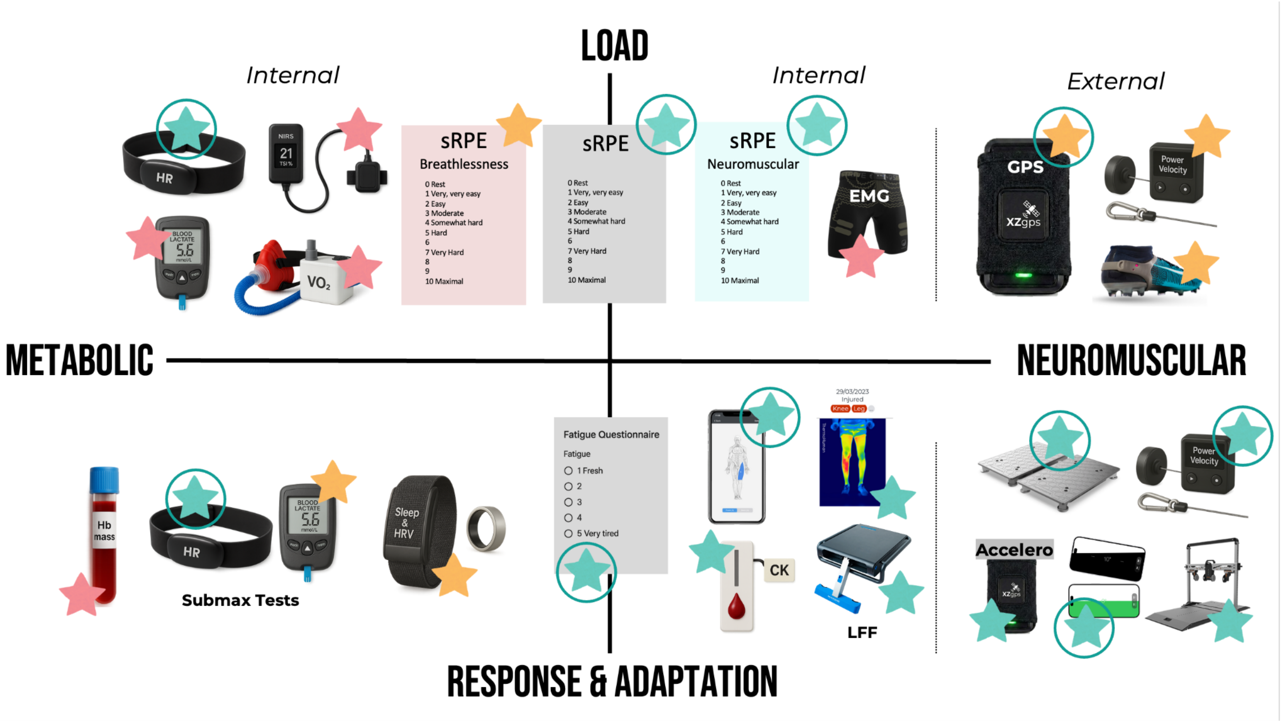


Fig. 1. **Tools available are mapped according to the quadrant-based monitoring framework that distinguishes load from response and metabolic from neuromuscular domains. GPS stands in the upper right quadrant as (only) a proxy of neuromuscular load. The colour of the stars reflects a combination of validity, practicality, and cost, ranging from green (ideal) to red (impractical and/or limited) (for more explanations, see Tables 2–5 in Buchheit & Hader 2025). Stars with a circle indicate the recommended practical minimum setup. Non-biological system-specific subjective ratings such as sRPE (load) and sleep, fatigue, mood, or recovery (response) are positioned between quadrants, as they likely reflect, influence or are associated with both metabolic and neuromuscular domains. While sleep is neither a direct metabolic nor neuromuscular response, it serves as both an indicator of overall wellness and a modulator of training response. Poor sleep is typically associated with increased fatigue and reduced training quality, which can ultimately affect the magnitude and direction of adaptation. ADI: athletic data innovation (`https://www.adi-data.co/`), CK: creatine phosphokinase, EMG: electromyography, GPS: global positioning system, Hbmass: hemoglobin mass, HR: heart rate, HRV: heart rate variability, LFF: low-frequency fatigue (combination of electrical stimulation and force sensing to measure low-frequency fatigue), NIRS: near-infrared spectroscopy, sRPE: session rating of perceived exertion, SMFT: submaximal fitness testing, SSG: small-sided games, VO_2: oxygen uptake. Reproduced from Buchheit & Hader 2025.**

Physiological and interpretive limitations

Low-frequency fatigue is muscle-specific and protocol-dependent, with its interpretation influenced by the tested muscle group, contraction mode, joint configuration, and stimulation parameters (Enoka & Duchateau, 2016; Allen et al., 2008; Millet et al., 2011). In applied football settings, stimulation-based monitoring is commonly implemented in the quadriceps under isometric conditions due to feasibility and standardisation, but this also narrows inference (Tito et al., 2025; Timbert et al., 2023; Reimann et al., 2024; Strepp et al., 2024; Ridard et al., 2022). While such assessments provide a controlled measure of local contractile function, they do not directly reflect the readiness of other muscle groups or the integrated neuromuscular coordination required in football actions (Enoka & Duchateau, 2016; Millet, 2011). Importantly, low-frequency fatigue may persist even when maximal voluntary force has returned to baseline, which supports its use to detect residual peripheral contractile impairment that may not be apparent from MVC alone. In addition, because the primary outcome is a low-to-high frequency ratio, the measure is less sensitive than absolute force to small day-to-day differences in electrode placement, which improves practicality in routine monitoring.

Electrical stimulation methods can quantify multiple components of neuromuscular function depending on the protocol, including voluntary activation and central contributions when twitch interpolation is applied (Gandevia, 2001; Enoka & Stuart, 1992; Millet et al., 2011; Millet & Lepers, 2004). The present focus is restricted to the low-frequency component as a peripheral marker associated with excitation–contraction coupling, and it should not be interpreted as a comprehensive index of global or functional fatigue (Enoka & Duchateau, 2016; Enoka & Duchateau, 2008; Millet, 2011). Extrapolation from a local signal to systemic fatigue or match readiness remains uncertain, and any link between a single local marker and injury risk should be treated cautiously given the non-linear and multifactorial nature of injury processes, including cumulative load, adaptive reserve, and delayed effects (Kalkhoven 2021). Accordingly, LFF should be interpreted within a broader monitoring framework that integrates training content, external load, internal load, clinical status, pain, and movement reconditioning, rather than used as a standalone proxy for readiness (Buchheit & Hader 2025).

Rehabilitation case series in elite footballers

Study design

This retrospective four-case series describes the time course of LFF during return-to-play rehabilitation in elite football. This manuscript was prepared in accordance with CARE case report/case series reporting principles (Gagnier et al., 2013; Díaz Ibarra et al., 2023).

Cases and setting

We report four clinical cases from routine return-to-play practice (Age: 24.5 ± 5.2 y; body weight: 79.4 ± 8.5 kg; body height: 181 ± 7.4 cm). Cases were identified retrospectively because complete datasets were available for (i) repeated LFF assessments, (ii) detailed daily training documentation, and (iii) aligned GPS and heart-rate data when applicable. Injuries represented three rehabilitation contexts: anterior cruciate ligament reconstruction (ACL), rectus femoris injury, and hamstring injury (two cases). Monitoring was conducted as part of routine rehabilitation and return to performance support practice.

Ethics and consent

This retrospective case series used routinely collected athlete monitoring data. All players provided written informed consent for the use of their monitoring data for research purposes. Data were anonymised prior to analysis and procedures adhered to institutional governance for secondary use of athlete monitoring data.

Rehabilitation process and training content classification

Rehabilitation was documented using daily staff records and categorised by session context to support dose–response interpretation. Training exposure was classified as gym-based rehabilitation or strength training, on-pitch rehabilitation, and integrated team training when applicable. Where available, session objectives and key elements were extracted from staff records, including emphasis on strength or power development, running reconditioning, change-of-direction exposure, and sprint exposure. Key rehabilitation milestones were recorded to contextualise longitudinal trajectories, including initiation of running, introduction of high-speed running, integration into team drills, clearance for full training, and match availability. Milestones followed our internal return-to-play criteria and were applied consistently within each case.

Low-frequency fatigue assessment

Low-frequency fatigue was assessed using an electrically evoked contractile assessment system (Myocene, Liège, Belgium, Figure 2) as part of our routine monitoring (Tito et al., 2025; Timbert et al., 2023; Reimann et al., 2024; Strepp et al., 2024; Ridard et al., 2022). Published protocols typically use a single pulse plus low-frequency (10 to 20 Hz) and high-frequency (80 to 120 Hz) stimulus trains delivered in repeated sets with stepwise increases in current, with electrodes placed over the quadriceps heads (Tito et al., 2025; Timbert et al., 2023). The assessment combines electrical stimulation with mechanical output measurement to quantify contractile function and the preferential reduction in evoked response at low stimulation frequencies relative to high frequencies (Tito et al., 2025; Timbert et al., 2023; Reimann et al., 2024; Strepp et al., 2024). Overall, the device delivers a fatigue index named Powerdex. It is computed as the median value of a set 12 ratios of force responses to low-frequency vs high-frequency stimulations, each of them corresponding to an increasing stimulation intensity. This approach was selected because it provides a passive, local marker of peripheral electromechanical function that can be repeated frequently without adding physical load to the athlete.

Validity

Field validity of the approach has been supported by Ridard et al. (2022), who compared the Myocene-derived low- to high-frequency force ratio (Powerdex) to a laboratory reference based on femoral nerve stimulation, expressed as the ratio of evoked force produced by a low-frequency doublet burst at 10 Hz to a high-frequency doublet burst at 100 Hz (DB10/DB100), before and after a strenuous eccentric protocol (repeated drop jumps). Powerdex decreased after the fatiguing task and the magnitude of change did not differ substantially from the laboratory DB10/DB100 change when expressed relative to baseline, with a strong correlation between methods ($r = 0.82$), supporting the ability of the portable system to detect low-frequency fatigue similarly to the laboratory technique.

In this applied setting, testing was performed on the quadriceps in a standardised isometric configuration to maximise feasibility and repeatability across repeated measurements (Tito et al., 2025; Timbert et al., 2023; Reimann et al., 2024; Strepp et al., 2024). This muscle-specific approach was used to track within-player changes over time and was not intended to represent whole-body fatigue.

Reliability

Under field conditions, Bernard et al. (2023) examined repeatability (two consecutive measures separated by 7 min) and reported limits of agreement consistent with a typical uncertainty of approximately ±3%, and concluded that a Powerdex depression of at least 3% is required to infer the onset of low-frequency fatigue beyond measurement noise under their repeatability conditions. Reproducibility across time-of-day showed wider limits of agreement (approximately -7% to +9%), suggesting that day-to-day activities and time-dependent potentiation or fatigue effects can contribute to additional variability and should be controlled where possible in applied monitoring. Test–retest reliability has also been examined in recent work by Maia and colleagues (2025), who assessed cross-condition reliability of Myocene-derived low-frequency fatigue in youth elite soccer players, with coefficients of variation of 4.1% and 3.4%, and ICCs of 0.62 and 0.75 for dominant and non-dominant limbs, respectively. However, the absence of an intra-day and inter-day reliability study across multiple days and operators in elite football remains a limitation for defining universal smallest detectable changes under applied conditions.

In the present case series, changes were interpreted relative to these reported reliability bounds, with emphasis on (i) within-limb changes exceeding approximately 6% (i.e., 2x the error) as a conservative minimum for a likely real change under controlled repeatability conditions, and (ii) the broader potential influence of intervening activities and time-dependent factors when interpreting smaller fluctuations, noting that circadian (time-of-day) effects have been reported more consistently for maximal force outputs than for low-to-high frequency ratios.

Fig. 2. Low-frequency fatigue assessment setup. A player seated in the standardised testing position during neuromuscular assessment using an electrically evoked quadriceps LFF protocol. Self-adhesive stimulation electrodes are placed bilaterally over the quadriceps, with mechanical output recorded during the stimulation sequence.

Timing and frequency of assessment

Players were assessed/monitored daily on arrival to the training facility to provide a baseline under consistent pre-training conditions. Additional assessments were conducted immediately post-session (within ≈5 min of session completion) to characterise acute neuromuscular responses to gym-based or on-pitch exposure. On days with multiple sessions, post-session measures were linked to the associated training exposure using timestamps and staff logs.

Standardisation and quality control

Assessments were standardised within players over time and performed using the same limb position and fixation setup at each test. Testing was scheduled at a consistent time of day within each player when feasible, with a standardised pre-test preparation period including a 2-min seated rest. Electrode placement was documented and reproduced across sessions, and joint angle and fixation were standardised to minimise movement artefact (Tito et al. 2025). Trials were repeated immediately if a technical artefact or poor signal quality was identified by the operator. The same device and configuration were used for all tests within a given player. The primary LFF outcome was derived from the relative evoked response at low versus high stimulation frequencies, reported as an index or ratio according to device output (Tito et al., 2025; Timbert et al., 2023; Reimann et al., 2024; Strepp et al., 2024).

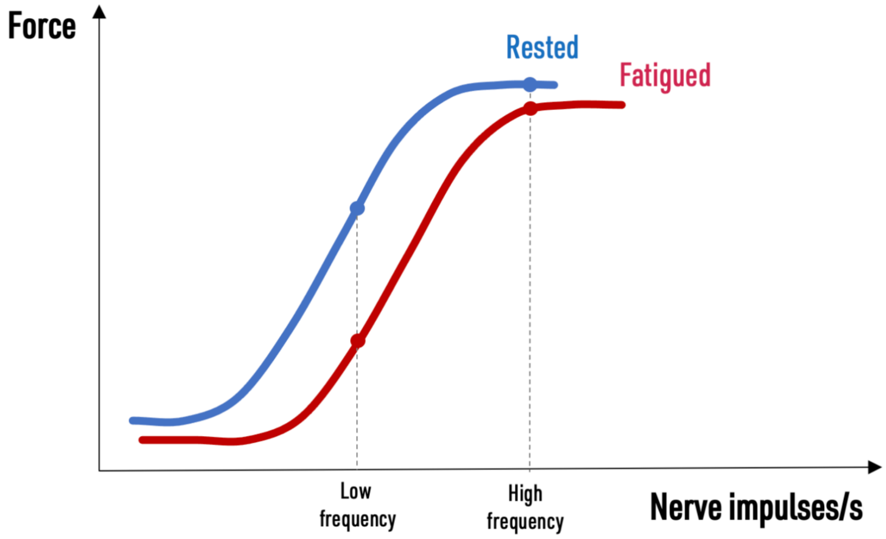


Fig. 3. Force–frequency relationship and low-frequency fatigue. Conceptual force–frequency curves for rested (blue) and fatigued (red) muscle. Following fatiguing exercise, force is reduced across stimulation frequencies, but the reduction is disproportionally greater at low stimulation frequencies than at high frequencies, reflecting a rightward shift of the force–frequency relationship and the characteristic signature of low-frequency fatigue. The time course of recovery depends on the underlying mechanism: when the low-frequency force depression is primarily driven by inorganic phosphate (Pi)-related effects on Ca^{2+} release and myofibrillar sensitivity, recovery can be relatively rapid, whereas longer-lasting low-frequency fatigue is typically associated with more persistent excitation–contraction coupling impairment.

Training load and contextual monitoring

To support dose–response interpretation, daily training load and contextual information were compiled alongside LFF assessments. All data streams were time-stamped and aligned to the corresponding training day and, where relevant, to the specific session associated with the post-session LFF assessment. While the quadrant framework emphasises that monitoring should also include subjective ratings, such as session-RPE to characterise internal load and wellness measures to capture global response (Buchheit & Hader, 2025), these variables were omitted here because they were not recorded consistently across the four cases.

Training contents

Both off- and on-pitch training sessions were documented using staff records and training logs. Where available, extracted descriptors included the session type and its primary focus. Session types included lower- or upper-body strength training, motor control, running mechanics, recovery, sport-specific field-based sessions, and off-pitch metabolic conditioning. Motor control comprised targeted exercises addressing specific muscle groups and movement patterns of the hip, ankle, and trunk stabilisers based on the individual needs identified during player assessment. Running mechanics referred to indoor gym-based work targeting sprint and acceleration mechanics according to the main limiting factors identified during evaluation. Recovery sessions included passive strategies selected according to player preference, such as massage, mobility work, compression boots, and cold- or hot-water immersion. Sport-specific sessions consisted of on-pitch work integrating the ball with movement patterns and actions specific to the player's position. Off-pitch metabolic conditioning refers to metabolic training performed without involving the injured segment. The main focus of each session was also recorded and included maximal strength, hypertrophy, tissue capacity, acceleration work, or technical work.

External mechanical work

On-pitch external load was monitored using GPS during each field-based session (Statsports, Northern Ireland, United Kingdom). Running-mechanics sessions were performed indoors and were therefore not monitored with GPS. Variables extracted for analysis were those routinely used and recorded at the session level, including session duration, total distance (TD; m), high-speed running (HSR; m) and sprint distance (m) using club-defined speed thresholds, high intensity acceleration and deceleration counts (#Acc and #Dec) and magnitudes (Max Acc and Max Dec; $m{\cdot}s^{-2}$), and Top speed ($km{\cdot}h^{-1}$). Additionally, mechanical work thigh (MWthigh) and mechanical work stride (MWstride) were included as GPS 3.0 variables (Buchheit, Sagarra et al., 2026). Intensity Exposure Time (IET) was also quantified and defined as the time spent above 80% of the 1-min Most Intense Period (MIP) achieved during match play for total distance (T>80% TD; min), acceleration and deceleration counts (T>80% #Acc&Dec; min), high-speed running (T>80% HSR; min), and mechanical work (T>80% MW; min). Given the mechanistic link between LFF and peripheral electromechanical function, interpretation prioritised mechanical-intensity exposure metrics (MWstride, MWthigh, and IET-derived T>80% variables) over volume-only descriptors (TD and distance-in-zones) when explaining session-to-session changes in Powerdex.

Metabolic load

Internal load was monitored using heart rate (HR, Statsports, Northern Ireland, United Kingdom) during on-pitch and metabolically-oriented off-pitch training sessions. Variables extracted included mean and peak HR, time accumulated within predefined HR intensity zones (i.e., > 85% maximal heart rate; T>85 HR; min) (Buchheit, Akubat et al.

2025). When an individual maximal HR value was not available or not transmitted by the player's club, maximal HR was estimated using the age-predicted equation 220 - age.

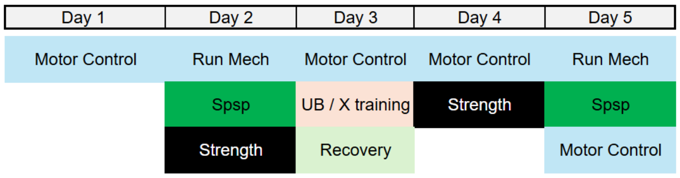
Analysis

Given the case-series design, analysis was descriptive and focused on within-player changes over time. LFF values were summarised relative to each player's early rehabilitation baseline and reported as absolute values and percentage change where appropriate. Acute session-response patterns were examined by comparing pre-session baseline with immediate post-session values, and short-term recovery was examined using next-day baseline values following specific training exposures. Where data density allowed, simple within-player smoothing or rolling summaries were used for visualisation, with raw values retained to ensure transparency.

Case 1

An 18-year-old female professional football player competing in the French First Division and representing the national youth team. She was a midfielder and entered the return-to-play programme at 6 months after a left ACL reconstruction.

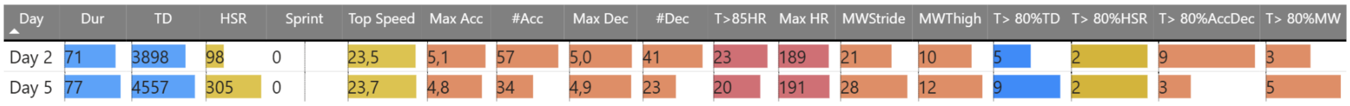
Table 1. Rehabilitation training content plan for Case 1. Overview of the 5-day return-to-play microcycle showing the planned daily sequence of rehabilitation components, including running mechanics (Run Mech), motor control, sport-specific football pitch work (SpSp), strength training, upper-body training, recovery sessions, and an off day (OFF).



Day 1	Day 2	Day 3	Day 4	Day 5
Motor Control	Run Mech	Motor Control	Motor Control	Run Mech
	Spsp	UB / X training	Strength	Spsp
	Strength	Recovery		Motor Control

Fig. 4. Time course of quadriceps LFF and inter-limb asymmetry during return-to-play monitoring for case 1. The operated knee was the left limb. Upper panel shows bilateral low-frequency fatigue output (Powerdex, A.U.) assessed at standardised time points across consecutive rehabilitation days, including pre-session baseline (PRE) and immediate post-session assessments (e.g., post sport-specific pitch work, post strength, post motor control, and post nap where applicable). The lower panel shows inter-limb fatigue asymmetry (%) derived from bilateral Powerdex values, with positive values indicating greater fatigue on the right limb and negative values indicating greater fatigue on the left limb.

Table 2. GPS workload data per sport-specific football pitch session for Case 1. Each Day corresponds to the rehabilitation training day described in the Rehabilitation Training Content Plan. Dur, duration (min); TD, total distance (m); HSR, high-speed running distance over 19.8 km·h^{-1} (m); Sprint, sprint distance (m) over 25.5 km·h^{-1}; Top Speed (km·h^{-1}), Max Acc, maximal acceleration (m·s^{-2}); #Acc, number of accelerations over 3 m·s^{-2}; Max Dec, maximal deceleration (m·s^{-2}); #Dec, number of decelerations over 3 m·s^{-2}; T>85HR, time spent >85% maximal heart rate (min); Max HR, maximal heart rate (#beats·min^{-1}); MWStride, stride mechanical work; MWThigh, thigh mechanical work; T>80%; time spent >80% of the individual 1-min MIP per variable.



Day	Dur	TD	HSR	Sprint	Top Speed	Max Acc	#Acc	Max Dec	#Dec	T>85HR	Max HR	MWStride	MWThigh	T> 80%TD	T> 80%HSR	T> 80%AccDec	T> 80%MW
Day 2	71	3898	98	0	23,5	5,1	57	5,0	41	23	189	21	10	5	2	9	3
Day 5	77	4557	305	0	23,7	4,8	34	4,9	23	20	191	28	12	9	2	3	5

Across the 5-day return-to-play microcycle (Table 1), quadriceps LFF assessed by Powerdex showed a stable bilateral profile with small inter-limb differences and a predominant pattern of session-specific perturbations followed by rapid restoration (Figure 4). This case is presented first because the injury context aligns directly with the tested muscle group, facilitating interpretation of limb-level neuromuscular status during return-to-play. Baseline values remained high across the block (approximately mid-70s to low-80s A.U.), and inter-limb asymmetry fluctuated around zero with brief, exposure-dependent deviations (Figure 4). The player had already been completing football pitch-based rehabilitation for approximately one month prior to this monitoring period, and the sessions reported here therefore represent continued progression rather than initial re-exposure to running.

Day 1 served as a reference day. Powerdex values were stable from the pre-session to post-session time point following motor control work, with minimal within-day change in either limb (Figure 4). Day 2 was the first clear stress-response day. Following sport-specific football pitch work, Powerdex decreased markedly, with the largest decrement observed in the operated left limb (Figure 4). This response coincided with a pitch exposure characterised by a high mechanical-intensity signature, with elevated acceleration–deceleration demands and, importantly, high MWthigh and IET-derived T>80% exposures, consistent with intense quadriceps-dominant braking and re-acceleration load on the operated limb (57 accelerations >3 m·s^{-2}, 41 decelerations >3 m·s^{-2}, 9 min >T80 Accel/Dec; Table 2). Given the substantial quadriceps demand associated with repeated acceleration and braking actions, this content profile provides a plausible explanation for why the operated limb showed a larger acute suppression, suggesting that the limb was not yet fully tolerant to this specific mechanical loading pattern despite prior pitch exposure. The subsequent post-strength assessment the same day showed recovery toward pre-session values, with near-normalisation of inter-limb asymmetry (Figure 4), indicating an acute perturbation rather than sustained impairment.

Day 3 and Day 4 were characterised by smaller fluctuations. On Day 3, motor control exposure was associated with a modest reduction in Powerdex, more evident on the right limb, producing a transient shift in asymmetry (Figure 4). On Day 4, Powerdex remained stable across the day, with pre-strength and post-strength measures showing minimal change and persistent near-symmetry (Figure 4). These two days support preserved tolerance to lower neuromuscular stressors and gym-based loading within the observed monitoring resolution.

Day 5 provided the most clinically informative contrast within the block. Following sport-specific football pitch work, Powerdex decreased only slightly in both limbs (Figure 4) despite this being the highest overall external and internal load session (77 vs 71 min, 4557 m vs 3898 total distance, 305 m vs 98 m HSR >5.5 m·s^{-1}, total MW 40 vs 31 Kj; Table 2). However, despite higher overall load, the session appeared less quadriceps-targeted based on a lower mechanical-intensity signature (reduced T>80% time for acceleration–deceleration and mechanical work, 34 accelerations >3 m·s^{-2} and 23 decelerations >3 m·s^{-1}; Table 2), which is consistent with the smaller acute Powerdex decrement in the operated limb.

This dissociation, with better tolerance of a session that was globally harder but less dominated by acceleration–deceleration demands, suggests that the operated limb's neuromuscular limitation was more specific to quad-dominant braking and re-acceleration actions than to high-speed running volume per se. After the pitch session, a nap occurred before the next assessment (Table 1). Powerdex increased markedly after the nap, exceeding the pre-session values (Figure 4), and was followed by a subsequent post-motor control measure later that day showing a return toward the earlier baseline range (Figure 4). While causality cannot be inferred, and the explanations are unclear, the within-day improvement after the nap suggests that short recovery opportunities can materially influence contractile status and therefore should be documented as a confounder when interpreting within-day dose–response.

At discharge on Day 5, the player demonstrated high baseline quadriceps LFF, minimal persistent inter-limb asymmetry, and rapid restoration after session-related perturbations, including after the highest-load football pitch exposure of the monitoring period (Figure 4; Table 2).

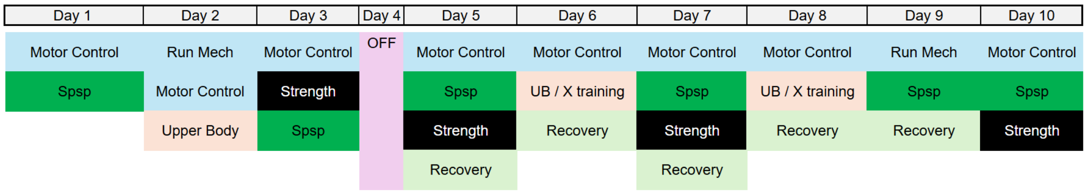
The most striking finding was that the operated left limb showed its largest acute suppression after the pitch session with the highest acceleration–deceleration density, while the subsequent pitch session with higher overall load but lower acceleration–deceleration demands was better tolerated. This pattern supports a status consistent with successful progression at this stage of ACL return-to-play, while indicating that continued exposure should prioritise graded development of acceleration and braking tolerance, with close monitoring of the operated limb response.

Case 2

A 26-year-old male professional football player, a central defender competing for a French First Division and UEFA Champions League club and representing his national team. He entered the return-to-play programme 3 weeks after myotendinous junction of the right rectus femoris with partial involvement of the indirect tendon.

Across this case, LFF was only monitored during Days 7–10 of the rehabilitation microcycle (Figure 5). Interpretation should therefore be restricted to the dose–response relationships observed across these four days, using the pitch-session GPS metrics reported in Table 4 to contextualise acute fatigability (PRE-to-post change) and tolerance to repeated load (next-day baseline restoration). Day 7 provided the clearest "high fatigability" response within the monitoring window. Following sport-specific football pitch work, Powerdex decreased markedly from PRE to post-session in both limbs, with a larger decrement on the right limb and a concomitant increase in inter-limb asymmetry (Figure 5). This occurred during a high-intensity exposure characterised by substantial high-speed and sprint demands (HSR 558 m; sprint 23 m; top speed 27.8 km·h^{-1}) and elevated mechanical-intensity indices (MWstride 19; MWthigh 13; T>80%TD 12; T>80%HSR 10; T>80%AccDec 12; T>80%MW 11) (Table 4). The persistence of asymmetry after the subsequent strength session on the same day suggests that the neuromuscular cost was not confined to the immediate post-pitch measurement and may reflect an exposure that exceeded the injured limb's current tolerance.

Table 3. Rehabilitation training content plan for Case 2. Overview of the 5-day return-to-play microcycle showing the planned daily sequence of rehabilitation components, including running mechanics (Run Mech), motor control, sport-specific football pitch work (SpSp), strength training, upper-body training, recovery sessions, and an off day (OFF).



Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10
Motor Control	Run Mech	Motor Control	OFF	Motor Control	Motor Control	Motor Control	Motor Control	Run Mech	Motor Control
Spsp	Motor Control	Strength		Spsp	UB / X training	Spsp	UB / X training	Spsp	Spsp
	Upper Body	Spsp		Strength	Recovery	Strength	Recovery	Recovery	Strength
				Recovery		Recovery			

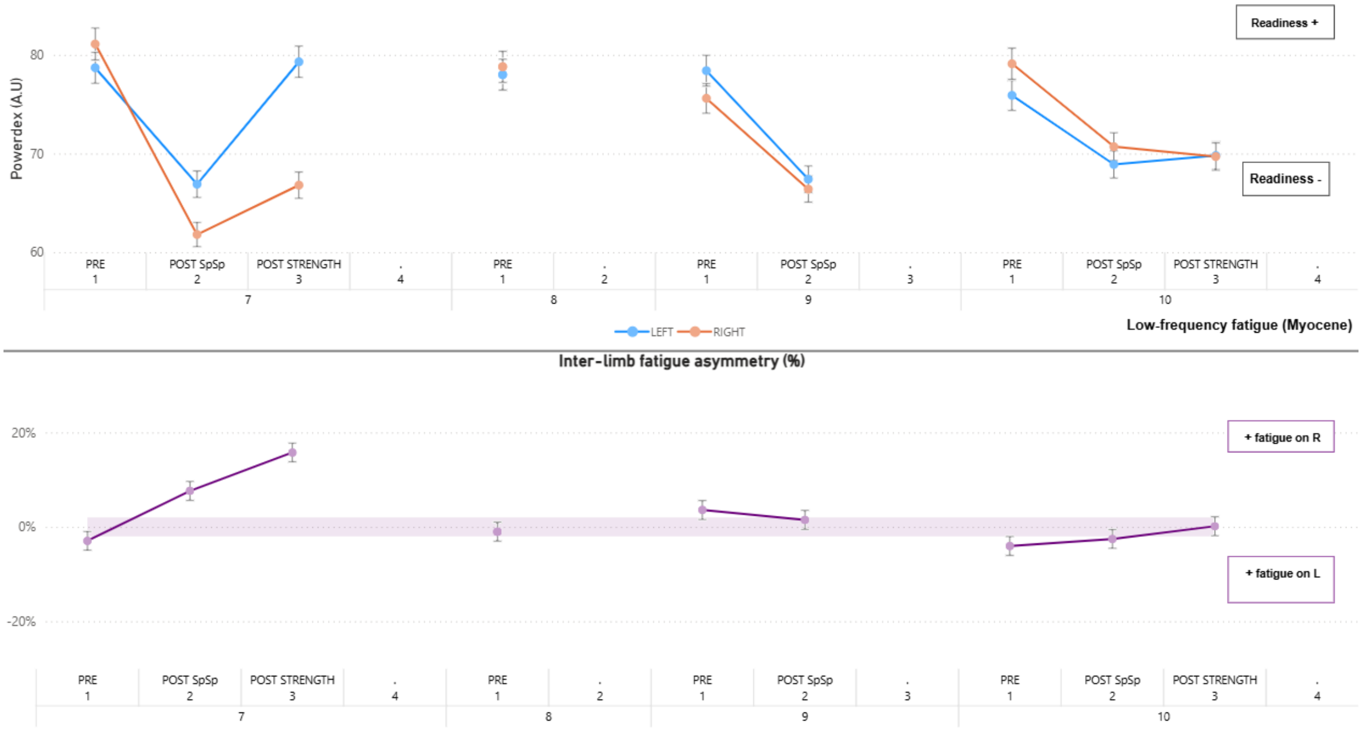
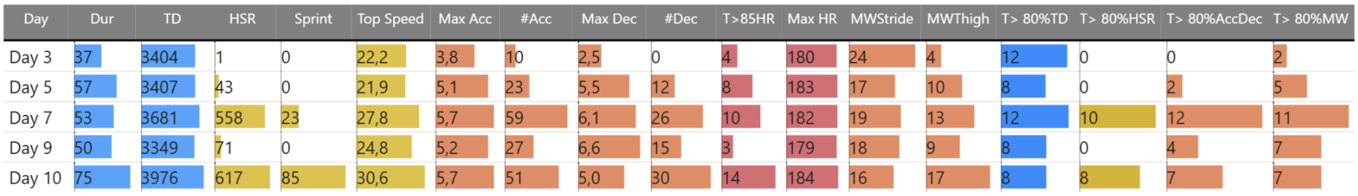


Fig. 5. Time course of quadriceps LFF and inter-limb asymmetry during return-to-play monitoring for case 2. Note that LFF was only monitored during the 4 last days of the rehabilitation i.e., days 7 to 10). Upper panel shows bilateral low-frequency fatigue output (Powerdex, A.U.) assessed at standardised time points across consecutive rehabilitation days, including pre-session baseline (PRE) and immediate post-session assessments (e.g., post sport-specific pitch work or post strength). Lower panel shows inter-limb fatigue asymmetry (%) derived from bilateral Powerdex values, with positive values indicating greater fatigue on the right limb and negative values indicating greater fatigue on the left limb.

Table 4. GPS workload data per sport-specific football pitch session for Case 2. Each Day corresponds to the rehabilitation training day described in Table 3. Dur, duration (min); TD, total distance (m); HSR, high-speed running distance over 19.8 km·h^{-1} (m); Sprint, sprint distance (m) over 25.5 km·h^{-1}; Top Speed (km·h^{-1}), Max Acc, maximal acceleration (m·s^{-2}); #Acc, number of accelerations over 3 m·s^{-2}; Max Dec, maximal deceleration (m·s^{-2}); #Dec, number of decelerations over 3 m·s^{-2}; T>85HR, time spent >85% maximal heart rate (min); Max HR, maximal heart rate (#beats·min^{-1}); MWStride, stride mechanical work; MWThigh, thigh mechanical work; T>80%; time spent >80% of the individual 1-min MIP per variable. Note that the SpSp pitch session on D1 was not monitored with GPS (i.e., easy job and a few easy linear strides at moderate speed).



Day	Dur	TD	HSR	Sprint	Top Speed	Max Acc	#Acc	Max Dec	#Dec	T>85HR	Max HR	MWStride	MWThigh	T> 80%TD	T> 80%HSR	T> 80%AccDec	T> 80%MW
Day 3	37	3404	1	0	22,2	3,8	10	2,5	0	4	180	24	4	12	0	0	2
Day 5	57	3407	43	0	21,9	5,1	23	5,5	12	8	183	17	10	8	0	2	5
Day 7	53	3681	558	23	27,8	5,7	59	6,1	26	10	182	19	13	12	10	12	11
Day 9	50	3349	71	0	24,8	5,2	27	6,6	15	3	179	18	9	8	0	4	7
Day 10	75	3976	617	85	30,6	5,7	51	5,0	30	14	184	16	17	8	8	7	7

Day 8 included a PRE assessment only and is informative for tolerance to repeated load. PRE Powerdex values returned to a high range and asymmetry was low (Figure 5), suggesting baseline restoration within 24 h after the Day 7 pitch exposure. This indicates adequate short-term recovery capacity despite the large acute decrement on Day 7. Day 9 showed a smaller or more symmetrical response relative to Day 7. The pitch session load was lower, for both typical and mechanical-intensity markers (HSR 71 m; sprint 0 m; top speed 24.8 km·h^{-1}; MWstride 18; MWthigh 9; T>80%TD 8; T>80%HSR 0; T>80%AccDec 4; T>80%MW 7) (Table 4). Consistent with this reduced dose, the post-session Powerdex decrement was more modest and inter-limb asymmetry remained close to zero (Figure 5), suggesting lower fatigability when the pitch exposure was less mechanically demanding.

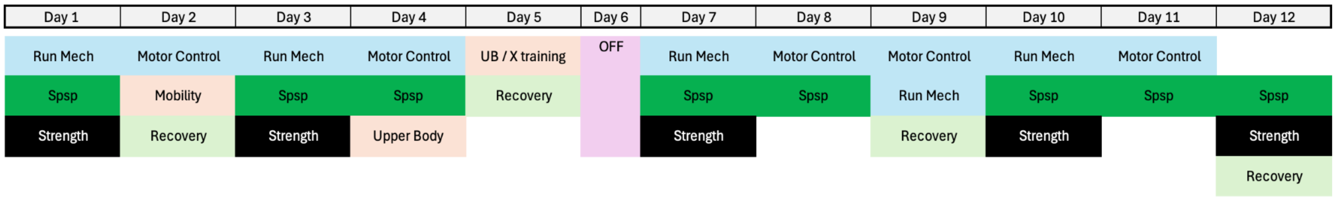
Day 10 is the key dose–response contrast supporting improved tolerance. This session had the highest overall pitch dose within the monitoring window (75 min; TD 3,976 m; HSR 617 m; sprint 85 m; top speed 30.6 km·h^{-1}) with high mechanical-intensity exposure (MWthigh 17; T>80%HSR 8; T>80%AccDec 7; T>80%MW 7) (Table 4). Despite this higher load, the post-pitch reduction in Powerdex was smaller than on Day 7 and asymmetry was attenuated, with values converging further after the subsequent strength session (Figure 5). This dissociation, less fatigue for more load, suggests improved tolerance across the monitored period. A plausible interpretation is that the player adapted rapidly to the mechanical demands of sport-specific work, such that a similar or greater external dose produced a lower peripheral contractile cost by Day 10.

Overall, the Days 7–10 monitoring window illustrates two applied features of LFF: (i) fatigability, captured by the large acute decrement and increased asymmetry after the most mechanically intense early exposure (Day 7), and (ii) tolerance to repeated load, reflected by next-day baseline restoration (Day 8) and a reduced acute contractile cost during a later, higher-dose session (Day 10). The alignment between Powerdex responses and the mechanical-intensity GPS 3.0 metrics (MWstride, MWthigh, and T>80% variables) supports prioritising these descriptors over volume-only metrics when interpreting neuromuscular response during return-to-play.

Case 3

A 26-year-old male professional football player from the Ivory Coast, a midfielder competing for a French First Division and UEFA Champions League club and representing his national team. He sustained a grade 4c distal right biceps femoris injury at the T-junction area and entered the return-to-play programme 4 weeks after injury. This case is presented alongside Case 4, which involved the same injury type and location, but a different clinical and load-tolerance trajectory.

Table 5. Rehabilitation training content plan for Case 3. Overview of the 12-day return-to-play microcycle showing the planned daily sequence of rehabilitation components, including running mechanics (Run Mech), motor control, sport-specific football pitch work (SpSp), strength training, upper-body training, recovery sessions, and an off day (OFF).



Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11	Day 12
Run Mech	Motor Control	Run Mech	Motor Control	UB / X training	OFF	Run Mech	Motor Control	Motor Control	Run Mech	Motor Control	
Spsp	Mobility	Spsp	Spsp	Recovery		Spsp	Spsp	Run Mech	Spsp	Spsp	Spsp
Strength	Recovery	Strength	Upper Body			Strength		Recovery	Strength		Strength
											Recovery

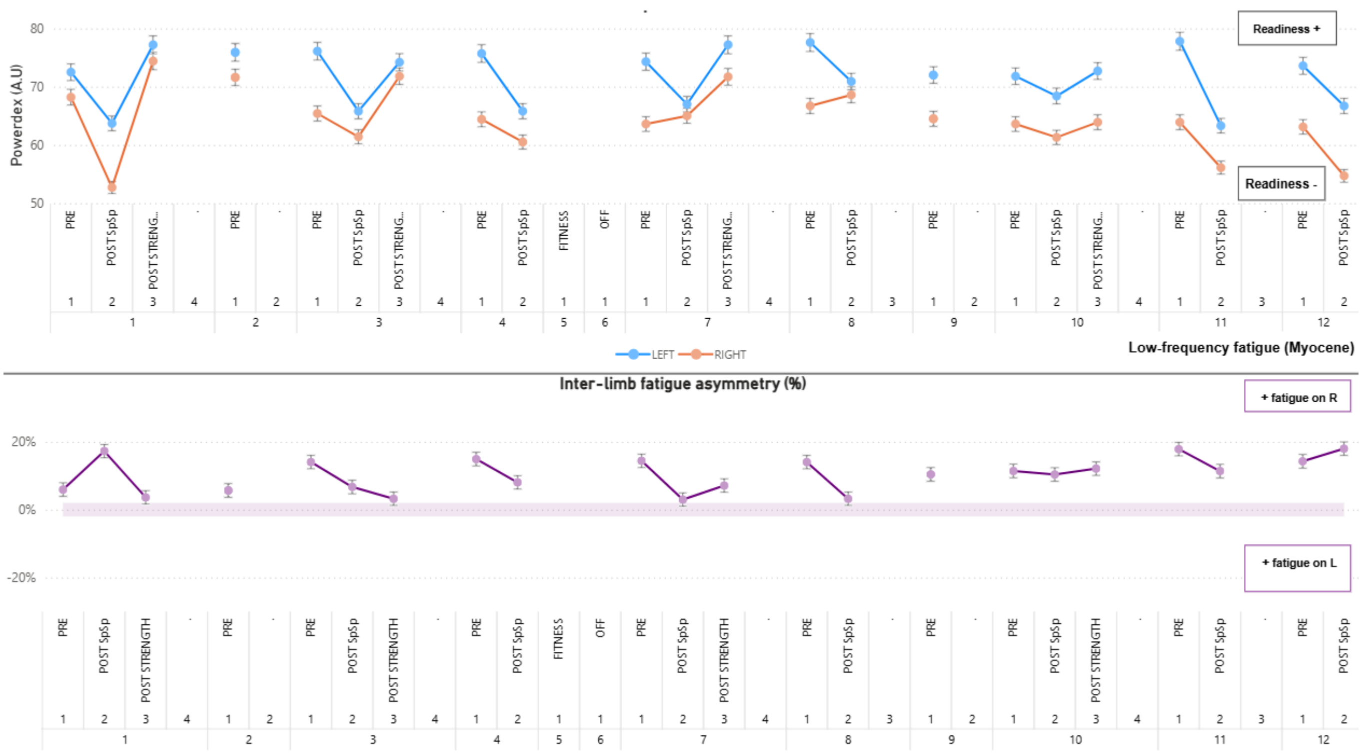
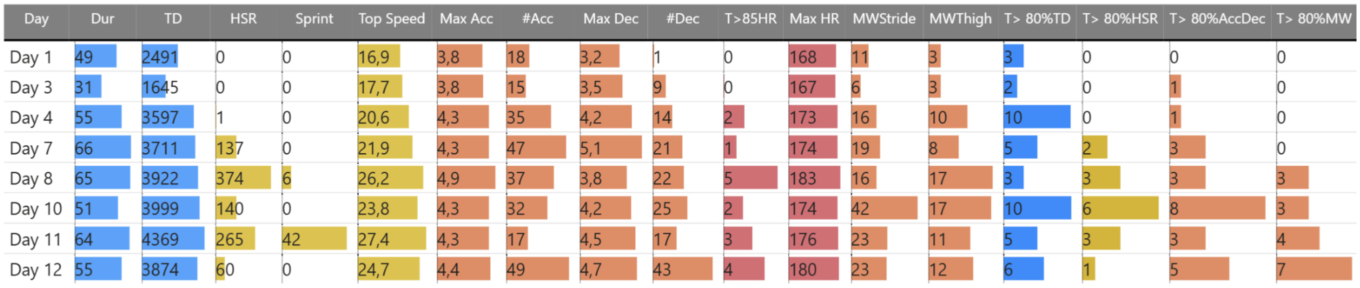


Fig. 6. **Time course of quadriceps LFF and inter-limb asymmetry during return-to-play monitoring for Case 3. Upper panel shows bilateral low-frequency fatigue output (Powerdex, A.U.) assessed at standardised time points across the 12-day rehabilitation microcycle, including pre-session baseline (PRE) and immediate post-session assessments (e.g., post sport-specific football pitch work, post strength). Lower panel shows inter-limb fatigue asymmetry (%) derived from bilateral Powerdex values, with positive values indicating greater fatigue on the right limb and negative values indicating greater fatigue on the left limb.**

Table 6. **GPS workload data per sport-specific football pitch session for Case 3. Each Day corresponds to the rehabilitation training day described in the Rehabilitation training content plan. Dur, duration (min); TD, total distance (m); HSR, high-speed running distance over 19.8 km·h^{-1} (m); Sprint, sprint distance (m) over 25.5 km·h^{-1}; Top Speed (km·h^{-1}), Max Acc, maximal acceleration (m·s^{-2}); #Acc, number of accelerations over 3 m·s^{-2}; Max Dec, maximal deceleration (m·s^{-2}); #Dec, number of decelerations over 3 m·s^{-2}; T>85HR, time spent >85% maximal heart rate (min); Max HR, maximal heart rate (#beats·min^{-1}); MWStride, stride mechanical work; MWThigh, thigh mechanical work; T>80%; time spent >80% of the individual 1-min MIP per variable.**



Day	Dur	TD	HSR	Sprint	Top Speed	Max Acc	#Acc	Max Dec	#Dec	T>85HR	Max HR	MWStride	MWThigh	T> 80%TD	T> 80%HSR	T> 80%AccDec	T> 80%MW
Day 1	49	2491	0	0	16,9	3,8	18	3,2	1	0	168	11	3	3	0	0	0
Day 3	31	1645	0	0	17,7	3,8	15	3,5	9	0	167	6	3	2	0	1	0
Day 4	55	3597	1	0	20,6	4,3	35	4,2	14	2	173	16	10	10	0	1	0
Day 7	66	3711	137	0	21,9	4,3	47	5,1	21	1	174	19	8	5	2	3	0
Day 8	65	3922	374	6	26,2	4,9	37	3,8	22	5	183	16	17	3	3	3	3
Day 10	51	3999	140	0	23,8	4,3	32	4,2	25	2	174	42	17	10	6	8	3
Day 11	64	4369	265	42	27,4	4,3	17	4,5	17	3	176	23	11	5	3	3	4
Day 12	55	3874	60	0	24,7	4,4	49	4,7	43	4	180	23	12	6	1	5	7

Across the 12-day return-to-play microcycle (Table 5), quadriceps LFF assessed by Powerdex showed a consistent inter-limb pattern, with the injured right limb presenting lower values than the left limb at most time points and a persistent positive inter-limb asymmetry, indicating a stable right-sided deficit throughout the monitoring period (Figure 6). The dominant signal was high fatigability of the injured limb (larger acute pre-to-post decrements after pitch sessions) combined with emerging reduced tolerance later in the block (incomplete restoration of the next-day baseline, Figure 6) in parallel with a progressive increase in field-based external and internal load across the monitored sessions (Tables 5 and 6).

The clinical diagnosis was a right hamstring injury, whereas Powerdex was derived from a standardised quadriceps evoked contraction assessment with the limb stabilised and mechanical output recorded. Before examining this case, we did not assume that a quadriceps-based LFF marker would differentiate limb status in a hamstring return-to-play context. The present data instead suggest that the injured limb expressed a broader limb-level neuromuscular impairment that was detectable at the quadriceps level, with persistent asymmetry and larger acute decrements after football pitch work on the injured side (Table 6). This provides applied evidence that the muscle group tested does not necessarily limit the value of stimulation-based LFF monitoring to track rehabilitation response and adaptation. One plausible explanation is that the hamstring injury induced limb-level protective strategies (pain-related inhibition and altered motor control) during running, accelerating, and braking tasks, which modified whole-limb neuromuscular function and increased the peripheral contractile cost of pitch work on the injured side (Fyfe et al., 2013; Sole et al., 2012). A second, non-exclusive explanation is altered load distribution within the injured limb, whereby changes in sprint and braking mechanics shifted relative demand toward the knee extensors to stabilise the limb and compensate for reduced hamstring contribution, resulting in greater quadriceps fatigability despite the primary injury being posterior (Lee et al., 2009; Morin et al., 2015). Finally, reduced use of the injured limb during early return-to-pitch exposures may have limited reconditioning of the limb as an integrated unit, such that repeated pitch doses elicited larger decrements and slower restoration in the injured limb compared with the contralateral side (Huygaerts et al., 2020). In this framework, the quadriceps signal is interpreted as an objective, repeatable marker of limb-level neuromuscular status and dose–response capacity during return-to-play, rather than a direct measure of hamstring tissue function.

Early in the programme, sport-specific pitch sessions elicited marked acute reductions in Powerdex on the injured limb (Figure 6). For example, on Day 1 the right limb showed a pronounced drop from the morning baseline to the immediate post-session assessment following football pitch work, whereas the left limb decreased to a smaller extent (Figure 6). This occurred during a low overall locomotor exposure, with minimal high-speed and sprint demands and a low mechanical-intensity signature (low MWstride and MWthigh, with negligible time spent above high-intensity exposure thresholds) (Table 6). Similar within-day responses were repeatedly observed on subsequent pitch days as pitch dose progressed (Figure 6) from short, low-speed sessions with low mechanical-intensity exposure to higher-intensity sessions characterised by greater high-speed and sprint content and higher mechanical-intensity signatures (higher MWstride and MWthigh, with increased time spent above high-intensity exposure thresholds, including T>80% HSR and T>80% MW) (Table 6). Across these progressive exposures, the pre-to-post decrement remained larger on the injured side, reinforcing that pitch work carried a higher neuromuscular cost for the injured limb despite completion of the prescribed work (Figure 6; Table 6).

In contrast, gym-based strength sessions, which targeted both the injured and contralateral limbs, did not appear to be the primary driver of acute Powerdex reductions. When pre- and post-session measures were available on the same day, post-gym values were typically similar to, or higher than, the immediately post-pitch values (Figure 6). Together, these patterns suggest that the player's limb-specific neuromuscular response was most sensitive to the pitch component of rehabilitation as mechanical-intensity exposure increased (MWstride, MWthigh, and time spent above high-intensity exposure thresholds, Table 6), rather than being explained by session volume metrics alone.

The capacity to tolerate consecutive pitch sessions was therefore asymmetric. The non-injured limb showed higher baseline values and smaller acute changes, suggesting greater robustness to repeated exposures (Figure 6). The injured limb demonstrated repeated acute suppression after football pitch work (Figure 6; Table 6), and although baseline recovery by the next morning appeared acceptable across much of the block, a more concerning pattern emerged late in the programme. Toward the end of the monitoring period, the injured-limb baseline value on arrival decreased compared with the typical mid-block baseline range, indicating reduced restoration or accumulating residual impairment following repeated exposures (Figure 6). This occurred in the context of late-block sessions combining higher high-speed and sprint exposure with increased mechanical-intensity demand, including higher acceleration–deceleration density and higher time spent above high-intensity exposure thresholds (Table 6). The late-block baseline suppression, combined with the persistent inter-limb asymmetry, coincided with the densest mechanical-intensity exposure sequence (higher MWthigh/MWstride and greater time spent above high-intensity exposure thresholds, Table 6). This supports the interpretation of reduced tolerance to repeated load and that the player had not fully normalised limb-level neuromuscular status by discharge (Figure 6).

At Day 12, the player appeared to have successfully completed a high-level rehabilitation microcycle (Buchheit, Balaña et al., 2025), but still displayed a right-sided deficit and limited robustness to repeated sport-specific football pitch exposure, as reflected by three consecutive pitch sessions (Tables 5 and 6). From a discharge perspective, the profile supports return to the club with continued progression and ongoing monitoring. Early reintegration should manage consecutive pitch doses and high neuromuscular exposures until inter-limb asymmetry and the acute post-pitch decrement on the injured side converge toward the contralateral profile, despite the player having already reached peak speeds up to 27.4 km·h^{-1} and sprint volumes up to 16 sprints within a single session during the final phase of the block (Table 6).

Case 4

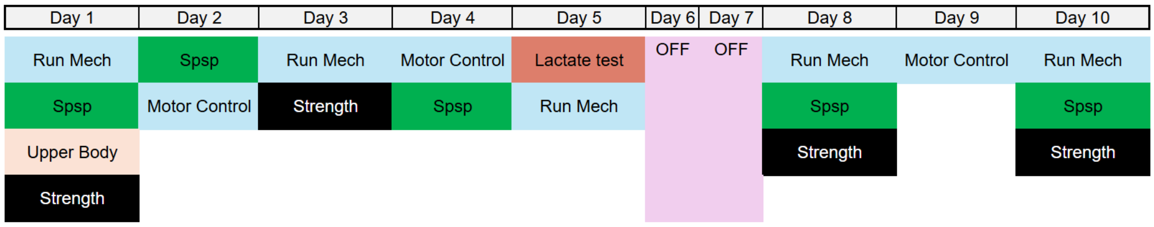
A 30-year-old male professional football player, a midfielder competing in the Saudi league. He sustained a grade 4c distal right biceps femoris injury at the T-junction area and entered the return-to-play programme 5 weeks after injury. Case 4 had the same injury type and location as Case 3, but symptoms persisted and progression was constrained, resulting in a less favourable trajectory.

Across the 10-day return-to-play microcycle (Table 7), quadriceps LFF assessed by Powerdex showed large within-day fluctuations that were strongly session dependent, with transient inter-limb asymmetry that was most pronounced in the first half of the block and attenuated after the two consecutive off-days (Figure 7). Although the clinical diagnosis involved the right hamstring, the data suggest a limb-level neuromuscular response pattern that was detectable at the quadriceps level and evolved with changes in field-based locomotor content and mechanical-intensity exposure (Figure 7; Tables 7 and 8).

In the early phase, baseline LFF was high but acute responses varied by session content. On Day 1, Powerdex changed minimally after a day including gym-based strength (Figure 7), despite a pitch exposure with moderate running volume and meaningful high-speed, MWstride and sprint content (Table 8). On Day 2, sport-specific football pitch work elicited a clearer acute suppression in both limbs with a modest asymmetry shift (Figure 7), despite low high-speed and sprint exposure and a relatively low mechanical-intensity signature (lower MWstride and MWthigh, with negligible time spent above high-intensity exposure thresholds) (Table 8). On Day 3, run mechanics was followed by a further decrement and a clearer right-sided asymmetry (Figure 7), coinciding with a session characterised by higher mechanical demand, reflected by increased MWthigh and higher time spent above high-intensity exposure thresholds (T>80% variables) (Table 8). Together, these early responses indicate that acute Powerdex suppression was not explained by total distance alone and aligned more closely with the mechanical-intensity characteristics of the session.

The most striking fatigue response occurred on Day 4 following sport-specific football pitch work, where right-limb Powerdex dropped sharply into the "readiness negative" range and inter-limb asymmetry peaked (Figure 7). Although the session duration, total and HSR distances were low, the relative intensity was high and the session included a pronounced mechanical-intensity signal (elevated MWstride/MWthigh and increased time spent above high-intensity exposure thresholds) (Table 8). This pattern supports the interpretation that the acute neuromuscular cost was driven by high mechanical strain content within a short exposure window and/or residual fatigue carried into the session from the preceding training sequence.

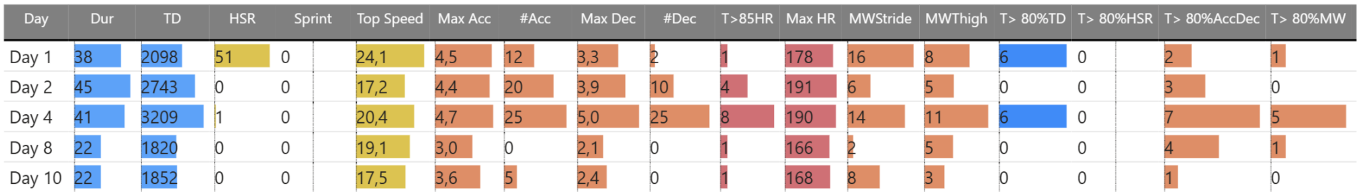
Table 7. Rehabilitation training content plan for Case 4. Overview of the 10-day return-to-play microcycle showing the planned daily sequence of rehabilitation components, including running mechanics (Run Mech), motor control, sport-specific football pitch work (SpSp), strength training, upper-body training, recovery sessions, and an off day (OFF).



Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10
Run Mech	Spsp	Run Mech	Motor Control	Lactate test	OFF	OFF	Run Mech	Motor Control	Run Mech
Spsp	Motor Control	Strength	Spsp	Run Mech			Spsp		Spsp
Upper Body							Strength		Strength
Strength									

Fig. 7. Time course of quadriceps LFF and inter-limb asymmetry during return-to-play monitoring for Case 4. Upper panel shows bilateral low-frequency fatigue output (Powerdex, A.U.) assessed at standardised time points across the 10-day rehabilitation microcycle, including pre-session baseline (PRE) and immediate post-session assessments (e.g., post sport-specific football pitch work, post strength). The lower panel shows inter-limb fatigue asymmetry (%) derived from bilateral Powerdex values, with positive values indicating greater fatigue on the right limb and negative values indicating greater fatigue on the left limb.

Table 8. GPS workload data per sport-specific football pitch session for Case 4. Each Day corresponds to the rehabilitation training day described in the Rehabilitation training content plan. Dur, duration (min); TD, total distance (m); HSR, high-speed running distance over 19.8 km·h^{-1} (m); Sprint, sprint distance (m) over 25.5 km·h^{-1}; Top Speed (km·h^{-1}), Max Acc, maximal acceleration (m·s^{-2}); #Acc, number of accelerations over 3 m·s^{-2}; Max Dec, maximal deceleration (m·s^{-2}); #Dec, number of decelerations over 3 m·s^{-2}; T>85HR, time spent ¿85% maximal heart rate (min); Max HR, maximal heart rate (#beats·min^{-1}); MWStride, stride mechanical work; MWThigh, thigh mechanical work; T>80%; time spent >80% of the individual 1-min MIP per variable.



Day	Dur	TD	HSR	Sprint	Top Speed	Max Acc	#Acc	Max Dec	#Dec	T>85HR	Max HR	MWStride	MWThigh	T> 80%TD	T> 80%HSR	T> 80%AccDec	T> 80%MW
Day 1	38	2098	51	0	24,1	4,5	12	3,3	2	1	178	16	8	6	0	2	1
Day 2	45	2743	0	0	17,2	4,4	20	3,9	10	4	191	6	5	0	0	3	0
Day 4	41	3209	1	0	20,4	4,7	25	5,0	25	8	190	14	11	6	0	7	5
Day 8	22	1820	0	0	19,1	3,0	0	2,1	0	1	166	2	5	0	0	4	1
Day 10	22	1852	0	0	17,5	3,6	5	2,4	0	1	168	8	3	0	0	1	0

Day 5 provided a contrasting and clinically informative response. Following a controlled submaximal lactate test with peak speed ≈16 km·h^{-1} (well below exhaustion), Powerdex rebounded markedly, with a large increase on the right limb and a reduction in asymmetry (Figure 7). This rebound is consistent with a potentiation-dominant response and may reflect short-term facilitation mechanisms such as increased muscle temperature, enhanced neural drive, and post-activation potentiation after controlled, non-exhaustive running. An alternative explanation is that the pre-test value captured transient residual suppression from Day 4, while the lactate test acted as an active warm-up, improving expression of excitation–contraction coupling during the subsequent assessment. Regardless of mechanism, this observation highlights that submaximal running exposures can acutely improve evoked LFF indices under applied conditions.

After two consecutive off-days (Days 6–7), the subsequent sport-specific exposure on Day 8 produced a smaller and more symmetrical post-session decrement, with asymmetry returning closer to zero (Figure 7). These late-phase pitch sessions were intentionally very light because the player continued to report right hamstring symptoms. In contrast to Case 3, persistent symptoms necessitated repeated downregulation of pitch dose, limiting exposure to higher mechanical-intensity demands and constraining progression. This was reflected in lower MWstride/MWthigh and minimal time spent above high-intensity exposure thresholds (Table 8). The limited dose likely explains the minimal Powerdex suppression on Day 8 and the similarly small changes observed on Day 10, where sport-specific football pitch work again elicited only a modest decrement with limited asymmetry (Figure 7; Table 8). This pattern strengthens the dose–response interpretation: when pitch content was deliberately downregulated due to symptoms and mechanical-intensity exposure was reduced, the neuromuscular response signal attenuated accordingly.

At discharge on Day 10, the player showed restoration of baseline LFF and reduced inter-limb asymmetry compared with the marked suppression observed on Day 4 (Figure 7; Table 8). However, this improvement occurred in the context of symptom-driven downregulation of pitch dose and reduced mechanical-intensity exposure rather than clear evidence of restored tolerance to high mechanical hamstring-demand tasks. Overall, the case illustrates that acute LFF responses can be dissociated from volume metrics, track sensitivity to mechanical-intensity exposure (MWstride/MWthigh and T>80% variables), and reflect clinical decisions to reduce pitch dose when symptoms persist.

Gym-based strength work and LFF response

Across the four cases, gym-based strength sessions, including multi-joint and isolated exercises and sessions targeting both the injured and contralateral limbs, did not appear to be the primary driver of acute Powerdex suppression when performed on the same day, most often after pitch exposure. In several instances, post-gym Powerdex values were similar to, or higher than, the immediately post-pitch values, suggesting that the dominant LFF signal was primarily elicited by football-specific pitch work and its mechanical-intensity characteristics rather than by controlled resistance training performed within the rehabilitation setting (Hodgson et al., 2005; Tillin & Bishop, 2009; Seitz & Haff, 2016). A plausible interpretation is that gym work was programmed to prioritise tissue loading quality and technical execution (i.e., controlled exercise selection and range of motion, submaximal or moderated volume), thereby developing capacity without systematically inducing large excitation–contraction coupling impairment detectable with the quadriceps protocol. In addition, acute post-strength assessments may reflect a balance between fatigue and potentiation, particularly after high-intent contractions (Buchheit & Laursen, 2026), which could attenuate observable suppression in the immediate post-session window (Rassier & Macintosh, 2000; Tillin & Bishop, 2009). Overall, these observations support the view that, within this return-to-play model, gym-based strength work can be progressed with limited additional impact on LFF when appropriately dosed, while pitch exposures remain the main driver of acute fatigability and day-to-day tolerance signals.

Discussion & Conclusion

This case series shows that low-frequency fatigue monitoring can capture limb-level peripheral contractile responses to rehabilitation loading in elite football under real-world constraints. The primary applied value was the ability to quantify fatigability, defined here as the acute contractile cost of a given exposure (pre-to-post session change). Present observations are consistent with modality-specific LFF recovery signatures reported outside rehabilitation settings, where distinct training modalities produced markedly different acute contractile costs and recovery time courses (Buchheit & Laursen, 2026). The second interest of the current monitoring approach is to track tolerance to repeated load, defined as restoration of the next-day baseline following consecutive training days. These two features are central to return-to-play progression because they indicate whether the athlete is “paying more” for a given dose and whether recovery capacity is keeping pace as pitch work is reintroduced and intensified. Across cases, LFF responses aligned more closely with the most demanding mechanical-intensity characteristics of pitch exposure, including GPS 3.0-derived metrics (Buchheit, Sagarra et al., 2026) such as MWstride, MWthigh, and time spent above high-intensity exposure thresholds (e.g., T>80%), than with volume descriptors alone.

Importantly, fatigability is difficult to assess with other neuromuscular response options typically available in practice. Performance-based tests such as jumps or standardised lifts are active, effort dependent, and add task burden and scheduling constraints, while biomarkers such as creatine kinase are invasive, indirect, and do not specifically target peripheral contractile fatigue. In contrast, LFF provides a passive and mechanistically grounded internal neuromuscular response marker that can be repeated frequently, including immediately post-session and on the following morning, enabling practical interpretation of both acute response and day-to-day recovery.

Although LFF was assessed at the quadriceps, the present cases also suggest that a quadriceps-derived LFF signal can reflect broader limb-level status during rehabilitation from other injury types. In both hamstring injury cases, LFF differentiated the injured limb and tracked changes in response and recovery across variations in pitch dose, supporting the use of quadriceps-based LFF as a pragmatic proxy of limb-level neuromuscular function when interpreted alongside symptoms, training content, and functional capacity rather than as a direct measure of the injured tissue itself.

Collectively, these observations support the role of low-frequency fatigue as a passive, mechanistically grounded internal neuromuscular response marker that complements contextual training information, together with usual load and response descriptors. Its practical value during return-to-play lies in refining progression of training content by identifying exposures associated with disproportionate contractile cost or persistent inter-limb asymmetry, and by documenting improvements in load tolerance over time through next-day baseline restoration. However, the method should not be interpreted as a standalone readiness signal. Interpretation requires integration with symptoms, clinical examination, functional performance, and contextual load information, particularly when pitch dose is deliberately reduced due to ongoing symptoms.

Key points for practitioners

- LFF monitoring quantifies fatigability (acute pre-to-post changes) and tolerance to repeated load (next-day baseline restoration), while alternative neuromuscular response measures such as jump testing and creatine kinase are less practical because they are active (effort dependent) or invasive; LFF is passive and independent of the athlete's motivation
- Mechanical-intensity metrics (MWstride, MWthigh, and time spent above high-intensity exposure thresholds, T>80% variables) aligned more closely with Powerdex responses than volume-only distance-in-zones descriptors (e.g., TD and HSR).
- In the ACL case, larger suppression in the operated limb followed the session with the most quadriceps-targeted mechanical-intensity signature, while a higher-load but less quadriceps-targeted session was better tolerated.
- In the rectus femoris case, reduced fatigue and asymmetry despite increased mechanical-intensity exposure suggested progressive improvement in load tolerance.
- In hamstring injuries, quadriceps-based LFF monitoring still differentiated limb status and response, supporting use as a limb-level response marker when interpreted alongside symptoms and training content.
- Gym-based strength work, including multi-joint and isolated exercises performed after pitch sessions, generally produced smaller acute LFF responses than football pitch exposures.
- Same-day strength work did not consistently worsen post-pitch LFF and was often compatible with recovery toward next-day baseline.
- Between-session recovery behaviours (e.g., a nap) may influence within-day perceived readiness, but direct effects on maximal force and especially LFF indices are uncertain; in this series, a post-nap Powerdex increase was observed, so such behaviours should be recorded to contextualise within-day changes and avoid attributing all variation to training dose.
- LFF is a local marker of peripheral impairment and adaptation, and should not be used as a standalone readiness or injury-risk signal; even when assessed in the injured muscle, it reflects only one component of neuromuscular status and must be interpreted alongside symptoms, functional performance, and training context.

Declarations

Confidentiality: Player confidentiality is protected through anonymisation and minimisation of identifying information. Cases are reported without names or unique identifiers, and potentially identifying contextual details are removed, aggregated, or time-shifted when required.

Data availability: De-identified data supporting the findings are not publicly available due to confidentiality and governance restrictions in the elite sport environment. Aggregate data are available from the corresponding author on reasonable request, subject to institutional approval and player consent where applicable.

Conflict of interest: Guillaume Y Millet is a member of the Myocene scientific board.

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