Biphasic Heart-Rate Recovery After Repeated Sprints: Sprint-Specific Responses to Off-Feet Sprint Interval Training in Elite Hurling Players

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Field Testing | Parasympathetic reactivation | Off-Feet Conditioning | Biexponential modelling | Work-to-rest ratio | Gaelic Games

Headline

Hurling is a 15-a-side field-based team sport native to Ireland (1), in which players are required to complete repeated sprints with short recoveries during match play that can last up to 70 minutes (1, 2). Conditioning in hurling commonly relies on game-based methods such as small-sided games and simulated phases of play (1, 2), which can improve physical and physiological fitness across a pre-season (2). The game demands that players recover quickly between repeated sprint actions, with sprint interval training (SIT) and, specifically, off-feet sprint interval training (OFSIT) potentially offering a time-efficient complement for amateur squads with limited time across the training process. Heart rate recovery (HRR) is a commonly used field marker of training response, with changes related to training status and fatigue changes (3, 4). Typically, HRR is reported as the fall in heart rate over 60 s (HRR60) or as a single exponential time constant (3, 5). However, it has been noted in the literature that heart rate declines in two phases: a fast phase driven by parasympathetic reactivation and a slower phase reflecting sympathetic withdrawal and metabolite clearance (6, 7). After maximal exercise, a single exponential function fits HRR poorly (8), with a biexponential function providing a more reflective fit in 61% of cases (9). HRR is also typically measured once, after the final effort. HRR after each sprint of an OFSIT has not been measured across hurling cohorts to date. Sprint-by-sprint profiling may better capture adaptation and help individualise work-to-rest ratios. Therefore, we profiled HRR after each of two 30 s sprints before and after an intervention period of a 3-week OFSIT.

Aim

Across the current case-study analysis, we aimed to (i) determine whether heart rate recovery after repeated sprints in hurlers is better described by a biexponential or monoexponential function, (ii) determine whether multi-phase HRR analysis is sensitive to 3 weeks of OFSIT protocols and (iii) compare responses between three OFSIT protocols with different work-to-rest ratios. We hypothesised that HRR would be biphasic and would improve after the OFSIT interventions across the group of elite hurling players.

Methods

Design: Applied case study using a single-squad, pre–post design with non-randomised allocation of players to one of three OFSIT protocols with no control group.

Participants: Eighteen (n = 18) elite-level, inter-county male hurling players from a single squad competing at All-Ireland level and in Division 1B of the National Hurling League (age: 24.7 ± 3.0 years; height: 182.7 ± 3.5 cm; body mass: 85.7 ± 6.9 kg) were recruited during the 2025–26 season. All data were collected as part of the routine monitoring of the squad by the performance staff of the team. Prior to the completion of the intervention period, players provided written informed consent for their anonymised data to be used for research, and the study was conducted in line with the Declaration of Helsinki.

Methodology: After a standardised warm-up (10 min on the air-braked arm–leg ergometer at a self-selected light-to-moderate intensity, followed by 5 × 10 s progressive accelerations and 4 min of passive rest), players completed two 30 s all-out sprints on an air-braked arm–leg ergometer (Assault Bike®, Assault Fitness Products, Carlsbad, CA, USA), separated by 60 s of passive [seated] recovery on the ergometer; heart rate was also recorded during 60 s of passive seated recovery after the second sprint, before (session 1; S1) and after (session 2; S2) a 3-week conditioning block. Both sessions were completed at the same time of day (18:00-21:00) and on the same day of the training week, ≥48 h after the last high-intensity session. The protocol has been used to assess muscle oxygenation kinetics (11) and maximal power (12), and arm–leg ergometry elicits a higher maximal heart rate than cycling (13). We recorded heart rate at 1 Hz with a Polar H10 chest strap (Polar Electro Oy, Kempele, Finland), which detects 99.6% of RR intervals during exercise (14). Between testing sessions, players completed three supervised OFSIT sessions per week for 3 weeks (9 sessions) on the same type of ergometer. Each session comprised 2 sets of the allocated protocol (Table 1) performed with maximal effort, with 3 min between each set of OFSIT. Players were assigned to one of three protocols based on their heart rate recovery after both sprints in S1 (Table 1). Players who recovered more than 30 beats within the 60 s recovery period, with an initial fast phase in which heart rate fell by 3–10 beats, received protocol A. Players with a slow initial phase and fewer than 30 beats recovered received protocol B. Players with several prolonged slow phases and fewer than 15 beats recovered received protocol C. Where criteria overlapped, the phase pattern determined allocation, and players who met none of the criteria received protocol C. Throughout the intervention, players also completed a typical pre-season squad programme of 3-4 field sessions per week (including games-based conditioning) and 1-2 resistance-training sessions per week.

Table 1. Off-feet sprint interval training (OFSIT) protocols and player characteristics by protocol (mean ± SD).

Protocol	Work: rest	Repetitions	n	Age (years)	Body mass (kg)
A	15 s: 8 s	× 6	4	26.0 ± 2.3	86.2 ± 8.0
B	10 s: 10 s	× 8	7	24.7 ± 3.5	86.9 ± 8.0
C	10 s: 20 s	× 6	7	23.9 ± 3.0	84.2 ± 5.9

Data Analysis

Raw heart rate data from the Polar H10 were imported into Physiological Solutions software (version 1.2; Physiological Solutions, Scotland, UK) for analysis, and no filtering or smoothing was applied to the data. For each 60 s recovery period, the drop in heart rate at 30 s and 60 s (HRR30, HRR60) and recovery completeness (% of the heart rate at the start of recovery) were determined. The number of recovery phases and the beats recovered in the fast and slow phases were determined from the shape of the heart rate recovery curve. Heart rate does not fall at a constant rate during recovery, but shows periods of faster and slower decline (4, 5). A third-order polynomial was therefore fitted to each recovery period to describe the overall trend. Each section where heart rate fell faster than the trend was classed as a fast phase, and each section where heart rate fell more slowly than the trend was classed as a slow phase.

Consecutive data points of the same type were combined into a single phase, and any phase shorter than 3 s was merged into the surrounding phase so that noise in the signal did not create false phases. For each recovery period this gave the number of fast and slow phases, the drop in heart rate across each phase and the rate of each phase, determined from a linear regression across the phase. A monoexponential time constant (τ) was also calculated, as this describes the rate of recovery independent of the peak heart rate reached. Each recovery period was fitted with a monoexponential function, $\mathrm{HR}(t) = C + A\,e^{-t/\tau}$, and a biexponential function, $\mathrm{HR}(t) = C + A_1\,e^{-t/\tau_1} + A_2\,e^{-t/\tau_2}$. Where C is the baseline heart rate, A is the amplitude of each component, and τ is the time constant of each component. Goodness of fit was compared using R^2, the corrected Akaike Information Criterion (AICc) and a nested F-test. This approach was used because monoexponential and biexponential functions assume a smooth decline, whereas beat-to-beat recordings after maximal sprints show alternating periods of faster and slower decline that these functions average out.

Statistical analysis

All data are mean ± standard deviation (SD) or mean [90% confidence interval (CI)]. Changes from session 1 to session 2 are mean paired differences [90% CI] and were tested with paired t-tests (significant results confirmed with Wilcoxon signed-rank tests). Effect size (ES) was the change divided by the session-1 between-player SD (trivial <0.2, small 0.2–0.6, moderate 0.6–1.2, large 1.2–2.0) (15). The smallest worthwhile change (SWC) was 0.2 × this SD, and we report the likelihood of each change being beneficial, trivial or harmful (likely 75–95%, very likely 95–99.5%) (15, 16) or, for phase count, which has no established direction of benefit, of an increase or decrease. Individual changes were judged against the SWC and the typical error of HRR60 (2.2 bpm). As no test–retest reliability trial (repeated baseline testing without intervening training) was performed in this squad, the typical error was taken from a published repeated-sprint protocol (coefficient of variation 10.9%; 90% CI 9.0–14.2%) (21) and applied to the session-1 mean HRR60 (10.9% × 19.8 bpm ≈ 2.2 bpm). Mono and bi-exponential recovery models were compared with a nested (extra-sum-of-squares) F-test and AICc, retaining the bi-exponential where it both improved fit and lowered AICc. The session × sprint interaction was the difference between the changes after sprint 1 and sprint 2, tested with a paired t-test of this contrast. As protocols were assigned on baseline recovery, we compared them using ANCOVA with the session 1 value as a covariate, reporting partial eta squared (η^2p; small 0.02–0.13, moderate 0.13–0.26, large >0.26) (17). Where one player's session-2 sprint-2 recording was truncated, the mean-of-two-sprints value used the available sprint, retaining all players for session-level and ANCOVA analyses (n = 18); sprint-2 comparisons used the 17 players with complete data.

Results

Model fit

Of the 72 recovery periods recorded (18 players × 2 sessions × 2 sprints), one was excluded as the recording stopped 17 s into recovery from sprint 2 in S2, leaving 71 recovery periods for analysis. Across these, the biexponential function gave a better fit than the monoexponential function, with a significantly higher R^2 (0.97 ± 0.03 vs. 0.95 ± 0.06; difference: 0.017 [0.009, 0.025]; p = 0.001). The biexponential function was preferred by AICc in 83% of recovery periods (59/71; mean ΔAICc: 16.4) and was significantly better by F-test in 76% (54/71). The two time constants differed by approximately ten-fold (fast τ: ∼11 s; slow τ: ∼155 s).

Session 1 vs. Session 2

There was a significant increase in HRR60 from session 1 to session 2 (p = 0.020; Table 2) with a moderate effect (ES = 0.97; *moderate*), and a significant increase in recovery completeness (p = 0.012; Table 2) with a moderate effect (ES = 1.11; *moderate*). The number of recovery phases was shown to increase from session 1 to session 2 (5.1 ± 0.5 vs. 5.8 ± 0.9; p = 0.028; ES = 1.33; *large*). HRR30 and τ did not change significantly (p > 0.05; Table 2), although both showed *small* effects (ES = 0.48 and −0.46, respectively). The improvement remained when HRR60 was expressed relative to peak heart rate: peak heart rate fell from 181.2 ± 9.6 bpm at S1 to 175.4 ± 7.9 bpm at S2 (p = 0.015), 14 of 18 players still improved HRR60 — 13 of them by more than the typical error (2.2 bpm) (Figure 1).

Sprint-specific recovery

HRR60 after sprint 1 significantly increased from 14.3 to 21.3 bpm (difference: 7.0 bpm [3.3, 10.7]; p = 0.004) with a *large* effect (ES = 1.31) (Figure 2). There was no change in HRR60 after sprint 2 (25.3 vs. 26.1 bpm; p = 0.83). There was a significant session × sprint interaction for HRR60 (6.5 [2.5, 10.5]; p = 0.012) and recovery completeness (3.5%; p = 0.011).

Repeated sprint protocol analysis

The change in HRR60 was greatest for protocol C (Δ +6.9 bpm), followed by protocol A (Δ +4.6 bpm) and protocol B (Δ +0.4 bpm). However, when session 1 HRR60 was included as a covariate, there was no significant effect of protocol (F(2,14)

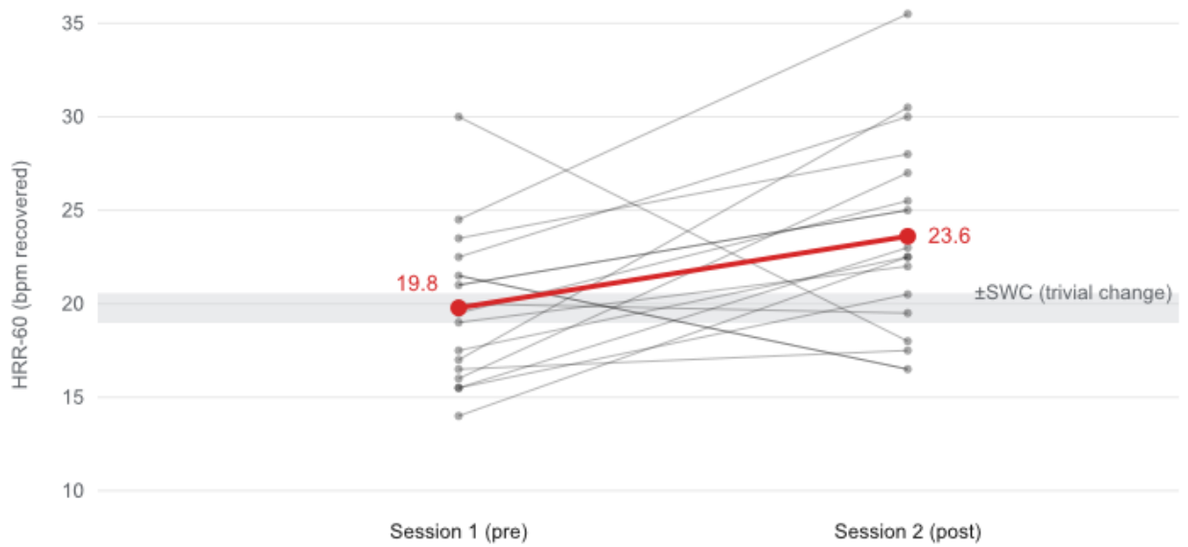

Fig. 1. Individual HRR-60 (beats recovered by 60 s; mean of the two sprints) at Session 1 (pre) and Session 2 (post); grey lines are individual athletes, the red line is the group mean. The shaded band is the smallest worthwhile change (± 0.8 bpm) around the Session 1 mean. The figure shows that 14 of 18 athletes (Δ +3.8 bpm) improved between session 1 and session 2.

Table 2. Heart rate recovery before and after the 3-week OFSIT block (n = 18; mean of the two sprints).

Measure	Session 1	Session 2	Δ [90% CI]	ES	Inference
HRR60 (bpm)	19.8 ± 4.0	23.6 ± 5.3	+3.8 [1.2, 6.4]	+0.97	*Very likely increase*
HRR30 (bpm)	12.6 ± 4.9	14.9 ± 3.7	+2.3 [−0.1, 4.7]	+0.48	*Likely increase*
Completeness (%)	10.9 ± 2.3	13.5 ± 3.2	+2.6 [1.0, 4.2]	+1.11	*Very likely increase*
Recovery phases (n)	5.1 ± 0.5	5.8 ± 0.9	+0.7 [0.2, 1.2]	+1.33	*Very likely increase*
τ (s)	105 ± 72	72 ± 37	−33 [−65, −1]	−0.46	*Likely decrease*

ES = change ÷ Session-1 between-athlete SD. Higher HRR and completeness, and lower τ, mean faster recovery.

= 0.42; p = 0.67) and a small effect (η^2p = 0.06), with adjusted session 2 values of 22.8, 22.4 and 25.3 bpm for protocols A, B and C, respectively. There was also no significant effect of protocol for recovery completeness (p = 0.69).

Discussion

Across the current case-study intervention, we showed that heart rate recovery after maximal sprints follows a biphasic pattern. We found that 3 weeks of OFSIT improved heart rate recovery after the first, but not the second, sprint. The two time constants differed about ten-fold, consistent with fast and slow recovery phases; a single time constant (5, 8) averages these and may not reflect the underlying physiology. The sprint-1 improvement after only 3 weeks is consistent with the faster autonomic recovery reported after 8 weeks of repeated-sprint training (18). Our data extend treadmill findings (9) to supramaximal sprints, with the biexponential function preferred in 83% of recovery periods. With 60 s recordings, the fast component is well defined, but the slow time constant (∼155 s) is extrapolated.

The two components likely reflect different control mechanisms. The fast phase, within roughly the first 30 s, is attributed mainly to rapid parasympathetic reactivation once central command ceases, whereas the slow phase depends on sympathetic withdrawal and on the clearance of metabolites from the working muscle (6–8). Consistent with this, HRR slowed across repeated sprints while oxygen uptake and muscle oxygenation recovery were maintained, suggesting that post-sprint HRR reflects central command and metaboreflex activity rather than oxidative recovery (23). After supramaximal sprints, metabolite accumulation is large (10), which may explain why the slow component was so prolonged here and why a single exponential fitted poorly. The 5–6 trend-based phases are short alternations within this two-component decline, not additional components. Their increase after SIT indicates a less uniform decline of unclear physiological meaning, so we treat phase count as a descriptor and base conclusions on HRR30, HRR60 and completeness.

After 3 weeks of OFSIT, HRR60 and recovery completeness increased moderately, including when HRR60 was expressed relative to peak heart rate, and τ fell slightly, suggesting faster recovery rather than a higher peak heart rate. HRR60 improves after 8 weeks of repeated sprint training (18), and 3 weeks of SIT improves mitochondrial function (19) and

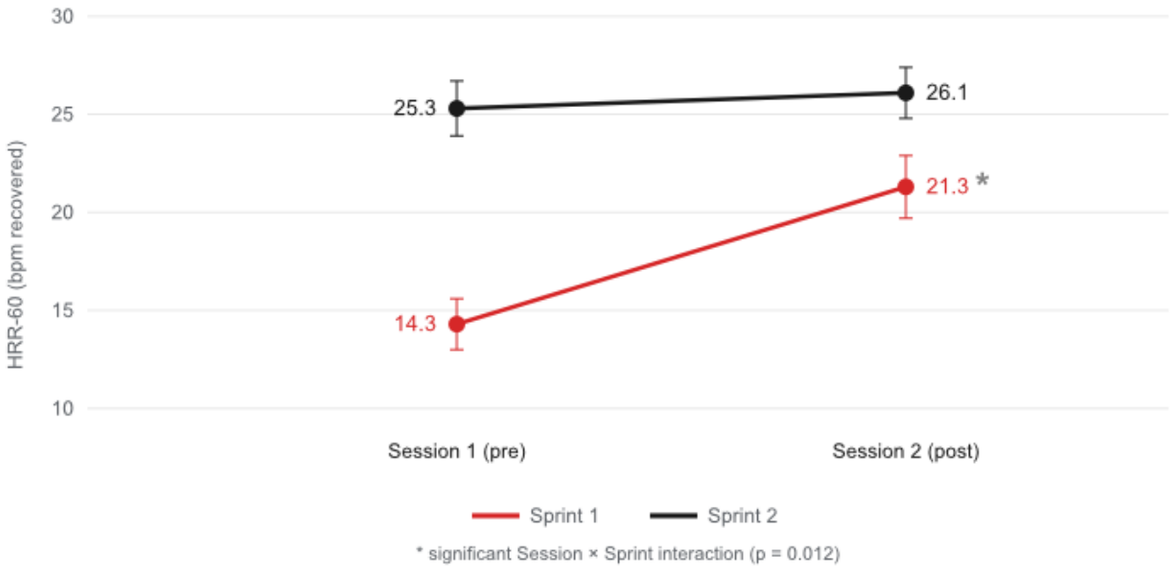

Fig. 2. HRR60 after sprint 1 and sprint 2 at session 1 (pre) and session 2 (post); mean ± SE. HRR60 after sprint 1 (red) increased between sessions, whereas HRR60 after sprint 2 (black) was unchanged (session × sprint interaction, p = 0.012). Sprint 2, session 2: n = 17 (one truncated recording excluded).

oxygen off-kinetics (20). Without a control group, however, we cannot separate the effect of OFSIT from other training or seasonal change. The absence of change after sprint 2 argues somewhat against a purely systemic or seasonal shift, although test familiarity would also be expected to affect mainly the first recovery. The improvement was only seen after sprint 1. Recovery from sprint 2 started from a higher heart rate and was already more complete at baseline, leaving less room for improvement; it may also be limited by metabolic disturbance and muscle oxidative capacity (11), which may respond less to a short block. In addition, recovery after sprint 1 occurred while players anticipated sprint 2, and greater familiarity with the test at session 2 may have reduced this anticipatory arousal independently of fitness. Recovery from each sprint should therefore be monitored separately.

For hurling practitioners, the sprint-specific response is the more relevant finding. Match play demands repeated high-intensity efforts with incomplete recovery, so recovering after an initial effort, before the next, is likely to matter more than recovery after a single bout. Profiling recovery after each sprint could therefore complement games-based conditioning (1, 2) by identifying players who recover slowly and may benefit from longer rest intervals during OFSIT. Unadjusted, the group with the longest recovery improved most, but not after adjustment for baseline, which may partly reflect regression to the mean as protocols were allocated on baseline recovery. No protocol was clearly superior; whether individualised prescription outperforms a common one requires a randomised comparison. In conclusion, HRR after OFSIT in elite hurlers was better described by a biexponential than a monoexponential function, and HRR after the first, but not the second, sprint improved following 3 weeks of OFSIT. The mean improvement in HRR60 (+3.8 bpm) exceeded the typical error (2.2 bpm), but individual changes should be interpreted cautiously. Sprint-by-sprint HRR offers a simple field method to monitor conditioning in hurlers; whether it can be used to individualise work-to-rest ratios requires a randomised comparison.

Practical Applications

- Heart rate recovery after maximal sprints has a fast and a slow phase; report HRR30 and HRR60 after each sprint rather than a single time constant or one post-session value.
- Two 30 s sprints with 60 s recovery and a standard heart rate strap provide a practical way to profile recovery; whether this improves the setting of individual work-to-rest ratios requires further research.
- Improvements in recovery may appear after the first sprint only, so track recovery from each sprint separately, and familiarise players with the test before baseline.
- The use of OFSIT alongside the typical on-feet methodologies employed within the hurling training process could be seen as a time effective method to improve players' physiological conditioning.
- Practitioners should analyse individual changes against the typical error and SWC, and interpret faster recovery alongside performance and wellness, as it can also reflect functional overreaching (4).

Limitations

- Protocols were assigned based on baseline recovery, not randomly, so protocol effects cannot be isolated.
- No control group or familiarisation session: changes may partly reflect other training, seasonal effects or test familiarity.
- Heart rate was analysed at 1 Hz, which limits the resolution of short recovery phases.
- Testing used an arm–leg ergometer; how these recovery profiles transfer to running-based efforts in hurling match play is unknown.

- The typical error of HRR60 was taken from a running-based repeated-sprint protocol (21), not measured in this squad on the arm–leg ergometer. Higher values have been reported after supramaximal exercise (CV 15–32%) (22), so individual responses should be interpreted with caution. A familiarisation session and a baseline retest a few days apart would allow future work to measure typical error in the squad.
- Phases were derived from heart rate alone; heart rate variability and muscle oxygenation would be needed to confirm their parasympathetic and peripheral contributions.
- The trend-based phase method is new and has not been validated against an established method; phase count may depend on the polynomial order and the 3 s merging rule.

GenAI Statement

Generative AI (Claude, Anthropic) was used for language and editing across the Headline, Discussion and Practical Applications, and to assist with reference checking. It was not used to collect or analyse data or to interpret results. The authors reviewed and edited all content and take full responsibility for the manuscript.

Conflict of Interest

A. Usher developed the Physiological Solutions application used to analyse the heart-rate data in this study but received no financial benefit in relation to this research. All authors declare that they have no other competing interests related to the research completed.

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