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Original Article

Rolling-Window Heart Rate Variability, Internal Training Load and Performance Consistency in Elite Orienteering: A 5-Year Longitudinal Case Study

Minoiu George-Emilian[1*]
Sirakov Ivan[2]
Minoiu Veronica[3]
[1] University of Craiova, Doctoral School of Social Sciences and Humanities, Romania
[2] St. Cyril and St. Methodius University of Veliko Tarnovo, Bulgaria
[3] University of Craiova, Romania

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Abstract

Heart rate variability (HRV) is increasingly used to monitor recovery and training adaptation in endurance sports, but long-term evidence in orienteering is limited. This 5-year longitudinal case study examined the interaction among rolling-window HRV, internal training load and split-based performance consistency in an elite male orienteer progressing from junior to senior international level. Daily morning HRV was recorded in the supine position and analysed with Kubios HRV using 7-day rolling windows. Internal load was quantified with TRIMP and related heart-rate metrics, while performance was evaluated through official results and split-time indicators from national and international competitions. Over time, rolling lnRMSSD increased, resting heart rate and Stress Index decreased, and TRIMP distribution became more economical. Split-based metrics showed fewer major navigation errors and greater execution consistency. Integrating HRV, internal load and split analysis offers a practical framework for monitoring elite orienteering performance.

1. Introduction

Orienteering is a complex endurance sport that requires the continuous integration of physical, cognitive and technical components. Unlike traditional linear running events, orienteers must repeatedly alternate between map reading, spatial decision-making, route choice and variable-speed running across mixed terrain (Larsson, Burlin, Jakobsson, & Henriksson-Larsén, 2002; Rattray &

* *E-mail*: vminoiu@yahoo.com

Roberts, 2012; Tønnessen et al., 2015). These rapid transitions between navigation and locomotion impose combined physiological and cognitive demands, challenging both metabolic efficiency and executive functioning (Bao, Liu, & Liu, 2022). As a result, evaluating performance in orienteering requires a multidimensional framework that captures not only physical capacity but also navigational consistency and decision-making precision.

Heart rate variability (HRV) has become an important marker of autonomic regulation, recovery status and adaptation to training in endurance sports (Buchheit, 2014). Time-domain indices such as the root mean square of successive differences (RMSSD) and its natural logarithm (lnRMSSD) are commonly used to assess parasympathetic activity and training readiness (Plews, Laursen, Stanley, Kilding, & Buchheit, 2013). The use of rolling averages and threshold-based interpretation, such as the smallest worthwhile change (SWC), improves the detection of meaningful variation in HRV over days and weeks (Addleman, Lackey, DeBlauw, & Hajduczok, 2024; Kaufmann, Gronwald, Herold, & Hoos, 2023). Recent findings in elite orienteers have shown that competitive pressure can acutely alter HRV, confirming its relevance for monitoring readiness and stress in this sport (Gorgulu, Oruç, Vasile, Corlaci, & Voinea, 2024). In younger orienteers, pre- and post-competition changes in self-esteem, activity and mood indicate that competition also affects the athlete's psychological state, not only physiological readiness (Sirakova, 2026).

Internal physiological load, often quantified using Training Impulse (TRIMP) and heart-rate zone distribution, provides complementary information about the cost of training and competition (Seiler & Kjerland, 2006; Tønnessen et al., 2015). In mixed-terrain and trail running, reductions in heart rate and TRIMP at similar or higher external workloads are considered markers of improved efficiency and submaximal tolerance (Coates, Berard, King, & Burr, 2021). For orienteers, who operate in complex terrain with frequent changes of speed and direction, the interaction between HRV-derived readiness and TRIMP-based internal load may be particularly informative.

Because success in orienteering is determined not only by physiological performance but also by navigational accuracy, split-based competition diagnostics are essential. Indicators such as Performance Index (PI), split-loss, time behind an idealized cumulative time ("Superman"), error-free time and the Consistency coefficient quantify leg-by-leg execution and error accumulation (Larsson et al., 2002; Minoiu & Minoiu, 2019; Sirakov & Belomazheva -Dimitrova, 2018). Previous work has shown that elite orienteers typically avoid large navigation errors and maintain stable execution rather than relying on isolated fastest legs (Minoiu & Minoiu, 2017; Minoiu & Minoiu, 2019). Analyses of youth athletes further emphasize the importance of reducing error frequency and improving consistency early in the development pathway (Minoiu, Orțănescu, & Minoiu, 2022).

Integrating HRV-based autonomic readiness, internal-load metrics and split-level execution analysis may therefore provide a more complete understanding of performance development in orienteering. Longitudinal single-athlete designs are particularly valuable in elite sport, where individual training responses and performance trajectories often cannot be captured adequately by group averages. Relatedly, recent longitudinal analyses of university-level orienteering results have shown that stable competitive patterns can be described from multi-season race records, reinforcing the value of performance tracking across successive seasons (Sirakov, 2025).

The present 5-year longitudinal case study (2020–2025) aimed to characterize how rolling-window HRV trends, internal training load and split-based competition indices evolved in an elite male orienteer progressing from junior to senior national team level. We examined changes in morning lnRMSSD and related autonomic indices across consecutive seasons, the interaction between HRV and TRIMP-based internal load, and the consistency of competition execution derived from split-time analysis in key national and international events. Beyond orienteering, integrating rolling-window HRV with TRIMP and split-based performance indices may offer a reusable template for long-term monitoring of training adaptation and competition execution in endurance and mixed-terrain disciplines.

2. Material and methods

Purpose of the study

The purpose of this longitudinal case study was to determine whether five-season changes in rolling-window HRV were associated with changes in internal training load and split-based competition consistency in an elite male orienteer progressing from junior to senior international level.

Hypotheses

It was hypothesized that favorable long-term adaptation would be reflected by higher rolling lnRMSSD and PNS Index, lower resting heart rate and Stress Index, lower internal load for comparable external demands, and better split-based outcomes, expressed by fewer major navigation errors, smaller cumulative time loss, and greater leg-by-leg consistency.

Study design and participant

This investigation was conducted as a longitudinal single-case study over five competitive seasons (2020–2025). The participant was an elite young male orienteer, part of a national development programme, competing at national and international level (sprint, middle and long distance). All measurements were integrated in the athlete’s normal monitoring process. Written informed consent was obtained from the athlete (and guardian in the early years), and data were anonymised for analysis and publication.

Heart rate variability monitoring and analysis

Daily morning heart rate variability (HRV) was recorded in the supine position for 5 minutes, immediately after waking, under stable conditions (no caffeine, standard room environment). RR intervals were collected using a validated chest-strap heart rate sensor (Garmin HRM-Pro / HRM-Pro Plus) paired with a sports watch (Mishica et al., 2022).

HRV analysis was performed using Kubios HRV Scientific (Tarvainen, Niskanen, Lipponen, Ranta-Aho, & Karjalainen, 2014). The following indices were extracted: root mean square of successive differences (RMSSD, ms), the natural logarithm of RMSSD (lnRMSSD), parasympathetic nervous system index (PNS Index), sympathetic nervous system index (SNS Index) and Stress Index. Artefact correction used the built-in threshold-based filter (low–very low). HRV trends were examined using 7-day rolling averages and 21–28-day baseline values, interpreted relative to the smallest worthwhile change and minimal detectable change as suggested in recent HRV monitoring literature (Addleman et al., 2024; Kaufmann et al., 2023).

Internal load monitoring

Internal load was quantified using Training Impulse (TRIMP and TRIMP per minute), heart-rate zone distribution with individually calibrated zone boundaries, acute and chronic training load indices, and the aerobic and anaerobic Training Effect. These metrics were obtained from Firstbeat Sports and TrainingPeaks, based on heart rate recordings during training and competition. Training intensity distribution (time in low, moderate and high heart-rate zones and time above the second ventilatory threshold, VT2) was used to describe the overall internal load profile in relation to external demands.

Standardized 6-km mixed-terrain test

To assess changes in mixed-terrain running performance and physiological cost under reproducible conditions, the athlete completed a standardized 6-km test with approximately +240 m elevation gain in May 2023 and May 2024. The route, surface and elevation profile were identical in both years, and tests were scheduled at a similar time of day and in comparable weather conditions.

During each test, we collected total time (min), mean and maximal heart rate (bpm), TRIMP and TRIMP per minute, estimated ventilatory thresholds (VT1, VT2) and the percentage of time above VT2, heart-rate zone distribution, respiratory rate, and estimated VO_2max (where available from Firstbeat reports). These tests provided a controlled comparison of physiological efficiency and pacing between the two seasons.

Competition execution analysis

Competition execution was analysed using data from South-East European Orienteering Championships (SEEOC) events in 2021 and 2022 (sprint and long distance). Official split times were imported into WinSplits Pro to compute time-behind Superman (cumulative deficit relative to the ideal combination of best leg times), split-loss (time lost per leg relative to reference speed), Performance Index (PI; relative speed compared with the fastest 25% of split times), the Consistency coefficient (variation of PI across legs, weighted by leg length), and error-free time and the occurrence of major mistakes.

Route choices and running lines were examined using Livelox GPS data to confirm navigation errors, route suboptimality and pack-related effects. The sprint race from SEEOC 2022 (M16) was selected as a key example for detailed split-based performance and consistency analysis.

3. Results and discussions

HRV readiness trends (2023–2024)

Daily morning HRV recordings demonstrated a favourable autonomic evolution across the analysed period. From 2023 to 2024, lnRMSSD increased by 8.49%, while RMSSD increased by 31.12%, indicating enhanced parasympathetic modulation. In parallel, the PNS Index increased by 50%, whereas Stress Index decreased by 9.76%, suggesting reduced overall autonomic strain and improved readiness for training.

Seven-day rolling lnRMSSD curves showed an oscillatory pattern with transient reductions during high-load microcycles, followed by recoveries to or above baseline in lower-load weeks. This pattern reflects an appropriate relationship between load and recovery and is characteristic of favourable training adaptation in endurance athletes.

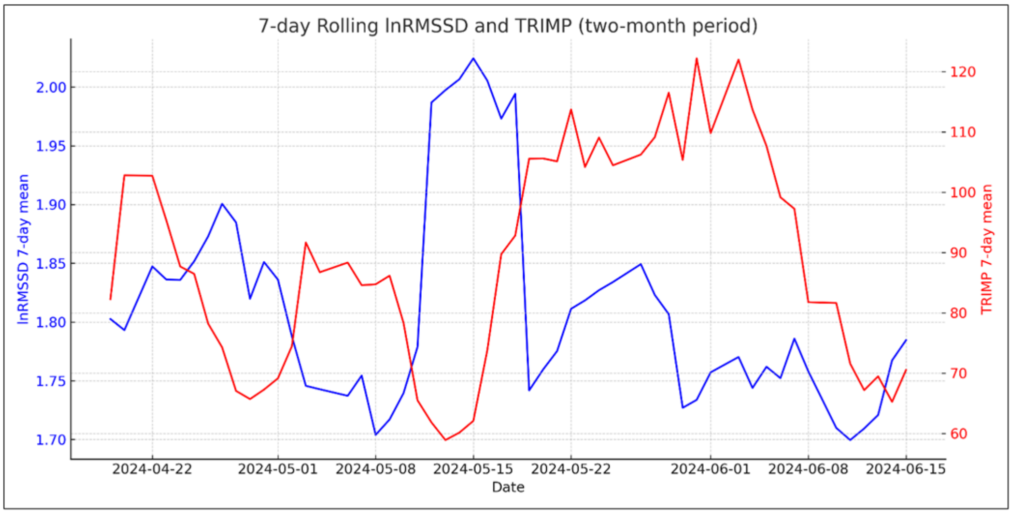

Figure 1. *7-day rolling lnRMSSD and TRIMP trends, April–June 2024*

Internal load

Internal physiological load showed a substantial reduction between 2023 and 2024, despite comparable external training volume and intensity. Training Impulse (TRIMP) decreased from 62.1 to 49.6, representing a relative reduction of 20.1%, indicating a lower cardiovascular and metabolic cost for similar workloads. Mean heart rate recorded during matched mixed-terrain sessions also declined from 180 to 174 beats per minute, suggesting improved submaximal efficiency and reduced autonomic strain during running efforts.

The distribution of training intensity shifted toward a more favourable aerobic profile. The proportion of training time spent above 182 beats per minute decreased by 10.8%, while time accumulated in lower and moderate heart-rate zones (below 160 bpm and between 160–182 bpm) increased. This redistribution reflects enhanced tolerance to aerobic intensities and greater efficiency in sustaining prolonged efforts.

Together, these internal-load adaptations indicate that the athlete required less physiological effort to sustain equal or slightly higher training demands, consistent with improved running economy in mixed-terrain conditions.

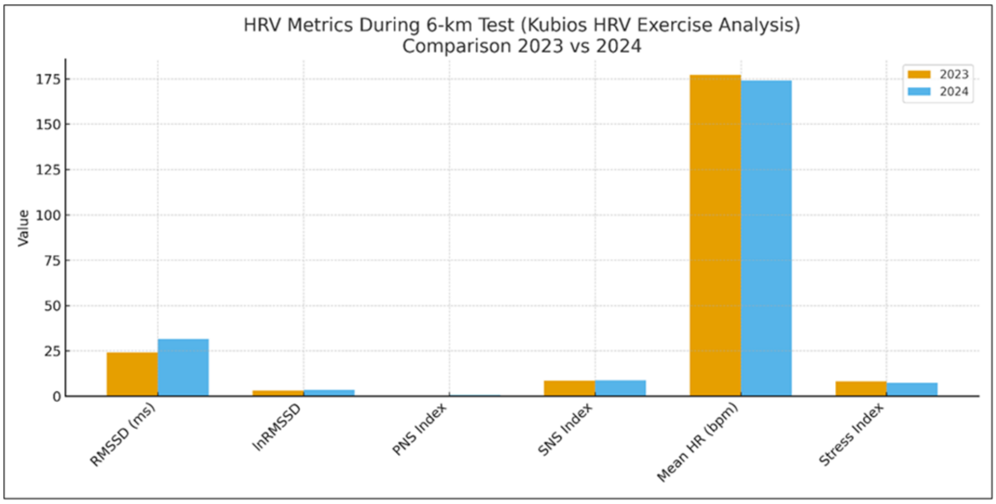

Figure 2. *HRV during effort: RMSSD, lnRMSSD, PNS, Stress Index, HR; comparison between test 2023 and 2024*

Changes in physiological and autonomic responses during the standardized 6-km test (2023 vs 2024)

Compared with 2023, the 2024 test was completed in a shorter time, corresponding to a 4.27% improvement in performance, with a lower mean heart rate and a markedly reduced internal load (TRIMP decreased by 20.1%; Figure 3). The proportion of time spent above the second ventilatory threshold (VT2) decreased by 10.8%, whereas time accumulated in the moderate-intensity zone between VT1 and VT2 increased by 59.7%.

These changes were accompanied by clear improvements in HRV metrics during the 6-km effort (Figure 2): RMSSD increased by 31.1%, lnRMSSD by 8.5%, and PNS Index by 50.0%, while SNS Index and Stress Index showed modest reductions. Together, these results indicate improved metabolic efficiency and autonomic regulation during the standardized mixed-terrain test.

Integrated interpretation of physiological and technical indicators

Across the 2023–2024 training cycle, improvements in HRV-based readiness were coherently aligned with reductions in internal load and enhancements in mixed-terrain test performance. Simultaneously, competition analyses documented high stability of execution and minimal cumulative time loss in a key international sprint event.

This convergence between autonomic readiness (lnRMSSD, RMSSD, PNS Index, Stress Index), physiological efficiency (TRIMP, heart rate, VT1–VT2 distribution) and technical performance (Performance Index, consistency, time-behind Superman) suggests that the athlete's overall performance capacity improved in a balanced and integrated manner. These findings support the use of combined HRV, internal load and split-analysis monitoring to guide micro-periodisation and performance management in elite orienteering.

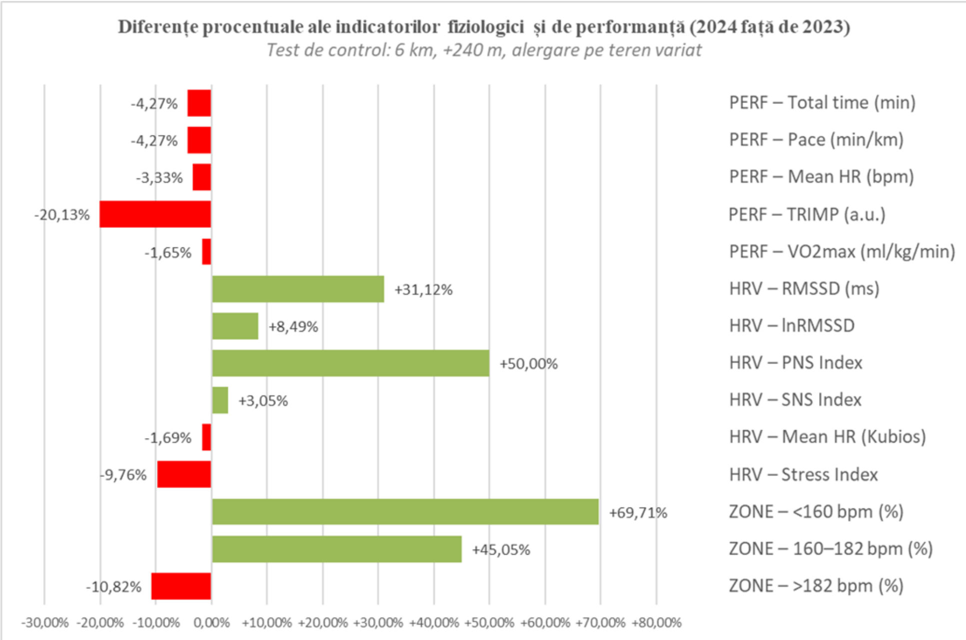

Figure 3. *Comparison of 6-km test performance and internal load between 2023 and 2024*

Competition execution analysis (SEEOC 2022 sprint)

Split-based analysis of the SEEOC 2022 sprint event highlighted the athlete's exceptional technical stability. The overall Performance Index (PI) was 101.8%, indicating that, on average, the athlete ran individual legs faster than the reference speed defined by the fastest 25% of split times. The Consistency value was 6.8%, reflecting low variability in PI across legs and highly uniform execution.

Cumulative time-behind Superman at the finish was +0:35, while the next three finishers accumulated deficits between +0:55 and +1:20. Per-leg PI values clustered predominantly between 102% and 108%, confirming consistently strong leg-by-leg performance rather than isolated fastest splits. The time-behind curve remained nearly horizontal throughout the course, indicating minimal cumulative time loss and the absence of major navigational errors.

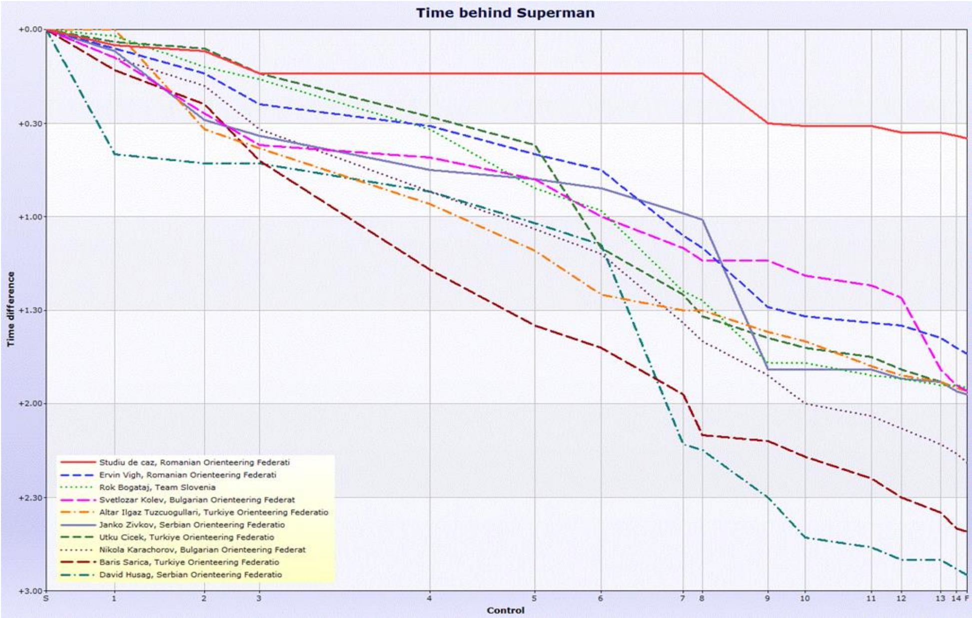

Figure 4. *Time-behind Superman curves for top 4 finishers; SEEOC 2022 Sprint, M16*

In addition to the time-behind analysis, Performance Index values for the athletes in the SEEOC 2022 sprint final (M16) are shown in Figure 5. The case-study athlete obtained the highest overall PI (101.8%), whereas the other finalists exhibited clearly lower values, ranging between 61.2% and 93.1%. This distribution confirms that, at the level of split analysis, the case-study athlete outperformed his competitors both in absolute terms and in relative leg-by-leg performance.

Studiu de caz, Romanian Orienteering Federati			
Result			
Final time	12:20	(1)	-1:09
Time behind winner (%)	+0,0%		
Time behind Superman	+0:35		
Time behind Superman (%)	+5,0%		
Performance index	101,8%		
Errors			
Number of legs with errors	0	(1)	
Time lost	0:00	(1)	
Time lost (%)	0,0%	(1)	
Error-free time	12:20	(1)	-0:40
Error-free performance index	101,8%		
Pack running			
Pull index	7,1%	(11)	
Following index	13,4%	(7)	
Time gained by following	0:01	(11)	
Miscellaneous			
Start time	18:00	(19)	+18:00
Consistency	6,5%	(3)	

Performance indices	
1. Studiu de caz	101,8%
2. Ervin Vigh	93,1%
3. Rok Bogataj	91,9%
4. Altar Ilgaz Tuzcuogullari	91,7%
4. Svetlozar Kolev	91,7%
6. Utku Cicek	91,6%
6. Janko Zivkov	91,6%
8. Nikola Karachorov	89,2%
9. Baris Sarica	87,0%
10. David Husag	85,6%
11. Djan Ahmedov	85,4%
12. Luka Seljak	84,8%
13. Lucas Tamas	84,0%
14. Stefan Gherciu	82,9%
15. Emre Kirgil	82,6%
16. Vlad Percec	81,3%
17. Artiom Babici	80,8%
18. Ion Ceban	77,8%
19. Noa Kelc	76,5%
20. Anton Hristov	75,2%
21. Bozo Bizjak	73,8%
22. David Petrovic	69,2%
23. Jaka Seljak	61,2%

Performance index per leg for Studiu de caz	
Leg 5-6	108,1%
Leg 6-7	107,9%
Leg 4-5	107,7%
Leg 3-4	105,5%
Leg 7-8	105,2%
Leg 13-14	105,1%
Leg 12-13	104,5%
Leg 10-11	103,4%
Leg 1-2	102,1%
Leg 9-10	102,0%
Leg 11-12	98,4%
Leg 14-F	98,1%
Leg S-1	98,0%
Leg 2-3	93,9%
Leg 8-9	82,9%

Figure 5. *Performance indices and leg-by-leg stability in the SEEOC 2022 sprint M16*

The figure shows (a) global race outcomes for each athlete (final time, time behind the “Superman”, overall Performance Index), (b) the distribution of Performance Index values for the top ten athletes, and (c) the leg-by-leg Performance Index of the case-study athlete.

Discussions

The purpose of this longitudinal case study was to explore the interaction between autonomic readiness (HRV), internal load (TRIMP and HR distribution), physiological efficiency (mixed-terrain testing) and technical execution (split-based indicators) in an elite youth orienteer over a five-year period. The main findings demonstrate a coherent progression across physiological and technical domains: improved HRV readiness, reduced internal load for similar external demands, enhanced running efficiency in standardized testing, and highly stable performance execution in competition.

Autonomic readiness and training response

The increase in lnRMSSD (+8.49%) and RMSSD (+31.12%) between 2023 and 2024 indicates a substantial enhancement in parasympathetic regulation. Elevated PNS Index (+50%) and reduced Stress Index (−9.76%) further support improved autonomic balance. Such patterns are typically associated with enhanced recovery capacity, reduced cumulative fatigue and balanced adaptation to training stimulus (Buchheit, 2014; Kaufmann et al., 2023). The sinusoidal but upward trend in rolling HRV windows suggests that the athlete tolerated training loads well and was able to recover efficiently between high-load microcycles. This pattern is consistent with recent evidence showing that morning heart rate–derived indices are reliable and sensitive markers of training-induced changes in autonomic function of young athletes (Mishica et al., 2022).

Competition pressure is known to affect autonomic regulation, particularly in technically demanding sports such as orienteering (Gorgulu et al., 2024). The favourable HRV profile observed during the pre-competitive period supports the hypothesis that sustained autonomic stability may facilitate improved decision-making and precision in navigation tasks, especially in sprint formats where errors are heavily penalized.

Internal load reduction and efficiency gains

Despite comparable external workload characteristics, the athlete displayed markedly reduced internal load in 2024. TRIMP decreased by 20.1%, and mean heart rate during matched sessions decreased from 180 to 174 bpm. This finding is highly relevant: reductions in internal load at equal or higher intensities typically reflect improved aerobic efficiency and lower physiological strain (Seiler & Kjerland, 2006; Tønnessen et al., 2015). The shift toward a more aerobic intensity distribution (increased time in <160 bpm and 160–182 bpm zones, and reduced time above 182 bpm) suggests improved metabolic flexibility and a better balance between aerobic and anaerobic contributions.

The reduction of time spent above VT2, from 56.2% to 40.4% during the standardized 6-km test, further reinforces this interpretation. A lower proportion of time above VT2 indicates reduced reliance on anaerobic metabolism, improved lactate clearance capacity and enhanced tolerance to sustained mixed-terrain efforts (Coates et al., 2021).

Improved performance in standardized mixed-terrain testing

The improvement in test time (−4.27%) reflects a meaningful enhancement in performance capacity. Considering that route, elevation gain, technical difficulty and environmental conditions were constant across years, performance benefits must be attributed to improved physiological readiness, technical running economy and pacing control. Reduced cardiovascular effort (−3.33% mean HR) and lower internal load accompanying improved performance confirm greater submaximal efficiency—an essential predictor of success in orienteering, where athletes must sustain variable intensities across uneven terrain.

Together, these adaptations support the utility of HRV-guided monitoring and load regulation in mixed-terrain athletes, extending prior findings from endurance disciplines (Kaufmann et al., 2023; Nuuttila, Nummela, Kyröläinen, Laukkanen, & Häkkinen, 2022; Plews et al., 2013).

Competition execution: stability as a key performance driver

Split-based analysis of the SEEOC 2022 sprint race revealed exceptionally stable execution. A Performance Index of 101.8% indicates superior leg-by-leg performance relative to class reference times, while the Consistency value of 6.8% reflects low variability across segments.

The distribution of Performance Index values for the top ten athletes (Figure 5) further supports this interpretation. The case-study athlete not only recorded the highest overall PI (101.8%) but also displayed a much more compact PI profile compared with the other finalists (61.2–93.1%). From a performance-analysis perspective, this pattern indicates that he was able to maintain a consistently high relative speed across legs, whereas the other athletes showed larger leg-to-leg variability and more pronounced time losses on specific segments. This higher level of stability is consistent with the longitudinal improvements in HRV-based readiness and reduced internal load observed in this study, suggesting that favourable autonomic and load profiles may be associated with more reliable technical performance under sprint-race pressure. Prior research demonstrates that consistent execution—not isolated best-leg performances—predicts competitive outcomes (Larsson et al., 2002; Minoiu & Minoiu, 2019; Sirakov & Belomazheva-Dimitrova, 2018).

The athlete remained within 35 seconds of the Superman time at the finish, despite other competitors achieving fastest-leg times on some segments. This finding aligns with evidence that minimizing large errors and maintaining close adherence to optimal navigation patterns is more important than producing occasional peak speeds (Minoiu & Minoiu, 2017; Minoiu & Minoiu, 2019). In sprint orienteering, where time-losses accumulate rapidly, such stability is a hallmark of elite technical proficiency. Beyond the competitions analysed in detail here, during the most recent season the athlete translated these adaptations into tangible results in athletics, obtaining 16 medals at national championships (indoor and outdoor) and podium finishes at Balkan level in 800 m, 1500 m, 10 km track event and mountain running events, in addition to his orienteering performances. These outcomes support the external validity and ecological robustness of the monitoring framework applied in this case study.

Practical applications

From a practical standpoint, the present 5-year case study suggests several guidelines for coaches and sport scientists working with orienteers and other endurance athletes:

Monitoring 3–7 day rolling lnRMSSD windows together with weekly TRIMP can help differentiate favourable from unfavourable adaptation during periods of intensified training.

Split-based performance and consistency indices across key competitions provide complementary information to global season metrics and can inform individual race strategies (for example, balancing pacing and risk-taking at decisive controls).

Simple morning heart rate and HRV recordings, analysed with dedicated software such as Kubios HRV, appear sufficiently sensitive for long-term monitoring of autonomic status, potentially reducing the need for more complex nocturnal recordings.

Collectively, these elements form a practical framework that can be adapted and tested in larger samples and across other endurance and mixed-terrain sports where both physiological load and decision-making under pressure are critical for performance.

4. Conclusions

This longitudinal case study demonstrated that integrating heart rate variability (HRV), internal load monitoring and split-based competition diagnostics provides a coherent and practical framework for understanding and optimising performance in elite orienteering. Improvements in autonomic readiness (higher lnRMSSD, RMSSD and PNS Index, and reduced Stress Index) coincided with lower physiological cost during training and testing, as shown by reductions in TRIMP, mean heart rate and time spent above the second ventilatory threshold (VT2).

The athlete's enhanced physiological efficiency was matched by superior technical performance. In the SEEOC 2022 sprint event, he achieved a Performance Index of 101.8%, no major errors and a low consistency value (6.8%), reflecting stable execution and minimal cumulative time-loss. The alignment between favourable HRV trends, reduced internal load and competition stability suggests that autonomic readiness may play a meaningful role in sustaining technical precision under competitive stress.

Overall, the integrated approach used in this study may provide a valuable model for micro-periodisation and monitoring in elite orienteering, supporting both physiological efficiency and technical consistency. Coaches and athletes may benefit from combining HRV monitoring, TRIMP-based load analysis and split-based diagnostics to guide load adjustments, identify readiness states and support performance planning.

Limitations and future directions

This study examined a single elite youth athlete, which limits the generalisability of the findings. Although HRV recordings were performed under standardised conditions, factors such as sleep quality, psychological stress and external life stressors could not be controlled with experimental precision. Internal load was quantified predominantly through heart rate-based metrics, while biomechanical and metabolic markers were not continuously monitored. Competition analyses were based on available split times and GPS tracking; environmental variability (terrain characteristics, vegetation density, weather) may have influenced execution and was not standardised across seasons.

Future studies should include larger samples and incorporate multi-sensor data (e.g., GNSS-based positioning, inertial measures, and indices of cognitive load) to characterise more comprehensively the interplay between physiological readiness and technical performance. It would also be valuable to examine HRV-guided training and its relationship with execution quality in different orienteering formats (sprint, middle, long distance; urban vs. forest terrain). Integrating machine-learning-based route analysis and real-time physiological monitoring may further enhance the predictive power of combined physiological–technical models.

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