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The cortisol awakening response (CAR) of elite athletes is elevated before a competition, but no interaction with sport type

M. Jiménez [a,h,*], G. Lopez-Lluch [b], F.J. Barón-López [c], J. Benítez-Porres [d,e,f], J. Gallardo-Pérez [a], Rivilla-Arias I [a], B.T. Crewther [g], P. Mehta [h]

[a] Departamento de Didáctica de la Educación Física y Salud, Facultad de Ciencias de la Educación y Humanidades, Universidad Internacional de La Rioja, Spain
[b] Departamento De Fisiología, Anatomía y Biología Celular, Centro Andaluz de Biología del Desarrollo (CABD-CSIC-JA), Centro de Investigación en Rendimiento Físico y Deportivo (CIRFD), Universidad Pablo de Olavide, Spain
[c] Departamento de Salud Pública y Psiquiatría, Facultad de Ciencias de la Salud, Universidad de Málaga, Spain
[d] Instituto de Investigación Biomédica de Málaga, IBIMA-Plataforma BIONAND, Málaga, Spain
[e] CIBER Fisiopatología de la Obesidad y Nutrición (CIBEROBN), Instituto de Salud Carlos III, Málaga, Spain
[f] Área de Educación Física y Deportiva, Facultad de Medicina, Universidad de Málaga, Spain
[g] Department of Endocrinology, Institute of Sport – National Research Institute, Warsaw, Poland
[h] Department of Experimental Psychology, Faculty of Brain Sciences, University College of London, United Kingdom

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ABSTRACT

The cortisol awakening response (CAR) is thought to represent an anticipatory mechanism to prepare for upcoming demands. In sport, competition increases in the CAR have been reported, although findings remain inconsistent. A study on amateur athletes identified a divergent CAR between individual-sport (IS) and team-sport (TS) athletes, thereby highlighting sport type as a confounding factor. Our aim was to determine whether competition-related changes in the CAR are robust in elite athletes and whether sport type moderates this response. Using a within-subject crossover design, 190 elite athletes (58 women) from seven sports (soccer, field hockey, handball, badminton, athletics, swimming, and judo) provided saliva samples upon awakening (T0) and 30 min after awakening (T30) on both a competition day and a rest day. The CAR was quantified as a change score (T30 − T0) based on log-transformed and raw values. Both sets of analyses revealed a significant trial effect ($p < 0.001$). The CAR was greater on competition days (back-transformed mean = 82.1%, 4.81 ng/mL raw units) than on resting days (mean = 24.7%, 0.99 ng/mL), representing large effect size differences. No significant effect of sport type, nor a trial × sport type interaction, was detected. In conclusion, we observed a robust elevation in CAR on competition mornings in elite athletes, compatible with anticipatory processes and potential training-related influences. In contrast to findings in amateur athletes, the CAR did not differ between IS and TS athletes, suggesting a relatively consistent CAR pattern across sports played at the elite level.

1. Introduction

The cortisol awakening response (CAR) is a distinct feature of hypothalamic-pituitary-adrenal (HPA) activity, characterised by a surge in cortisol concentrations within the first 30–45 min following awakening (Pruessner et al., 1997). According to the Anticipation Hypothesis (Fries et al., 2009; Powell and Schlotz, 2012), the CAR represents an adaptive mechanism to support expected demands of the forthcoming day. In sport, evidence supporting this hypothesis includes reports of an augmented CAR prior to athletic competition compared with rest or control days (Meggs et al., 2016; Lee et al., 2020; Kayacan et al., 2022). Here, a more marked CAR may help meet the physical, cognitive, and psychosocial demands of competitive sports performance (Kayacan et al., 2021). Similarly, Aguilar et al. (2018) observed a higher CAR in climbers on ascent days compared with Sherpas at the same altitude and non-climbers at sea level, further supporting the role of anticipated challenge in shaping CAR magnitude.

The CAR is a rapid activation of the HPA axis regulated by the interplay of circadian rhythms, emotional responses, and anticipatory cognition (Fries et al., 2009; Stalder et al., 2025). This phenomenon is

* Correspondence to: Departamento de Didáctica de la Educación Física y Salud, Facultad de Ciencias de la Educación y Humanidades, Universidad Internacional de La Rioja, Avenida de la Paz, 137, Logroño 26006, Spain.
E-mail address: manuel.jimenez@unir.net (M. Jiménez).

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associated with increased alertness, energy mobilisation, and goal-directed behaviour, supporting the interpretation that CAR functions as a preparatory mechanism for specific contextual demands rather than stress per se (Stalder, Oster et al., 2025). Among elite athletes, CAR is also linked to physiological systems, including the metabolic, immune, and nervous systems (Fries et al., 2009; Kayacan et al., 2021). This response reflects coordinated activation of the HPA axis and is associated with broader physiological regulation, including interactions with autonomic function in athletic populations (Kayacan et al., 2021).

The CAR can be understood as a dynamic indicator of HPA axis response to anticipated demands in sports competition. Some studies suggest that the CAR can be regarded as a valuable marker of preparedness for physical or mental challenges (Meggs et al., 2016; Lee et al., 2020). However, given that our study utilized only two sampling time points, the interpretation is restricted to acute CAR reactivity rather than broader or sustained hormonal patterns.

Despite this general pattern, findings on the CAR in sport are not uniform, with several studies reporting attenuated or absent competition-related effects (Strahler et al., 2010; Balthazar et al., 2012; Díaz et al., 2013; MacDonald and Wetherell, 2019). One potential source of this heterogeneity is sport type, particularly between individual-sport (IS) and team-sport (TS) athletes. Page et al. (2024) also reported no overall difference in CAR between competition and baseline trials in amateur athletes. However, IS athletes demonstrated an elevated CAR on competition days, whereas TS athletes exhibited a blunted response. These patterns may reflect different psychosocial demands: IS athletes bear greater individual responsibility for performance outcomes, whereas TS athletes operate within shared responsibility structures and collective goal environments. Moreover, individual evaluation in sport may elicit stronger social-evaluative threat responses, including HPA-axis activity, compared with team-based performance (Rohleder et al., 2007). However, interpretation of these findings is constrained by small sample size (IS n = 24; TS n = 13), and empirical evidence supporting sport-type differences remains limited, particularly in elite athletic populations.

Whether competition-related changes in CAR are robust across different physiological demands in sport and consistent at the individual level in elite populations remains unclear, particularly as elite athletes may differ from amateur populations in their psychophysiological responses to competition, including HPA-axis regulation and anticipatory response, due to repeated exposure to high-pressure environments, structured training routines, and refined coping strategies. To address these limitations and evaluate the reproducibility of sport-type differences in the CAR, the present study replicated the Page et al., (2024) work in a large, multisport sample of elite IS and TS athletes of both sexes. By focusing on elite performers and increasing statistical power, this study aims to clarify whether competition-related changes in the CAR are robust and whether sport type modulates these changes. Two hypotheses were tested: (H1) the CAR would be greater on competition days than on resting days, and (H2) the competition-related CAR would differ between IS and TS athletes.

2. Materials and Methods

2.1. Participants

One hundred and ninety elite athletes (58 women) from seven different sports (i.e., soccer, field hockey, handball, badminton, athletics, swimming, judo) were recruited from professional clubs in Spain, Russia, and the United Kingdom. The athletes had at least 10 years of training experience, were members of the top division in their respective sports, and had competed in continental, world, and/or Olympic championships. The IS ($n = 85$) and TS ($n = 105$) groups had a mean age (±SD) of 24.3 ± 4.2 and 25.9 ± 4.7 years, and body-mass index (BMI) of 22.01 ± 1.87 and 22.41 ± 1.47 kg/m^2, respectively. Exclusion criteria included any diagnosed metabolic, endocrine, or psychiatric disorder, as well as the current use of oral contraceptives and/or psychotropic medications. Ethics approval was obtained from the Research Ethics Committees of the International University of La Rioja (PI010/2022) and the University of Malaga (CEUMA35/2018H).

2.2. Study design

A within-subject crossover design was employed, whereby allocation to the treatment (competition) and control (rest) trials was determined by practical constraints inherent to elite sport settings rather than by true random assignment. Consequently, the study is best described as quasi-experimental. Nevertheless, each athlete served as their own control when evaluating the competition CAR and the rest-day response. Both trials were conducted during the competitive season for each sport and were separated by 2 −7 days. As is standard in elite sport, the athletes followed a planned taper prior to competition, involving a reduction in training load over several days and no intense exercise in the final 24 h. To minimise training-induced effects on HPA activity, the rest days were scheduled in consultation with coaching staff to ensure 24–48 h recovery after the most recent training session.

In each trial, saliva samples were collected upon awakening (T0) and 30 min later (T30), with sampling permitted within ±2 min of the target times; athletes exceeding this window were excluded from the main analyses. Two-point sampling is common in elite sport (Balthazar, Garcia and Spadari-Bratfisch, 2012, MacDonald and Wetherell, 2019, Crewther et al., 2025) and other challenging (e.g., mountain climbing) environments (Aguilar et al., 2018), allowing us to capture the rising phase of the CAR while minimising disruptions to athletes' routines. To enhance compliance and reduce sampling error, sample collections were conducted at team accommodations by coaching staff and study investigators. Athletes were woken by alarm or staff (typically between 6:30–8:30 a.m.) and instructed to avoid eating, drinking, brushing teeth, or consuming supplements until after the T30 sample.

2.3. Salivary cortisol testing

The saliva samples were stored in a refrigerator for ~20 min, centrifuged at 3000 rpm for 15 min, before a separate aliquot was saved in a commercial freezer. The samples were transported to the Hospital Regional Materno-Infantil de Málaga, Spain, for testing. Cortisol concentrations were determined in duplicate using an immunoassay kit (Diametra®, Milano, Italy) with a sensitivity of 0.12 ng/mL and range of 0.5 −100 ng/mL. All manual assay steps were automated using the Triturus® Multi-Immunoanalyzer (Grifols©, Barcelona, Spain). The intra- and inter-assay coefficients of variation (CV) across all plates were 3.5% and 10.3%, respectively. Each participants' samples were tested in the same plate to reduce inter-assay variability, with all cortisol assays run by the same experienced technicians.

2.4. Statistical analyses

This study examined the CAR as an index of hormone reactivity to awakening rather than total secretory output, as the latter may conflate dynamic response with overall cortisol volume. To capture this, the CAR was quantified as the log-transformed delta change between awakening (T0) and post-awakening (T30) cortisol concentrations (Crewther, Serpell et al., 2024). This approach accounts for interindividual differences in baseline (T0) cortisol, as the log difference between two values approximates a proportional (%) change, and it yielded a normally distributed outcome. Moreover, this metric correlates strongly with the CAR derived from area under the curve with respect to increase (AUCi) (Crewther, Serpell et al., 2024). Subset analyses ($n = 12$) in this study confirmed very strong correlations ($r = 0.89$ −0.95) between the CAR log-difference and AUCi measurements at T0-T15, T15-T30 and T0-T30.

Study hypotheses were tested using a two-way analysis of variance (trial, sport type, and their interaction) in a linear mixed-effects

framework. The model included a random intercept for each participant and gender as a covariate. When significant effects were observed, estimated marginal means were calculated with a 95% confidence interval (CI) and Tukey-adjusted post hoc contrasts performed. Cohen's *d* was computed as an effect-size estimate. At the request of a reviewer, we repeated this model on the raw (untransformed) delta change in cortisol concentrations and estimated within-person variability in the CAR. All analyses were conducted in R Studio, with statistical significance set at $\alpha = 0.05$.

3. Results

Participant distribution by sport type, discipline, and gender is outlined in Table 1. Study participation was higher among TS athletes (55.3% of total sample), largely driven by football players (40.5%, all male). In contrast, IS athletes (44.7%) presented a more even distribution across sport disciplines and genders. Within the IS category, female representation (51.8%) was comparable to males (48.2%), while those athletes in the TS group were predominantly male (86.7%).

Descriptive means (±SD) for cortisol measurements at T0 and T30 are presented in Fig. 1A. The model-estimated marginal means are shown as a percentage change (Fig. 1B) after back transformation of the log differences [100*(exp(x) – 1)]. A significant trial effect was observed, $F(1, 188) = 66.98$, $p < 0.001$. The CAR on competition days (82.1%) was substantially greater than on rest days (24.7%), with a large effect size ($d = 0.84$, 95% CI [0.63, 1.06]). No effect of sport type was detected, $F(1, 187) = 0.008$, $p = 0.928$, nor a trial × sport type interaction, $F(1, 188) = 0.100$, $p = 0.753$. Analysis of the raw cortisol changes revealed identical patterns (Fig. 1C). The trial effect was significant, $F(1, 188) = 78.6$, $p < 0.001$, with a larger CAR on the morning of competition (4.81 ng/mL) versus rest (0.99 ng/mL), representing a large effect ($d = 0.91$, 95% CI [0.70, 1.13]). Non-significant effects emerged for sport type, $F(1, 187) = 0.041$, $p = 0.839$, and the interaction term, $F(1, 188) = 0.0001$, $p = 0.991$. A Wald test indicated that the cortisol change scores (both log and raw values) were significantly greater than zero across all trials ($p \leq 0.003$).

Although models were fitted to both the log-transformed and raw CAR, variability estimates were derived from the former model due to improved distributional properties. Briefly, we extracted the residual SD to estimate a CV relative to the estimated marginal mean. The residual SD of the log-transformed CAR was 0.45, corresponding to a CV of 47.3%, indicating substantial within-subject variability from the marginal mean CAR.

At the request of another reviewer, we repeated our main analyses based on a physiological classification of endurance-dominant ($n = 141$) and power/technical-dominant sports ($n = 49$). Replicating the main results, the trial effect was significant ($p < 0.001$), whereas the group effect and trial × group interaction were both non-significant ($p \geq 0.203$). The classification criteria and model output are provided in a supplemental file. Finally, the CAR was plotted (as a %) across individual sport disciplines: see Figure S1. The proportional changes in cortisol were consistently higher on competition days (48.6 −181.7%) than on rest days (2.5 −58.0%), with a mean difference of 62.1% across all disciplines.

Table 1
Participant distribution across sport type and discipline by gender, presented as counts and percentage of the total sample.

Sport type	Discipline	Gender	Count	% Total
Individual	Swimming	Female	4	2.1
Individual	Swimming	Male	8	4.2
Individual	Athletics	Female	13	6.8
Individual	Athletics	Male	11	5.8
Individual	Badminton	Female	20	10.5
Individual	Badminton	Male	14	7.4
Individual	Judo	Female	7	3.7
Individual	Judo	Male	8	4.2
Team	Field hockey	Male	14	7.4
Team	Handball	Female	14	7.4
Team	Football	Male	77	40.5

4. Discussion

This study investigated the CAR of elite athletes in a wide range of competitive sports, as it relates to the Anticipation Hypothesis (Fries, Dettenborn and Kirschbaum, 2009; Powell and Schlotz, 2012). In support of H1, the CAR was found to be substantially higher on competition days than that observed on rest days, expressed both as a percentage change and a raw change. Contrary to H2, the CAR did not differ between elite IS and TS athletes, either as a main effect or interaction.

The salivary CAR was significantly higher on competition days (mean increase: 82.1%) than on rest days (24.7%) across all elite athletes tested, consistent with previous sport-related research (Meggs et al., 2016; Aguilar et al., 2018; Lee et al., 2020; Kayacan et al., 2022). The magnitude of this effect (more than a threefold difference) was demonstrated in a comparatively large athlete sample, thereby providing more precise evidence and greater statistical power than prior studies, which commonly use relatively small cohorts ($n \leq 41$). Similar results emerged when the sports were grouped by the dominant physiological demands (endurance vs power/technical). Furthermore, the competition effect was preserved across all sports tested in both genders, indicating that the observed CAR difference is unlikely to be primarily driven by sport typology. These findings support an anticipatory interpretation of the CAR (Fries et al., 2009; Powell and Schlotz, 2012; Stalder et al., 2025), reflecting context-dependent HPA-axis activation in preparation for upcoming competitive demands.

We acknowledge that tapering practices (i.e., reduced training load) in sport might also, in part, regulate the elevated CAR prior to competition. Supporting this idea, male judoists showed a dampened CAR after one week of heavy training following a lighter training week (Crewther et al., 2024), suggesting that load reductions may facilitate a heightened CAR. However, a rise in CAR was observed in a soccer team after a short (1 week) period of intensive training (Minetto et al., 2008). Seasonal context adds to the difficulty of understanding the impact of training load on the CAR. During the competitive season, athlete training is often characterized by day-to-day adjustments in load based on recovery status and readiness to perform. These microcycles may exert less influence on the CAR than sustained, intensive training over longer periods, particularly in athletes who are already highly adapted to such demands. The reported training effects, which were quantified using different CAR metrics (Minetto et al., 2008; Crewther et al., 2024), were still noticeably smaller (as a proportion) than the competition-to-rest day effect observed herein. Hence, training load may contribute, but is unlikely to fully account for the observed competition effect.

The CAR was comparable between elite IS and TS athletes. This finding contrasts with amateur athletes (Page et al., 2024), among whom IS athletes displayed an elevated competition CAR and TS athletes a blunted one (vs. baseline day), yielding no net competition–baseline difference. Evidence from real-life competitive settings among amateur athletes, such as ballroom dancers, similarly indicates role-dependent variation in cortisol secretion across the day, including in the morning (Rohleder et al., 2007). Elite athletes, however, appear to exhibit a different pattern of stress adaptation, characterized by more regulated HPA-axis responses. Consistent with this, elite athletes show attenuated cortisol responses and state anxiety to standardized psychosocial stressors compared to amateur athletes (Rimmele et al., 2009), a pattern that may generalize to anticipatory contexts. Repeated exposure to competitive demands and intensive training may also promote habituation of the HPA axis to sport-specific stressors (Strahler et al., 2010; MacDonald and Wetherell, 2019). Taken together, competition itself, rather than sport type, represents the primary determinant of the CAR in elite athletes.

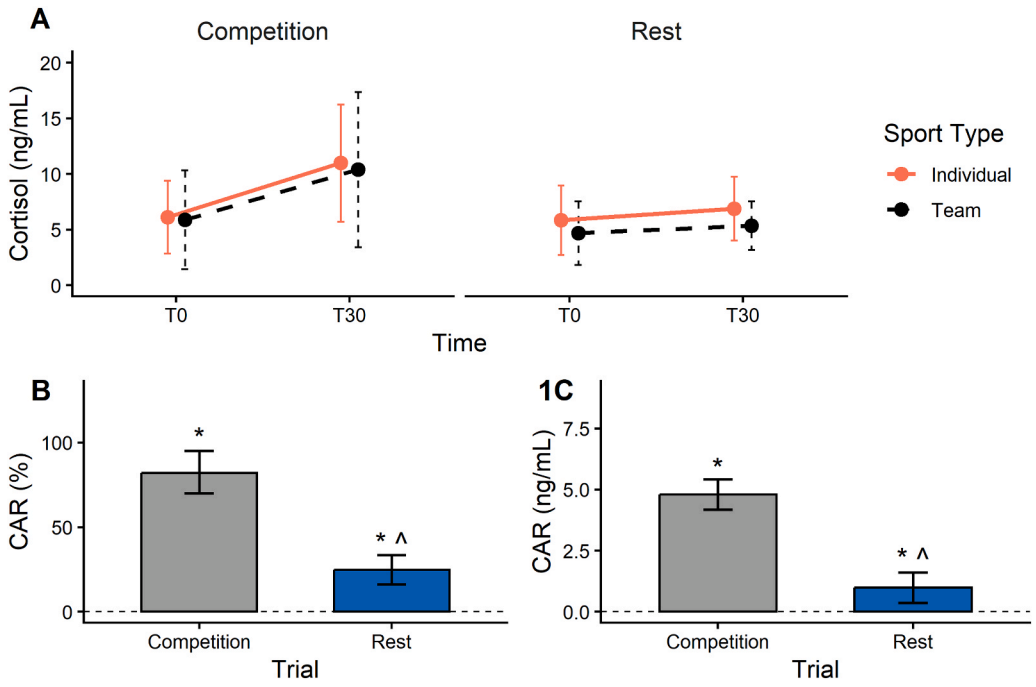

Fig. 1. Descriptive means (±SD) for the cortisol concentration measures at T0 and T30 across both trials are shown in 1 A. The model-estimated marginal means for the cortisol awakening response (CAR) is displayed in 1B. The CAR data are expressed as a percentage change and a raw change with a 95% confidence interval. Key: IS = individual-sport athletes, TS = team-sport athletes. ^Significantly different from competition $p < 0.001$; *Significantly different from baseline $p < 0.01$.

5. Limitations

The current findings should be interpreted in light of some limitations. First, the T0–T30 sampling protocol, although intentional, limited our ability to capture the entire CAR (e.g., peak timing, total output during rising phase). Some studies have used more dense sampling (4–5 samples) in the first hour of awakening (Strahler, Ehrlenspiel et al., 2010; Kayacan, Makaracı et al. 2021; Kayacan, Derebasi et al., 2022), which aligns to suggested protocols for CAR research (every 10–15 min for 30–60 min post-awakening) (Stalder, Oster et al., 2025). This was not possible due to the large cohort in this study and cost restrictions. On the other hand, the magnitude of the CAR and trial differences may be underestimated by our approach. Second, training load was not systematically quantified across all participants, nor did we explicitly measure expected next-day competition demands. Thus, the current design does not allow a full disentanglement of the relative contributions of training load and anticipatory processes to the observed CAR. Third, the athlete sample was not fully balanced with respect to gender and sport type, which may limit generalisability. Fourth, we did not control for differences in menstrual-cycle phase among female athletes, which can influence single measurements of HPA activity (Klusmann, Schulze et al., 2022). However, studies of healthy women (Haase, Vehlen et al., 2024) and elite sportswomen (Kayacan, Makaracı et al. 2021) found no differences in the CAR across the menstrual cycle, with further support from a literature review (Klusmann, Schulze et al., 2022).

A further consideration is how the CAR is operationalised. Several sport studies (Strahler, Ehrlenspiel et al., 2010; Díaz, Bocanegra et al., 2013; Meggs, Golby et al., 2016; Lee, Park et al., 2020; Page, Glandorf et al., 2024) used area under the curve with respect to ground (AUCg), a metric reflecting total cortisol output rather than the dynamic post-awakening increase from waking or T0. This is an important distinction to make, as AUCg may conflate baseline cortisol secretion with subsequent reactive changes, potentially obscuring anticipatory effects. To illustrate this point, relative cortisol changes (e.g., T45–T0 or T30–T0) were calculated using published means from Page et al., (2024). The peak relative increase on competition days (IS = 37.8%, TS = 48.7%) were found to be marginally higher than baseline days (IS = 34.1%, TS = 43.1%) and thus consistent with an anticipatory response, whereas the competition day AUCg revealed divergent outcomes (IS = elevated, TS = depressed). Accordingly, conclusions regarding the CAR anticipation effect may depend on the CAR metric employed.

6. Applications and future directions

In elite sport, field-based CAR profiling may offer a practical tool for assessing competitive readiness, as real-time cortisol testing becomes more accessible. Within this framework, CAR can be interpreted as an index of anticipatory physiological activation, where deviations from an athlete's typical profile may signal suboptimal readiness to perform. For example, an attenuated CAR may reflect insufficient arousal or incomplete physiological preparation for upcoming demands, whereas an exaggerated CAR may indicate heightened stress or maladaptive anticipatory load. Accordingly, targeted interventions (e.g., light exposure, psychological strategy) can be used to recalibrate CAR toward an athlete-specific optimal range.

A common feature of the CAR, like other measures of HPA activity, is a high degree of individuality (Minetto, Lanfranco et al., 2008) and sport-specific variability (see Figure S1). Day-to-day variation in the CAR is another source of variability (Crewther, Serpell et al., 2025), measured here at ~47% from the population mean CAR. Consequently, intensive within-person monitoring will be needed to establish individual reference values and to determine what constitutes an optimal CAR for a given athlete. Assessing the testosterone awakening response may also be informative, as it was recently associated with the CAR and its components in elite rugby players but not sedentary men (Crewther, Serpell et al., 2025). Such investigations may clarify another proposed role of the CAR in counter-regulating adverse emotional experiences from the previous day (Stalder, Oster et al., 2025). Finally, given the limitations listed above, it would be prudent to link CAR dynamics to other regulatory factors (e.g., training load, competitive expectations) and their combined influence on key performance indicators in sport.

7. Conclusions

An elevated CAR was observed on competition mornings in a large, multisport sample of elite athletes, likely reflecting a combination of anticipatory stress and, to a lesser extent, training-related influences. No differences emerged between IS and TS athletes, suggesting a more consistent CAR across competitive sports at the elite level than that reported in an amateur population. In elite sport, CAR profiling may offer a practical tool for assessing competitive readiness, thereby informing targeted interventions.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.psyneuen.2026.107905.

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