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Heart Rate Dynamics and Quantifying Physical Fatigue in Canadian Football

Abdullah Zafar [1], Samuel Guay [2], Sophie-Andrée Vinet [2], Francine Pilon [3], Géraldine Martens [2], François Prince [2,4,5,*,†] and Louis De Beaumont [2,4,†]

1 Department of Kinesiology, University of Waterloo, Waterloo, ON N2L 3G1, Canada
2 Centre de Recherche, Hôpital du Sacré-Cœur de Montréal, Montréal, QC H4J 1C5, Canada
3 Department of Kinesiology, University of Montréal, Montréal, QC H3T 1J4, Canada
4 Department of Surgery, Faculty of Medicine, University of Montréal, Montréal, QC H3T 1J4, Canada
5 Institut National du Sport du Québec, Montréal, QC H1V 3N7, Canada
* Correspondence: francois.prince@umontreal.ca
† These authors contributed equally to this work.

Abstract: The cardiac response to physical exertion is linked to factors such as age, work intensity, and fitness levels. The primary objective of this study was to characterize within-session changes in cardiac response to running in Canadian football athletes, which may indicate physical fatigue. Performance profiles were collected from GPS and heart rate (HR) sensors worn by 30 male Canadian varsity football players (20–26 years old) over 28 games and practices. Running efforts with 60–180 s of rest were detected, and the maximum HR (HRmax) and peak HR recovery (HRRpk) during rest were extracted. Additionally, a new metric of cardiovascular cost (CVC) was developed to reflect the efficiency of the HR response to physical workload. HRmax was higher in games ($p < 0.001$) and in linemen ($p < 0.001$), and it increased over time ($p < 0.001$). HRRpk was higher in skilled players ($p < 0.001$) and changed over time ($p < 0.001$) depending on the rest period. CVC was higher in linemen ($p < 0.001$) and increased over time ($p < 0.001$). This study demonstrated the utility of HR response metrics to quantify ongoing fatigue experienced by Canadian football athletes and proposed a novel fatigue metric capable of monitoring an athlete's fatigue state in real time.

Keywords: workload; sport performance; recovery; high-intensity running; cardiac demands

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1. Introduction

The aerobic fitness levels of football athletes are highly dependent on the tactical position, with linemen having much higher body weight, body mass index (BMI), and body fat percentage with lower aerobic capacity than skilled players [1–4]. Current methods for evaluating aerobic fitness typically include testing for heart rate [5,6], maximal oxygen consumption [7], repeated sprint ability [8], and blood lactate accumulation [9]. Among the HR post-exercise parameters, the use of heart rate recovery (HRR) has been shown to reflect aerobic fitness levels in intermittent sport athletes [10]. Due to the high accessibility of heart rate sensors and Global Positioning System (GPS) vests, the use of the HR response to exercise has been widely studied in its application to athlete monitoring [11–13].

Previous work evaluating the heart rates of football athletes within the course of a game or a practice session is limited. The maximum HR recorded over the course of a session is one metric used [14]; however, HRmax only captures an instant in a performance and is not reflective of the entire performance during the session. As such, HRmax observed between tactical positions may be due to factors such as age, the running speeds achieved during a session, or work-to-rest ratios [14–16]. Another metric is HR variability (HRV), which has been used to identify recovery and physical readiness among football players [6,17]. More specifically, these studies examined trends in HRV and training loads over the course of multiple sessions, and while longitudinal markers of HRV can provide judgments on the physical readiness of an athlete prior to a session [6,18], such markers have not been used to evaluate the level of physical fatigue within a session. Thus, identifying a marker sensitive to the accumulation of fatigue within a session could be relevant information for tactical decisions and injury prevention.

HR dynamics and physical work was investigated in other team sports such as rugby and soccer by examining the time spent above a certain HR threshold set relative to HRmax [19–21]. The use of relative thresholds accounts for individual differences in performances, while HRmax or percent-based thresholds are still arbitrary and assume that the distribution of the athlete's HR is consistent across individuals and performances. Recent work in evaluating speed thresholds in Canadian football athletes has shown that such assumptions do not align with the multimodal nature of running performances and that data-driven approaches like a Gaussian mixture model are better suited to determine threshold levels [22].

As an alternative to thresholding approaches, HRR was used in field hockey players to evaluate the short-range response (10 to 60 s) of HR to physical exertion during games, which involves discrete blocks of activity and rest like football [23]. The differences in HRR across playing positions was related to the amount of high-intensity running performed by the athletes and thus could be used to assess the physical fitness of players relative to positional demands. Typically, HRR was computed as the percentage of maximal heart rate (%HRmax) post-exercise, and this metric showed high correlations with aerobic fitness, especially in the first 10 to 30 s of rest [10]. However, reducing the short-range HR response to a single summary metric such as %HRmax does not completely describe the relationship between HR and physical bouts of exertion, such as the timing of the HR response or the rate of recovery.

The primary aim of this paper was to characterize the within-session cardiac load experienced by skilled players and linemen in Canadian football beyond limited summary metrics such as HRmax by evaluating the short-range HR response to intermittent physical exertions. It was hypothesized that HRmax following runs of similar intensity would increase with time and HRR metrics during rest would decrease with time. However, computing these HR response metrics is dependent on the detection of distinct bouts of activity and rest, which are unevenly distributed over the course of a session. To mitigate that effect, this study proposed a metric allowing for the live and continuous monitoring of the athlete's physical fatigue levels.

2. Materials and Methods

Data were recorded from 30 male football athletes (Table 1) recruited from two Canadian varsity football teams who underwent random doping assessments, were given no specific instruction given regarding caffeine intake, and followed the hydration and nutrition guidelines set by the team nutritionist. Data were collected during normal game and practice conditions, for a total of 311 collected performances (156 games, 155 practices). Games followed a weekly schedule with a duration of 190 min $\pm$ 24 min, and practices were recorded once a week with a duration of 123 min $\pm$ 20 min. Vest-worn Catapult sensors (Catapult Sports, Melbourne, Australia) collected GPS and heart rate data at 10 Hz, as illustrated in Figure 1. Athletes were categorized based on tactical position as either skilled players (receivers, defensive backs, running backs, linebackers) or linemen (offensive linemen, defensive linemen). Ethics clearance for the study was received through the Aging–Neuroimaging Research Ethics Committee of the CIUSSS Centre-Sud-de-l'Île-de-Montréal Office of Research Ethics Committee (ethics no. MP-53-2020-191).

Table 1. Physical characteristics of athletes according to athlete group.

Athlete Group	Age (Years)	Height (m)	Weight (kg)	BMI ($\frac{kg}{m^2}$)
Skilled players	23.1 $\pm$ 1.6	1.79 $\pm$ 0.06	85.6 $\pm$ 9.5	26.5 $\pm$ 2.6
Linemen	22.9 $\pm$ 1.8	1.88 $\pm$ 0.04	120.4 $\pm$ 9.6	34.1 $\pm$ 3.6

Figure 1. Depiction of Catapult vest and sensor location on athlete.

Efforts of running activity were detected by first using a 2 km/h threshold to filter out standing and low-speed walking segments of the velocity data. The remaining activity was identified as a running effort if a velocity of at least 12 km/h was reached during the effort and if the effort duration was at least 2 s in duration, as the minimum duration of a football play is about 1.9 s [24]. In order to ensure adequate recovery when analyzing the HR response, efforts which were followed by less than 60 s of rest before the next run were excluded (Figure 2a). Additionally, to evaluate the HR response across longer periods of activity and rest, running series were detected by grouping individual runs such that there was at least 180 s of rest following the series of running efforts (Figure 2b). The HR response was processed using a second-order, lowpass Butterworth filter with a cutoff frequency (FC) corresponding to the recovery interval being analyzed (i.e., FC = $\frac{1}{60}$ for 60 s recovery and FC = $\frac{1}{180}$ for 180 s recovery). The overall running velocity of each series was taken as the average of the maximum velocity for each effort in the series. Running intensity speed thresholds for each performance were determined using a 5-zone Gaussian mixture model [22], and then each effort or series was categorized into medium-intensity running (MIR: one 3/4) and high-intensity running (HIR: zone 5).

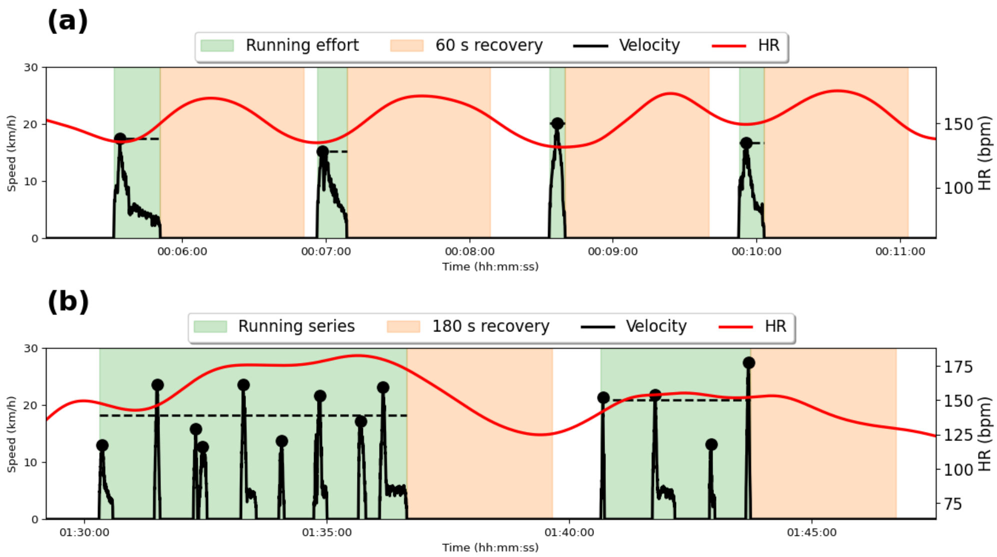

Figure 2. Running event detection and windowing for a skilled player. The thresholded running velocity signal is in black (left y axis) with the heart rate signal in red (right y axis). Running and recovery periods are shown for (**a**) running efforts and (**b**) running series. The maximum velocity for each individual running effort is denoted by a black dot, while the average of all maximum velocities of runs within an effort or series is denoted by the black horizontal dashed line.

The HRmax in the recovery period was extracted for each running event. Additionally, the rate of change in heart rate was taken from a centered difference approximation of the first derivative of the filtered HR signal. The peak rate of HR recovery (HRRpk) was then taken as the absolute value of the largest minimum value in the HR derivative signal; larger values of HRRpk indicate faster return towards baseline post-exertion, while smaller values of HRRpk indicate a slower return. Both HRmax and HRRpk were computed for all bouts and series. In order to characterize whether HRmax and HRRpk measures change over the course of a session, the time of each running event was binned according to its occurrence in the first (start), second (middle), or final (end) of the session. Two 3-way mixed analyses of variance (ANOVA) were run to examine the effect of athlete group (between), running intensity (within), and time (within) on HRmax and DHRpk for running efforts, and another two 3-way mixed ANOVAs were run to determine the effects of the same factors on HRmax and DHRpk for running series.

Additionally, a more continuous measure of HR dynamics and physical effort was explored, without the need for detecting running events with adequate recovery which occur infrequently during a session. Physical effort was considered as the total distance covered (in meters) within a window of time, and cardiovascular load was taken as the total number of heartbeats in that window. Total heartbeats were computed by dividing the HR signal (beats per minute) by 60 to obtain the number of beats per second and then taking the sum over the number of seconds in the time window. The number of heartbeats was then divided by the total distance covered as a measure of cardiovascular cost (CVC). A sliding window of 60 s was used to compute the CVC over the course of each session (Figure 3). In order to remove large spikes in the CVC time series due to a small denominator (i.e., small distance covered), a threshold of 2 km/h was used (similar to the bout detection) to remove time windows where the athlete was walking at a slow speed. A linear regression was fit to each CVC time series to evaluate the general trend in the metric, then the first and last regression values were extracted for comparison for each session. In order to analyze changes to CVC within a performance, a two-way mixed-measures ANCOVA was run to examine the effect of athlete group (between) and time (within) on CVC values, with a covariate of BMI to account for the differences in physical running efforts between athlete groups.

Additionally, in order to evaluate the potential of CVC to capture long-range trends of fatigue, the mean CVC from each performance was correlated with the number of days from the start of the season using a Pearson correlation coefficient. Data for the correlation were taken only from athletes who had performed over the entirety of the season, resulting in 28 performances analyzed from 3 skilled players and 10 performances from 1 lineman.

Significance levels for all statistical tests were set at $p = 0.05$, and all tests were run in R 4.1.2 [25]. Bonferroni corrections were performed for all post hoc pairwise comparison tests, and effect sizes were calculated using Cohen's d with thresholds of 0.2 (small), 0.5 (medium), and 0.8 (large) [26].

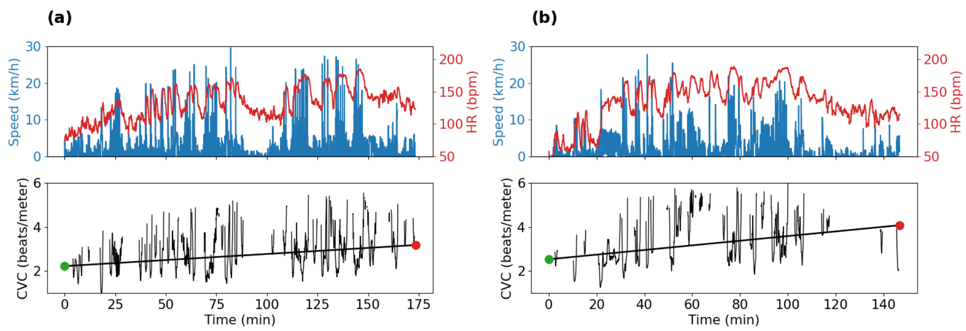

Figure 3. Cardiovascular cost (CVC) for (**a**) a skilled player and (**b**) a lineman. Top subplot shows velocity (blue) and heart rate (red) signals over time. Bottom subplot shows CVC (black solid) with walking period discontinuities removed; overall CVC trend represented by linear regression (black solid) and starting (green) and ending (red) regression values are highlighted.

3. Results

The within-session changes of the heart rate response for short running efforts (with a rest period of 60 s) and longer running series (with a rest period of 180 s) were evaluated, while also considering factors of the athlete group and the running intensity. Overall, HRmax values were higher in games compared to practices ($p < 0.001$), and HRRpk showed no significant difference between games and practices ($p = 0.95$).

Within-session changes to the CVC metric were also evaluated, and the changes in CVC over the course of a season were explored.

3.1. HR Response to Running Efforts

A total of 5816 running efforts (4261 skilled players, 1555 linemen) were detected. Running efforts where the detected peak heart rate was less than 100 bpm were excluded, leaving 5164 efforts (3829 skilled players, 1335 linemen; 88.8% retention) for analysis.

During the 60 s rest period following a running effort, HRmax increased ($F(2, 5152) = 39.1$, $p < 0.001$, Figure 4a) and HRRpk decreased ($F(2, 5152) = 16.1$, $p < 0.001$, Figure 4c) over the course of a session.

Running intensity affected the HR response, as HRmax and HRRpk were higher following HIR efforts compared to MIR efforts (Figure 4b) for both skilled players ($p < 0.001$, $d = 0.44$) and linemen ($p < 0.01$, $d = 0.16$). Additionally, HRRpk was higher in skilled players compared to linemen ($p < 0.001$, $d = 0.19$).

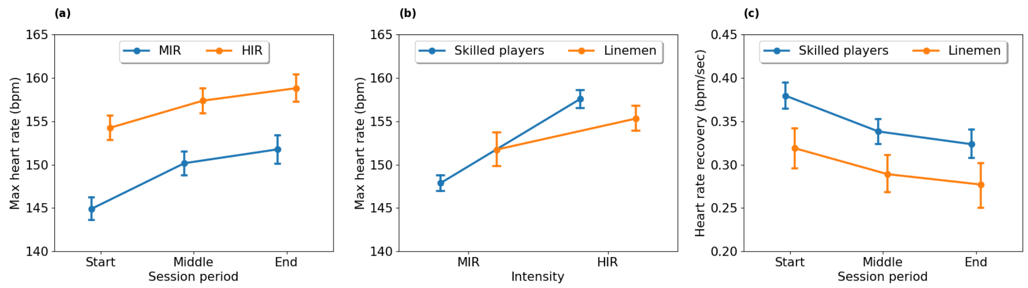

Figure 4. HR response within 60 s recovery of a running effort. Maximum heart rate (**a**) over the course of a session (start/middle/end) and (**b**) according to running effort intensity (medium/high), and (**c**) peak heart rate recovery over the course of a session (start/middle/end). Means and 95% confidence intervals are depicted.

3.2. HR Response to Running Series

A total of 3107 running series (2103 skilled players, 1004 linemen) were detected. Running series where the detected peak heart rate was less than 100 bpm were excluded, leaving 2765 series (1907 skilled players, 858 linemen; 89.0% retention) for analysis.

During the 180 s rest period following a running effort, both HRmax increased ($F(2, 2753) = 3.9$, $p = 0.02$, Figure 5a) and HRRpk increased ($F(2, 2573) = 13.2$, $p < 0.001$, Figure 5c) over the course of a session.

Similar to the shorter running efforts, running intensity also affected the HR response after running series, as HRmax and HRRpk were higher following HIR efforts compared to MIR efforts (Figure 5b) for both skilled players ($p < 0.001$, $d = 0.35$) and linemen ($p = 0.04$, $d = 0.15$). Additionally, HRRpk in general was higher in skilled players compared to linemen ($p = 0.03$, $d = 0.09$).

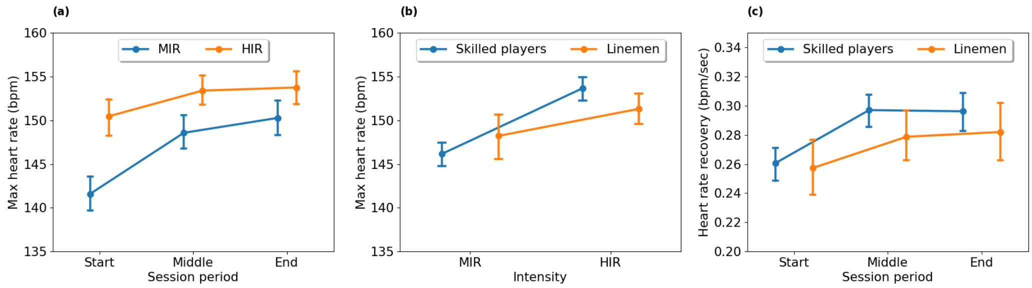

Figure 5. HR response within 180 s recovery of a running series. Maximum heart rate (**a**) over the course of a session (start/middle/end) and (**b**) according to running series intensity (medium/high), and (**c**) peak heart rate recovery over the course of a session (start/middle/end). Means and 95% confidence intervals are depicted.

3.3. Cardiovascular Cost

The CVC changes between the start and end of a session were evaluated for all games and practices. There was a significant two-way interaction effect of time and athlete group ($F(1, 341) = 6.47$, $p = 0.01$, Figure 6a) on CVC, with BMI as a significant covariate ($p < 0.01$). Post hoc comparisons showed that CVC increased from the start to the end of a session for both linemen ($p < 0.001$, $d = 0.75$) and skilled players ($p < 0.001$, $d = 0.43$).

In order to explore whether longitudinal trends in CVC may also be applied to detect chronic fatigue, changes in the average CVC of each session were also evaluated over the course of the season for the three skilled players and one lineman who consistently played throughout the season. There was a significant positive correlation between days from the start of the season and net performance CVC for only the skilled players ($r = 0.4$, $p < 0.03$, Figure 6b).

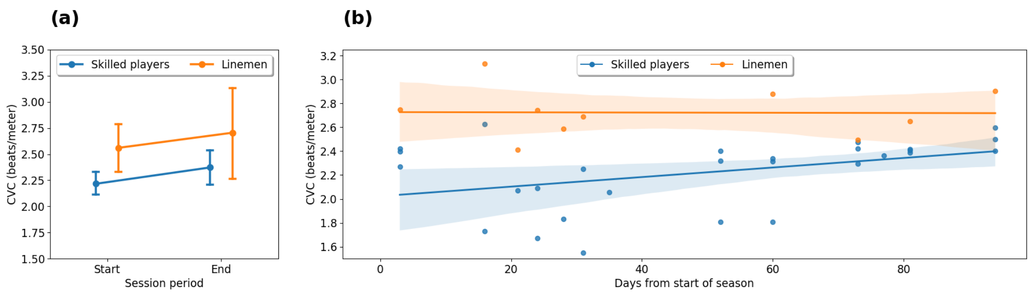

Figure 6. Cardiovascular cost (CVC) by athlete group. CVC changes (**a**) over the course of a single session and (**b**) over the course of a competitive season. Means and 95% confidence intervals are depicted.

4. Discussion

This study evaluated the cardiac load experienced by Canadian football athletes with respect to tactical position and is the first to characterize the short-range HR response to bouts of physical exertion. Furthermore, this study looked at the relevant HR response metrics capable of distinguishing positions based on physical work performed for the purpose of providing insight into the training and monitoring of the physical conditioning of athletes. Although the cause–effect relationship has not yet fully been established between cardiovascular disorder (CVD), heart abnormalities, and endurance training [27–30], there is some evidence that cardiac load and aerobic fitness in football athletes may lead to the development of cardiovascular health disorders later in life [31]. As such, there is a necessity for validating methods of assessment within game and training contexts. The proposed novel metric presented in this study can monitor physical fatigue and cardiac load relative to physical work, with the possibility of informing on potential injury and health risks in real time.

4.1. Position—Linemen vs. Skilled Players

Peak HRs were higher in linemen after medium intensity efforts of running, reaching speeds of less than 14 km/h. Previous work in American football showed higher maximal HRs across an entire session for skilled players compared to linemen [14]; however, this may be due to the higher speeds generally reached by skilled players. The higher HR at submaximal running speeds can be linked to lower cardiovascular fitness, as previously noted in soccer players [32,33]. In these studies, differences in exercise HR during 12 km/h runs was indicative of the accumulation of blood lactate levels. The increase in HRmax in response to medium- and high-intensity runs over the course of a session could, thus, also be interpreted as the accumulation of fatigue.

4.2. Peak HRR (HRRpk) Changes within a Session

Similarly, peak HRR showed notable changes over the course of the session and were generally higher in skilled players compared to linemen, which could be another indication of the differences in aerobic fitness between athlete groups [10]. Previous studies computing HRR have looked at the percentage of HRR from 10 s post-exercise up to 5 min post-exercise [10]. However, for the evaluation of HRR in a dynamic, intermittent team sport context, where the length of the recovery period is variable, the current study used the derivative of the HR signal to find the peak recovery rate (HRRpk) during the recuperation window. The extracted HRRpk values were lower during the 180 s compared to the 60 s recovery window, though this may be due to the larger amount of filtering involved with the HR trace for the longer recovery window, which consequently smooths out the HR derivative signal.

Interestingly, while HRRpk within 60 s post-running effort decreased over the course of a session, HRRpk within 180 s post-running series increased over the course of a session. These results suggest that after individual runs, HRR tends to slow over time, but a higher HR is accumulated after a series of runs (as observed with the HRmax values). As a result, a faster post-running series HRR is observed, as indicated by physiological models of HR dynamics [34]. Another possible explanation of the different changes in HRRpk over time is that the overall HRR is delayed as fatigue accumulates over the course of a session, and as such, the short-range recovery within 60 s decreases, while the longer-range recovery within 180 s increases.

4.3. Fatigue

A new metric of cardiovascular cost (CVC) was explored in this study to evaluate fatigue on two timescales: (a) permanent fatigue experienced within a session, and (b) chronic fatigue experienced over the course of a season. Based on running performances within a session, the overall CVC was higher in linemen compared to skilled players. For both groups of athletes, we observed an increased CVC over the course of a session which could be linked to an increased and perhaps permanent fatigue state experienced by the athletes over the course of a game or training session. Higher CVC may indicate lower cardiovascular fitness, and since low-level evidence is reported linking aerobic fitness and concussion risks [35,36], future work should explore relating baseline CVC and its changes during a session to head impacts experienced by the athlete.

Previous studies in soccer have attempted to quantify permanent fatigue experienced by athletes by relating the amount of high-intensity running performed between the start and end of a session, as well as in relation to the peak intensity period and averages of the session [37]. Other methods for quantifying permanent fatigue have used physical tests such as vertical jumps or sprints before and after sessions [38]. These methods have examined fatigue from only physical outputs which may also be influenced by match context and pacing [39], and they use techniques which cannot be used to assess possible fatigue continuously during a session. By contrast, the cardiovascular cost metric proposed here represents the relationship between internal cardiac load and external physical loads, theoretically accounting for any changes in match context.

Furthermore, when exploring the potential of CVC as a measure of chronic fatigue, there was a moderate positive correlation between the net CVC and days from the start of the season for the three skilled players who performed over the course of the whole season. No correlation was present for the one lineman analyzed, which may be due to the limited number of samples. As such, there may be some motivation for further investigating CVC as a metric for identifying the accumulation of fatigue over the course of a season as an alternative to resting heart rate or heart rate variability [6,18]. Additionally, there may be added sensitivity of CVC to assess physical readiness or chronic fatigue due to its derivation from performance outcomes rather than measurements during resting state, which should be investigated further.

4.4. Limitations

The limitations of the metric are that it only considers total distance covered as the measure of physical load, which is only one aspect of the external physical load experienced by athletes during Canadian football. Additionally, the need to exclude moments of low-speed walking or standing (less than 2 km/h) in order to avoid large spikes in the metric results in discontinuities, which may affect real-time monitoring. To overcome the current limitations in using the CVC metric, future work should examine longitudinal trends of the short-range HR response characteristics and the CVC metric as a potential means of evaluating changes in fitness levels or injury risks compared to heart rate variability metrics. Since only 4 of 28 players consistently performed over the whole season, the analysis of longitudinal trends in CVC was also limited in statistical power.

5. Conclusions

Overall, the results from this study demonstrate the capability of HR response metrics in assessing the increased cardiac load experienced by linemen compared to skilled players in Canadian football within game and training contexts. Additionally, the novel metric of CVC proposed in this study is a more continuous measure of physical fatigue that can be implemented in real time, using heart rate and GPS monitors commonly used in high performance settings. The integration of the proposed CVC metric with head impact data to evaluate concussion risks and outcomes in game and training sessions should also be explored further.

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Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

BMI	Body mass index
GPS	Global Positioning System
HR	Heart rate
HRmax	Maximum heart rate
HRRPk	Peak heart rate recovery
CVC	Cardiovascular cost
HRV	Heart rate variability

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