# Sport-specific electrocardiographic patterns in Moroccan university athletes: a Seattle criteria-based cross-sectional study

*Patrones electrocardiográficos específicos por deporte en atletas universitarios marroquíes: estudio transversal basado en criterios de Seattle*

## Authors

Younes Brouki [1]
Omar Ben Rakaa [2]
Walid Bouzid [1]
Youssef El Machrouh [1]
Mohamed Barkaoui [1]
Abdeljalil Elgot [3]
Aziz Eloirdi [1]
Aziz Chokri [1]

[1, 3] Hassan I University Settat, (Morocco)
[2] Hassan II University of Casablanca, (Morocco)

Corresponding author:
Younes Brouki
younes.brouki@gmail.com

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## Abstract

Background: Exercise-induced cardiac remodelling results in electrocardiographic alterations that vary by sport and ethnicity. International screening criteria, derived primarily from Caucasian populations, may inadequately capture physiological variations in North African athletes.
Aim: To establish electrocardiographic profiles of Moroccan university athletes using the Seattle International Criteria and to analyse sport-specific variations.
Methods: This cross-sectional study enrolled 149 university athletes (79 male, 70 female, aged 18-25 years) from Hassan I University in Morocco, classified into endurance, mixed/team and strength/power sports. Standardised 12-lead electrocardiography was interpreted independently by two specialists. ANOVA and chi-square tests were used for statistical analysis, and effect sizes were reported. Results: Significant differences in heart rate between sports emerged ($p < .001$, $\eta^2 = .124$): endurance athletes showed lower rates (58.4 ± 11.2 bpm) compared to mixed/team athletes (65.1 ± 11.8 bpm) and strength/power athletes (68.9 ± 12.5 bpm). The prevalence of sinus bradycardia was higher in endurance athletes (47.5% vs. 27.0% in mixed/team and 25.0% in strength/power; $p = .018$). Training-related findings were frequent (34.9% sinus bradycardia overall), borderline findings occurred in 5.4-8.1% and abnormal findings were minimal (6.0%).
Conclusions: Moroccan athletes demonstrate sport-specific electrocardiographic adaptations with lower abnormality rates than those reported in sub-Saharan African populations, suggesting North African heterogeneity. The findings challenge assumptions about continental generalisations and support region-specific regulatory frameworks rather than universally applicable criteria, especially among endurance athletes who show pronounced bradycardic adaptations.

## Keywords

Athlete's heart; electrocardiography; sport type; sports cardiology; Seattle criteria.

## Resumen

Introducción: El aumento de los casos de muerte súbita entre los atletas aficionados marroquíes destaca la importancia de realizar exámenes médicos exhaustivos que incluyan electrocardiogramas.
Objetivo: Este estudio transversal tuvo como objetivo identificar la frecuencia de los hallazgos en el ECG de atletas aficionados marroquíes, examinar las disparidades de género y evaluar cómo los niveles de actividad física afectan los patrones eléctricos cardíacos.
Metodología: El estudio incluyó a 149 atletas aficionados (70 hombres, 79 mujeres) de la Universidad Hassan I de Settat. Los participantes se sometieron a un ECG de 12 derivaciones, mediciones antropométricas y una evaluación de la actividad física mediante el Cuestionario Internacional de Actividad Física - Versión Corta (IPAQ-SF).
Resultados: Los atletas masculinos mostraron tasas significativamente más altas de bradicardia sinusal (41.4 % frente a 12.7 %) y elevación del segmento ST (41.4 % frente a 0 %) que las mujeres ($p<.0001$). Los altos niveles de actividad física se asociaron significativamente con cambios en el ECG relacionados con el entrenamiento ($p=.010$) y con la elevación del segmento ST ($p=.027$).
Discusión: Estos hallazgos enfatizan la importancia de considerar los niveles de actividad física al interpretar los patrones del ECG en atletas aficionados y destacan las diferencias significativas de género en las adaptaciones cardíacas.
Conclusiones: Se necesitan guías de interpretación del ECG específicas por género para atletas aficionados, prestando especial atención a las adaptaciones relacionadas con el entrenamiento en los hombres y a la relación entre la intensidad de la actividad física y los patrones eléctricos cardíacos.

## Palabras clave

Corazón de atleta; electrocardiografía; tipo de deporte; cardiología deportiva; criterios de Seattle.

## Introduction

Exercise-induced cardiac remodelling represents a fundamental physiological adaptation characterised by distinct electrocardiographic patterns that require careful differentiation from pathological conditions (Palermi et al., 2023). Endurance training induces eccentric left ventricular hypertrophy due to volume overload, which manifests electrocardiographically as sinus bradycardia, prolonged atrioventricular conduction and increased QRS voltages (Di Gioia et al., 2026; Pamart et al., 2025). In contrast, resistance-based training produces concentric hypertrophy through pressure overload, showing a proportional increase in wall thickness with less pronounced electrocardiographic alterations (Pamart et al., 2025; Zimmermann et al., 2022). These sport-specific adaptations require specialised interpretation frameworks to avoid misdiagnosis of physiological remodelling as cardiac pathology.

The Seattle International Criteria provide a standardised framework for the interpretation of athletes' electrocardiograms, stratifying findings as training-related (physiological), borderline or abnormal (potentially pathological) (Drezner et al., 2017; Zorzi et al., 2020). However, these criteria were validated predominantly in Caucasian and mixed ethnicity populations, with limited representation of African athletes (Churchill et al., 2021; Wang et al., 2021). Ethnic stratification significantly influences electrocardiographic phenotypes, with sub-Saharan African athletes showing a markedly higher prevalence of repolarisation abnormalities and T-wave inversions without corresponding structural pathology (Ozo & Sharma, 2020; Pambo & Scharhag, 2021; Tardo & Papadakis, 2025). This ethnic heterogeneity defies universal application of international criteria and requires population-specific validation studies.

Despite the extensive literature on electrocardiography in athletes, significant knowledge gaps persist for North African populations, particularly non-elite collegiate and amateur athletes, who constitute the majority of participants in competitive sports worldwide, but remain under-represented in the cardiovascular screening literature. Morocco's expanding university sports programmes lack region-specific baseline electrocardiographic data, which may lead to diagnostic misinterpretations when applying internationally derived criteria (El Ouali et al., 2025). Recent evidence shows the existence of sex-specific differences in Moroccan athletes, with males having higher rates of sinus bradycardia (41.4% vs. 12.7%) than females (Brouki et al., 2025). This deficiency is of clinical concern, given the increasing participation of North African athletes in international competitions and the possible genetic, environmental and training methodology differences from reference populations.

The aim of this study is to establish complete electrocardiographic profiles of Moroccan amateur university athletes according to the Seattle International Criteria and to analyse sport-specific variations in endurance, mixed/team and strength/power disciplines. By characterising electrocardiographic parameters and identifying prevalence patterns of training-related, borderline and abnormal findings, this research aims to provide evidence-based baseline data to improve the accuracy of cardiovascular screening in North African athletic populations.

## Method

### *Participants*

We conducted an observational cross-sectional study at the Institute of Sport Sciences of Hassan I University in Settat, Morocco, between April and June 2023. The study included 149 qualified student-athletes (79 males and 70 females) who met the following inclusion criteria (1) age between 18 and 25 years, (2) actively competing at the university level, (3) regular participation in training (minimum of 3 sessions per week) for at least 12 months prior to enrolment, and (4) absence of medical contraindications to participation. Exclusion criteria included known cardiovascular disease or family history of sudden cardiac death, use of medications that could affect cardiac function, pregnancy, any contraindications to physical activity as determined by medical history and clinical examination, and inability to give informed consent.

Participants were recruited by non-probability convenience sampling of all student-athletes registered at the Institute of Sport Sciences of Hassan I University during the 2023 academic year. All athletes who met the eligibility criteria were invited to participate, resulting in a participation rate of 87.6% (149 out of 170 eligible athletes). For this study, "amateur athletes" were operationally defined as collegiate-level competitors training regularly (≥3 sessions per week for ≥12 months) without professional contracts, financial compensation for sport performance or full-time dedication to sport as a primary vocation. All participants competed at the collegiate level or in regional competitions, and none were registered as professional athletes or current members of national teams. This amateur designation distinguishes our cohort from elite professional athletes, while ensuring that participants maintain consistent and sufficient training loads to induce physiological cardiac adaptations.

Athletes were systematically classified into three main sport types based on the predominant physiological demands of their disciplines: Endurance sports, including distance running, cycling and sports with predominantly aerobic demands; Mixed/team sports, including football/soccer, basketball, volleyball, handball and sports combining aerobic and anaerobic elements; and Strength/power sports, including weightlifting, throwing and sports with predominantly anaerobic/power demands. For the analysis of individual sports, only sports with adequate sample representation (n ≥ 10) were included to ensure sufficient statistical power for group comparisons. This resulted in six main sports: football/soccer (n = 39), athletics/track and field (n = 18), basketball (n = 19), volleyball (n = 16), handball (n = 14) and tennis (n = 11), representing 117 of the 149 total participants (78.5%). The remaining 32 athletes (21.5%) competed in sports with smaller sample sizes, including cycling (n = 8), weightlifting (n = 7), martial arts (n = 6), swimming (n = 5), gymnastics (n = 4) and other disciplines (n = 2), which were retained in sport category analyses but excluded from individual sport comparisons due to insufficient power to detect significant effect sizes.

*Measuring instruments*

All participants underwent a comprehensive assessment, including collection of demographic data, anthropometric measurements and 12-lead electrocardiography. Anthropometric measurements were taken following standardised protocols, including height, weight, waist circumference and hip circumference. Body mass index (BMI) was calculated as weight (kg) divided by height squared ($m^2$), and waist-to-hip ratio (WHR) as waist circumference divided by hip circumference. Training characteristics, including frequency of weekly sessions, duration of training and participation in competitions, were assessed using a structured questionnaire developed by the research team based on established sports medicine assessment protocols (Saavedra et al., 2010). The questionnaire collected information on sport discipline, years of practice, weekly training frequency and competitive level. Twelve-lead resting electrocardiograms were recorded using a standardised Aspel AsCARD Grey electrocardiograph with consistent settings (paper speed 25 mm/s, amplitude 10 mm/mV). All ECG recordings followed a standardised protocol with participants at rest supine for at least 5 minutes prior to recording during quiet breathing. Two qualified specialists (a registered cardiologist and a sports medicine physician with formal training in ECG interpretation) independently interpreted all electrocardiograms, without knowledge of the sports disciplines or demographic characteristics of the athletes. In case of disagreement, consensus was reached through joint reassessment and structured discussion among the interpreters, with reference to the definitions of the 2017 Seattle International Criteria. All final classifications used in the analyses represent agreed interpretations following consensus. ECG interpretation followed the 2017 Seattle International Criteria for Electrocardiographic Interpretation in Athletes (Drezner et al., 2017). Parameters measured included heart rate (HR), PR interval, QRS duration, QT interval, corrected QT interval (QTc) using Bazett's formula, P-, QRS- and T-wave axis measurements, and R-wave voltage amplitudes in leads I, II, V1, V5 and V6. All findings were systematically classified as training-related (normal) findings, including sinus bradycardia, first-degree AV block, incomplete right bundle branch block, early repolarisation and isolated QRS voltage criteria for left ventricular hypertrophy; borderline findings, such as left atrial enlargement, axis deviations, right atrial enlargement and complete right bundle branch block; and abnormal findings, such as T-wave inversion, ST-segment depression, pathological Q waves, complete left bundle branch block, QTc prolongation (>450 ms in men, >460 ms in women) and ventricular pre-excitation.

## *Ethical considerations*

The study was conducted in accordance with the principles described in the Declaration of Helsinki. Ethical approval was obtained from the Moroccan Association of Research and Ethics (Ref. no.:

1/REC/24), with institutional authorisation from the Institute of Sport Sciences of Settat. All participants gave written informed consent prior to enrolment, and confidentiality was maintained throughout the study in accordance with data protection regulations.

### *Data analysis*

Statistical analysis was performed using SPSS version 28.0 (IBM Corp., Armonk, NY, USA). Before performing parametric statistical tests, the normality of the data was assessed using the Shapiro-Wilk test. Results indicated that all continuous variables met the assumptions of normality (all p > .05), justifying the use of one-way ANOVA for between-group comparisons. Data are presented as mean ± standard deviation for continuous variables and as frequencies with percentages for categorical variables. One-way analysis of variance (ANOVA) was used to compare continuous variables between sport groups, with Tukey's honestly significant difference (HSD) post hoc test for pairwise comparisons when main effects were significant. Chi-square tests of independence were used to analyse categorical variables, and Fisher's exact test when the expected cell frequency was less than 5. Effect sizes were calculated using the eta-square method. Effect sizes were calculated using eta-squared ($\eta^2$) for ANOVA results and Cramer's V for chi-squared analyses, applying conventional interpretations: $\eta^2$ values of .01, .06 and .14 representing small, medium and significant effects, respectively; Cramer's V values of 0.1, 0.3 and 0.5 representing small, medium and large associations, respectively. The alpha level was set at p < .05 for all analyses, and 95% confidence intervals were calculated and reported for significant results.

## Results

The results are organised into three analytical approaches: (1) baseline characteristics between sport categories, (2) electrocardiographic parameters by sport type and (3) prevalence of specific ECG findings classified according to the Seattle International Criteria.

### *Initial characteristics of the sample and intergroup comparisons according to sport type*

The study included 149 amateur student-athletes from Hassan I University, who were involved in endurance sports (n = 59), mixed/team sports (n = 74) and strength/power sports (n = 16). Baseline characteristics and anthropometric measurements are shown in Table 1. Comparisons between sport groups revealed no significant differences in age (p = .564), gender distribution (p = .643), height (p = .554) or hip circumference (p = .252). However, significant differences emerged for training frequency (p = .042, $\eta^2$ = .043), weight (p = .018, $\eta^2$ = .057) and BMI (p = .008, $\eta^2$ = .068). In addition, waist circumference (p = .024, $\eta^2$ = .051) and waist-to-hip ratio (p = .037, $\eta^2$ = .045) showed significant variations between groups. Effect sizes for significant parameters ranged from small to medium ($\eta^2$ = .043- .068).

Table 1. Baseline Characteristics and Anthropometric Parameters by Sport Type

| Variable | All Athletes (n = 149) | Endurance (n = 59) | Mixed/Team (n = 74) | Power/Strength (n = 16) | p-value | $\eta^2$ |
|---|---|---|---|---|---|---|
| Age (years) | 20.9 ± 1.4 | 20.8 ± 1.4 | 21.0 ± 1.4 | 21.1 ± 1.6 | .564 | .008 |
| Male sex, n (%) | 79 (53.0) | 29 (49.2) | 42 (56.8) | 8 (50.0) | .643 | — |
| Training frequency (sessions/week) | 4.2 ± 1.1 | 4.5 ± 1.0$^a$ | 4.1 ± 1.1 | 3.8 ± 1.2$^b$ | .042* | .043 |
| Weight (kg) | 67.8 ± 11.4 | 65.2 ± 10.8$^a$ | 68.9 ± 11.2 | 73.5 ± 12.8$^b$ | .018* | .057 |
| Height (cm) | 172.1 ± 8.9 | 171.2 ± 9.2 | 172.8 ± 8.7 | 172.6 ± 8.8 | .554 | .008 |
| BMI (kg/m$^2$) | 22.8 ± 2.8 | 22.2 ± 2.6$^a$ | 23.0 ± 2.8 | 24.6 ± 3.1$^b$ | .008** | .068 |
| Waist circumference (cm) | 76.8 ± 7.2 | 75.1 ± 6.8$^a$ | 77.6 ± 7.3 | 80.2 ± 7.9$^b$ | .024* | .051 |
| Hip circumference (cm) | 95.2 ± 8.1 | 93.8 ± 7.9 | 95.9 ± 8.2 | 97.1 ± 8.5 | .252 | .019 |
| WHR | 0.81 ± 0.06 | 0.80 ± 0.06$^a$ | 0.81 ± 0.06 | 0.83 ± 0.05$^b$ | .037* | .045 |

Data presented as mean ± SD for continuous variables and n (%) for categorical variables. One-way ANOVA is used for continuous variables; chi-square test for categorical variables. Post-hoc comparisons were performed using Tukey's HSD test. Different superscript letters ($^a$, $^b$) indicate significant pairwise differences (p < .05). Statistical significance: *p < .05, **p < .01, ***p < .001. Effect sizes reported as eta-squared ($\eta^2$): small (.01), medium (.06), large (.14).
Abbreviations: BMI, body mass index; HSD, honestly significant difference; SD, standard deviation; WHR, waist-to-hip ratio; $\eta^2$, eta-squared.

### *Athletes' Electrocardiographic Parameters by Sport Categories*

All 149 participants completed a standardised 12-lead resting electrocardiogram following the interpretation guidelines of the Seattle International Criteria. Table 2 comprehensively summarises the electrocardiographic parameters. The analysis revealed significant differences between groups for multiple cardiac parameters. Specifically, heart rate ($F= 9.12$, $p < .001$, $\eta^2 = .124$) showed highly significant differences between sport groups, with endurance athletes exhibiting markedly lower rates than mixed/team and strength/power athletes. In addition, both PR interval ($F = 3.18$, $p = .042$, $\eta^2 = .043$) and QT interval ($F = 6.21$, $p = .003$, $\eta^2 = .073$) showed statistically significant differences. In contrast, QRS duration ($p = .524$), QTc interval ($p = .334$), QRS axis ($p = .605$), P-axis ($p = .428$) and T-axis ($p = .576$) showed no significant differences. Effect sizes for significant parameters ranged from small to large ($\eta^2 = .043$- .124). Tukey's post-hoc tests confirmed significant pairwise differences between endurance athletes and the mixed/team and strength/power groups for heart rate (all $p < .01$), with endurance athletes showing the lowest values.

Table 2. Electrocardiographic Parameters by Sport Type

| ECG Parameter | All Athletes (n = 149) | Endurance (n = 59) | Mixed/Team (n = 74) | Power/Strength (n = 16) | F-value | p-value | $\eta^2$ |
|---|---|---|---|---|---|---|---|
| HR (bpm) | 62.8 ± 12.1 | 58.4 ± 11.2$^a$ | 65.1 ± 11.8$^b$ | 68.9 ± 12.5$^b$ | 9.12 | <.001*** | .124 |
| PR interval (ms) | 158.9 ± 24.6 | 164.2 ± 26.8$^a$ | 155.8 ± 22.9$^b$ | 152.4 ± 21.2$^b$ | 3.18 | .042* | .043 |
| QRS duration (ms) | 95.4 ± 11.8 | 96.8 ± 12.5 | 94.6 ± 11.2 | 94.2 ± 11.6 | 0.65 | .524 | .009 |
| QT interval (ms) | 398.6 ± 32.4 | 408.2 ± 35.1$^a$ | 392.8 ± 29.6$^b$ | 388.4 ± 28.2$^b$ | 6.21 | .003** | .073 |
| QTc interval (ms) | 412.5 ± 18.9 | 409.8 ± 19.2 | 413.9 ± 18.6 | 415.2 ± 19.4 | 1.10 | .334 | .015 |
| QRS axis (°) | 68.4 ± 28.6 | 71.2 ± 29.4 | 66.8 ± 27.9 | 65.1 ± 29.2 | 0.50 | .605 | .007 |
| P axis (°) | 52.1 ± 19.8 | 54.6 ± 20.4 | 50.8 ± 19.2 | 48.9 ± 20.1 | 0.85 | .428 | .011 |
| T axis (°) | 48.9 ± 24.2 | 51.4 ± 25.1 | 47.2 ± 23.6 | 46.8 ± 24.8 | 0.56 | .576 | .008 |

Data presented as mean ± SD. One-way ANOVA performed for between-group comparisons with post-hoc Tukey's HSD test. Different superscript letters ($^a$, $^b$) indicate significant pairwise differences ($p < .05$). Statistical significance: *p < .05, **p < .01, ***p < .001. Effect sizes reported as eta-squared ($\eta^2$): small (.01), medium (.06), large (.14). 95% confidence intervals for significant mean differences: PR [2.1, 18.7] ms, QT [6.8, 28.4] ms.
Abbreviations: ANOVA, analysis of variance; bpm, beats per minute; ECG, electrocardiogram; HR, heart rate; HSD, honestly significant difference; ms, milliseconds; QTc, corrected QT interval; SD, standard deviation; °, degrees; $\eta^2$, eta-squared.

### *Prevalence of ECG Findings by Sport Categories*

ECG findings were classified according to the Seattle International Criteria into training-related, borderline and abnormal categories. Table 3 presents the distribution of ECG findings by type of sport. Chi-square analysis revealed a significant association between sport type and sinus bradycardia ($\chi^2 = 8.12$, $p = .018$, Cramer's $V = .195$), with sinus bradycardia being more prevalent in endurance athletes (47.5%) compared to mixed/team athletes (27.0%) and strength/power athletes (25.0%). Training-related findings were observed in all sport categories, with sinus bradycardia being the most prevalent (34.9% overall) and showing significant variation by sport. Individual training-related findings, including first-degree AV block (12.1%), incomplete RBBB (15.4%), early repolarisation (27.5%) and LVH voltage criteria (22.8%) occurred with comparable frequencies in all sport groups without reaching statistical significance (all $p > .05$). In contrast, individual findings such as first-degree AV block ($p = .239$), incomplete BRD ($p = .386$), early repolarisation ($p = .542$) and LVH voltage criteria ($p = 0.774$) did not reach statistical significance. Furthermore, neither borderline findings ($p = .481$) nor abnormal findings ($p = .486$) showed significant sport-related associations. The effect sizes of the significant associations ranged from small to moderate (Cramér's $V = .173$- .195).

Table 3. Electrocardiographic Parameters by Sport Type

| ECG Finding | All Athletes n = 149 | Endurance n = 59 | Mixed/Team n = 74 | Power/Strength n = 16 | p-value |
|---|---|---|---|---|---|
| Training-Related Findings | | | | | |
| Sinus bradycardia (<60 bpm) | 52 (34.9) | 28 (47.5)$^a$ | 20 (27.0)$^b$ | 4 (25.0)$^b$ | .018* |
| First-degree AV block | 18 (12.1) | 10 (16.9) | 7 (9.5) | 1 (6.3) | .239 |
| Incomplete RBBB | 23 (15.4) | 12 (20.3) | 9 (12.2) | 2 (12.5) | .386 |
| Early repolarization | 41 (27.5) | 19 (32.2) | 18 (24.3) | 4 (25.0) | .542 |
| LVH voltage criteria only | 34 (22.8) | 15 (25.4) | 16 (21.6) | 3 (18.8) | .774 |
| Borderline Findings | | | | | |
| LAE | 8 (5.4) | 5 (8.5) | 2 (2.7) | 1 (6.3) | .274 |
| LAD | 12 (8.1) | 6 (10.2) | 5 (6.8) | 1 (6.3) | .715 |

| | | | | | |
|---|---|---|---|---|---|
| RAD | 9 (6.0) | 2 (3.4) | 6 (8.1) | 1 (6.3) | .486 |
| RAE | 6 (4.0) | 3 (5.1) | 2 (2.7) | 1 (6.3) | .639 |
| Complete RBBB | 4 (2.7) | 2 (3.4) | 2 (2.7) | 0 (0) | .739 |
| Abnormal Findings | | | | | |
| T-wave inversion | 3 (2.0) | 1 (1.7) | 2 (2.7) | 0 (0) | .742 |
| ST-segment depression | 2 (1.3) | 1 (1.7) | 1 (1.4) | 0 (0) | .850 |
| Pathological Q waves | 1 (0.7) | 0 (0) | 1 (1.4) | 0 (0) | .620 |
| QTc prolongation | 5 (3.4) | 1 (1.7) | 3 (4.1) | 1 (6.3) | .560 |

Data presented as n (%) where n represents number of athletes and percentage represents proportion of sport category. Chi-square test performed for categorical comparisons. Different superscript letters ([a], [b]) indicate significant pairwise differences based on standardized residuals (|z| > 1.96). Statistical significance: *p < .05, **p < .01, ***p < .001. Effect sizes (Cramér's V): sinus bradycardia = .195, QTc prolongation defined as >450 ms in men, >460 ms in women.
Abbreviations: AV, atrioventricular; bpm, beats per minute; ECG, electrocardiogram; LAD, left axis deviation; LAE, left atrial enlargement; LVH, left ventricular hypertrophy; ms, milliseconds; QTc, corrected QT interval; RAD, right axis deviation; RAE, right atrial enlargement; RBBB, right bundle branch block; $\chi^2$, chi-square.

### *Athletes' Electrocardiographic Parameters Across Individual sport*

Individual sport analyses examined six major sports with adequate sample representation (n ≥ 10): football/soccer (n = 39), athletics/track (n = 18), basketball (n = 19), volleyball (n = 16), handball (n = 14) and tennis (n = 11), with a total of 117 athletes (78.5% of the cohort). Sports with smaller sample sizes (n < 10; total n = 32) were excluded from individual comparisons to maintain adequate statistical power, although all athletes remained in the sport category analyses. Despite this inclusion threshold, the smaller sample sizes for tennis (n = 11) and handball (n = 14) warrant cautious interpretation of the results specific to these disciplines. One-way ANOVA revealed significant differences between sports for heart rate (F= 4.03, p = .002, $\eta^2$ = .154) and QRS duration (F= 3.32, p = .008, $\eta^2$ = .130). Tukey's post-hoc analysis for heart rate identified a significant pairwise comparison between football/soccer and volleyball (p = .002, mean difference = 13.77 bpm, 95% CI 3.59-23.95). Given the variable sample sizes across sports, statistical power differed substantially between comparisons. Comparisons between football and football (n = 39) demonstrated adequate power (>0.80) to detect medium and large effects, whereas comparisons between sports with smaller sample sizes (e.g. tennis, n = 11; handball, n = 14) had reduced power, increasing the risk of type II error. The non-significant differences observed for the PR interval (p = .790), QT interval (p = .128) and QTc interval (p = .065) may reflect insufficient power rather than a true absence of effect, particularly for the near-significant QTc finding (p = .065, $\eta^2$ = .088). Similarly, electrical axis measurements (QRS axis p = .852, P-wave axis p = .101, T-wave axis p = .933) and R-wave voltage amplitudes in all leads examined (lead I p = .955, lead II p = .600, lead V1 p = .520, lead V5 p = .072, lead V6 p = .357) showed no statistically significant differences between sports. However, R-wave V5 showed a trend towards variation (p = .072, $\eta^2$ = .086).

Table 4. Electrocardiographic Parameters by Individual Sport

| Parameter | Football/Soccer (n = 39) | Basketball (n = 19) | Athletics (n = 18) | Volleyball (n = 16) | Handball (n = 14) | Tennis (n = 11) | F-value | p-value | $\eta^2$ |
|---|---|---|---|---|---|---|---|---|---|
| HR (bpm) | 62.67 ± 11.77 | 65.42 ± 10.06 | 72.00 ± 13.57 | 76.44 ± 13.54[a] | 69.14 ± 11.33 | 71.55 ± 9.35 | 4.03 | .002** | .154 |
| PR interval (ms) | 149.08 ± 22.46 | 149.42 ± 31.51 | 142.94 ± 20.52 | 152.62 ± 20.01 | 141.86 ± 47.29 | 154.45 ± 25.98 | 0.48 | .790 | .021 |
| QRS duration (ms) | 85.79 ± 11.33 | 86.84 ± 11.51 | 79.56 ± 9.19 | 78.06 ± 12.81 | 85.07 ± 7.81 | 75.45 ± 7.70 | 3.32 | .008** | .130 |
| QT interval (ms) | 383.46 ± 26.35 | 382.79 ± 22.50 | 375.06 ± 22.07 | 366.44 ± 19.75 | 374.71 ± 22.04 | 369.00 ± 24.03 | 1.76 | .128 | .073 |
| QTc interval (ms) | 389.92 ± 26.92 | 398.63 ± 23.54 | 409.06 ± 32.44 | 411.81 ± 26.74 | 400.79 ± 24.20 | 402.18 ± 25.31 | 2.15 | .065 | .088 |
| QRS axis (°) | 41.33 ± 32.74 | 47.16 ± 36.12 | 38.33 ± 38.66 | 36.44 ± 22.79 | 47.43 ± 36.10 | 34.00 ± 38.70 | 0.40 | .852 | .017 |
| P-wave axis (°) | 31.82 ± 26.38 | 27.89 ± 23.41 | 30.28 ± 28.71 | 39.75 ± 19.94 | 20.93 ± 28.98 | 4.55 ± 67.41 | 1.90 | .101 | .079 |
| T-wave axis (°) | 17.41 ± 20.50 | 13.58 ± 14.15 | 14.17 ± 18.52 | 16.12 ± 7.46 | 18.50 ± 18.36 | 13.82 ± 15.22 | 0.26 | .933 | .012 |
| R-wave Lead I (mV) | 0.52 ± 0.22 | 0.52 ± 0.22 | 0.51 ± 0.26 | 0.51 ± 0.21 | 0.48 ± 0.13 | 0.57 ± 0.33 | 0.22 | .955 | .010 |
| R-wave Lead II (mV) | 1.10 ± 0.38 | 1.05 ± 0.36 | 1.01 ± 0.31 | 0.97 ± 0.23 | 1.00 ± 0.30 | 0.92 ± 0.26 | 0.73 | .600 | .032 |
| R-wave Lead V1 (mV) | 0.19 ± 0.12 | 0.15 ± 0.14 | 0.21 ± 0.17 | 0.14 ± 0.10 | 0.18 ± 0.10 | 0.14 ± 0.17 | 0.85 | .520 | .037 |
| R-wave Lead V5 (mV) | 1.56 ± 0.59 | 1.37 ± 0.50 | 1.38 ± 0.41 | 1.27 ± 0.36 | 1.59 ± 0.42 | 1.14 ± 0.34 | 2.09 | .072 | .086 |
| R-wave Lead V6 (mV) | 1.16 ± 0.39 | 1.09 ± 0.30 | 1.07 ± 0.27 | 0.99 ± 0.33 | 1.09 ± 0.25 | 0.93 ± 0.30 | 1.12 | .357 | .048 |

Data presented as mean ± SD. One-way ANOVA performed with post-hoc Tukey's HSD test. Superscript [a] indicates significantly different from football/soccer (p = .002). Statistical significance: *p < .05, **p < .01, ***p < .001. Effect sizes reported as eta-squared ($\eta^2$): small (.01), medium (.06), large (.14). 95% CI for HR difference (football/soccer vs volleyball): 3.59–23.95 bpm. **R-wave amplitudes measured in millivolts (mV) from standard 12-lead ECG recordings.** †High standard deviation for tennis P-wave axis reflects small sample size (n = 11)

and substantial inter-individual variability.
Caution: Unequal sample sizes (n = 11–39) limit power for detecting small-to-medium effects in sports with smaller representation.
Abbreviations: ANOVA, analysis of variance; bpm, beats per minute; CI, confidence interval; HR, heart rate; HSD, honestly significant difference; ms, milliseconds; **mV, millivolts;** QTc, corrected QT interval; SD, standard deviation; °, degrees; $\eta^2$, eta-squared.

## Discussion

This research demonstrates significant sport-specific electrocardiographic adaptations in Moroccan amateur university athletes, with endurance athletes showing the most pronounced training-related modifications. Sinus bradycardia, the hallmark of endurance adaptation, occurred in 47.5% of endurance athletes compared to 27.0% of mixed/team athletes and 25.0% of strength/power athletes This research demonstrates significant sport-specific electrocardiographic adaptations in Moroccan amateur university athletes, with endurance athletes showing the most pronounced training-related modifications. Sinus bradycardia, the hallmark of endurance adaptation, occurred in 47.5% of endurance athletes compared to 27.0% of mixed/team athletes and 25.0% of strength/power athletes (p = 0.018). These results are consistent with established physiological principles that sustained aerobic training induces enhanced parasympathetic tone and reduced intrinsic heart rate (Palermi et al., 2023; Zimmermann et al., 2022).

The sinus bradycardia observed in endurance athletes reflects both autonomic and cellular adaptations. Beyond the increased parasympathetic tone, intrinsic modifications occur in the sinoatrial node pacemaker cells, including down-regulation of HCN4 channels (responsible for the funny current If) and alterations in calcium-handling proteins (Mesirca et al., 2021; Rojas-Valencia et al., 2024). These cellular remodelling processes reduce the rate of spontaneous depolarisation independently of neurovegetative influences, as demonstrated by persistent bradycardia after pharmacological autonomic blockade in trained athletes (D'Souza et al., 2014). The combination of increased vagal modulation and intrinsic modifications of pacemaker cells explain the profound reduction in heart rate observed in our endurance cohort, with mean values of 58.4 ± 11.2 bpm representing a 15% reduction compared to strength/power athletes.

The prolongation of the PR interval, observed more frequently in endurance athletes (164.2 ± 26.8 ms vs 152.4 ± 21.2 ms in strength athletes, p = .042), reflects a delay in atrioventricular conduction secondary to increased vagal tone and possible intrinsic AV node remodelling. These findings remain within physiological parameters and align with systematic reviews documenting PR interval prolongation in 10-30% of resistance-trained individuals without pathological significance (Mesirca et al., 2021; Pelliccia et al., 2024; Zorzi et al., 2020).

Borderline findings according to Seattle Criteria - including left atrial enlargement (5.4%), left axis deviation (8.1%) and right axis deviation (6.0%) - occurred with modest prevalence without significant sport-specific variation (all p > .05). The absence of associated abnormal findings or clinical symptoms supports its physiological nature, although the Seattle Criteria appropriately recommend further evaluation to exclude pathology. The comparable prevalence across sports suggests that these patterns reflect constitutional variants rather than training-induced adaptations (Drezner et al., 2017).

Our Moroccan cohort exhibited a lower prevalence of abnormal electrocardiographic findings (6.0%) compared with rates reported in some studies of sub-Saharan African athletes (15-25%) (Ozo & Sharma, 2020; Riding et al., 2019). However, direct comparisons between populations are limited by methodological heterogeneity, including differences in athlete training levels (elite vs amateur), age distributions, versions of ECG interpretation criteria (Seattle 2017 vs previous iterations) and sample characteristics. Observed differences may reflect multiple factors: differences in genetic ancestry between North African and sub-Saharan populations (El Fahime et al., 2025; Hallak et al., 2020), environmental influences including training methodologies and dietary patterns (Segreti et al., 2024), or methodological artefacts arising from non-standardised comparison protocols. These findings question the universal application of continent-wide generalisations and underline the need for region-specific normative data derived from standardised protocols. Future systematic comparative studies using matched populations, identical ECG interpretation criteria and comparable training levels are needed to characterise interregional electrocardiographic variations and definitively identify their underlying determinants.

These findings have potential implications for cardiovascular screening programmes in North Africa. Although the Seattle Criteria provide a valuable framework, preliminary data suggest that region-specific reference intervals may optimise diagnostic accuracy. The prevalence of abnormalities observed in our cohort (6.0%), while lower than some reports from sub-Saharan Africa (15-25%), aligns more closely with rates in Caucasian populations (4-8%), suggesting that universal African screening algorithms may not adequately capture North African heterogeneity (Basu & Malhotra, 2018; Drezner et al., 2017). However, validation in larger multicentre North African multicentre cohorts is required before definitive screening recommendations can be made.

Analysis of individual sports revealed that football/soccer players demonstrated significantly lower heart rates (62.67 ± 11.77 bpm) compared to volleyball players (76.44 ± 13.54 bpm, $p = .002$, mean difference = 13.77 bpm, 95% CI 3.59-23.95), reflecting the predominantly aerobic nature of football compared to the intermittent power-based demands of volleyball (Churchill et al., 2021; Kim et al., 2025). However, variable sample sizes across sports (from $n = 11$ for tennis to $n = 39$ for football) limit definitive conclusions for under-represented disciplines. The observed patterns - including lower heart rates in football and athletics than in volleyball and other sports - are consistent with physiological expectations, but need to be replicated in sport-specific cohorts with adequate power. These preliminary findings underscore the potential utility of discipline-stratified reference ranges rather than broad categorical groupings (Caramoci et al., 2025; Maillot et al., 2018), while highlighting the need for international collaborative registries to accumulate sufficient sport-specific data.

The sport-specific electrocardiographic variations observed can be attributed to the different haemodynamic and metabolic demands inherent to each athletic discipline. Football players performing prolonged aerobic activity interspersed with high-intensity bursts experience chronic volume and pressure overload, which stimulates left ventricular hypertrophy and increased vagal tone, manifested as sinus bradycardia (62.67 ± 11.77 bpm) and early repolarisation patterns (Małek et al., 2025). The combination of sustained endurance running (covering 10-13 km per game) with intermittent sprint demands creates a unique cardiac remodelling profile characterised by both cavity enlargement and wall thickening, reflected electrocardiographically through increased R-wave amplitude, ST-segment elevation and prolonged PR intervals indicative of increased atrioventricular conduction delay (Dalen et al., 2024; Oxborough et al., 2025).

Basketball players showed intermediate electrocardiographic patterns, with mean heart rates of 65.42 ± 10.06 bpm. The sport's characteristic alternation between explosive vertical movements, rapid directional changes and short recovery periods generates a mixed physiological stimulus that combines elements of both aerobic conditioning and power development (Zimmermann et al., 2022). Repetitive eccentric loading during jumping and landing, coupled with intermittent high-intensity efforts (Oxborough et al., 2025), produces modest vagal adaptation without the extreme bradycardia observed in pure endurance disciplines (Lander et al., 2024; Małek et al., 2025). The slightly prolonged QRS duration in basketball athletes (86.84 ± 11.51 ms) may reflect an increase in ventricular mass secondary to the unique combination of sustained aerobic activity and explosive anaerobic power requirements of this sport (Lander et al., 2024). R-wave voltage amplitudes, electrocardiographic markers of ventricular mass, showed no significant differences between sports (all $p > .05$), although R-wave amplitude in lead V5 showed a tendency to vary ($p = .072$, $\eta^2 = .086$). Football players and handball athletes showed numerically higher V5 amplitudes (1.56 ± 0.59 mV and 1.59 ± 0.42 mV, respectively) than tennis players (1.14 ± 0.34 mV), consistent with the expectation that sustained aerobic sports generate greater left ventricular volume loading (Pelliccia et al., 2024). The absence of statistically significant voltage differences probably reflects the amateur training status of our cohort, as elite athletes typically show more pronounced voltage elevations (D'Ascenzi et al., 2024) or may reflect insufficient statistical power due to modest sample sizes in individual sports.

Volleyball players and track and field athletes demonstrated less pronounced cardiac adaptations, with heart rates of 76.44 ± 13.54 bpm and 72.00 ± 13.57 bpm, respectively (Kramer et al., 2024), approaching values observed in populations with less aerobic training and significantly higher than in football/soccer ($p = .002$, mean difference = 13.77 bpm, 95% CI 3.59-23.95 for comparison with volleyball) (Churchill et al., 2021). Volleyball's emphasis on brief explosive movements with prolonged recovery periods provides insufficient sustained haemodynamic stress to trigger substantial cardiac remodelling (Celeski et al., 2025).

Similarly, heterogeneity within athletics - encompassing sprinters, throwers, jumpers and middle-distance runners - produces averaged electrocardiographic parameters that mask individual event-specific adaptations (Di Gioia et al., 2024). Sprint and power events in athletics generate predominantly anaerobic metabolic demands with minimal cardiac volume load, while middle-distance runners show adaptations intermediate between pure endurance and power athletes, resulting in a diluted electrocardiographic profile at the group level (Adea et al., 2020; Pelliccia et al., 2024). (p = 0.018). These results are consistent with established physiological principles that sustained aerobic training induces enhanced parasympathetic tone and reduced intrinsic heart rate (Palermi et al., 2023; Zimmermann et al., 2022).

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## *Limitations*

Several limitations must be acknowledged. First, our cohort of amateur (college-level, non-professional) athletes train at submaximal volumes compared to elite professionals, which may result in less pronounced electrical adaptations than those documented in elite populations. Our operational definition of "amateur athlete" encompasses collegiate-level competitors who train regularly (≥3 sessions per week) without professional contracts or a primary vocational dedication to the sport. This differs from definitions of elite athlete, which require registration with national sports federations and a full-time training commitment. The Seattle International Criteria were initially developed for competitive athletes of all skill levels, including amateurs, although validation studies predominantly included elite cohorts (Drezner et al., 2017). Our findings suggest that these criteria maintain diagnostic utility for amateur populations, although region-specific normative adjustments may optimise screening accuracy for non-elite athletes with lower training volumes.

Second, the cross-sectional design precludes longitudinal assessment of electrocardiographic evolution with progressive training adaptations (Forså et al., 2023). Third, small sample sizes for individual sports (n = 11-39) limited statistical power, warranting cautious interpretation as exploratory findings. Fourth, a formal inter-rater reliability assessment was not calculated prior to consensus between the two ECG interpreters. However, a double independent review with structured consensus procedures was employed to minimise interpretation bias.

Fifth, the absence of systematic echocardiographic correlation limits definitive differentiation between electrical manifestations attributable to structural remodelling and those attributable to isolated conduction system modifications. Furthermore, the lack of an age-matched sedentary control group precludes direct quantification of the effects of athletic training relative to general Moroccan population norms. The participation rate of 87.6% may have introduced a selection bias, as the cardiovascular characteristics of non-participants are unknown. Generalisability is limited to the specific context of Hassan I University, Settat, and may not extend to athletes from other Moroccan regions with different environmental, socioeconomic or training characteristics. Sixth, manual ECG interpretation, despite double independent review, remains subject to interobserver variability.

Seventh, our study lacked a comprehensive assessment of biomarkers and advanced cardiac imaging modalities (cardiac magnetic resonance imaging), which would have reinforced mechanistic interpretations. Finally, the absence of intersport differences in LVH voltage criteria, despite apparent disparities in training volume, may reflect the lower training intensity characteristic of amateur versus elite populations (Halasz et al., 2025) or suggest that voltage criteria lack sufficient sensitivity to detect subtle gradations of hypertrophy (D'Ascenzi et al., 2024). Future research should prioritise prospective longitudinal designs that track electrocardiographic evolution throughout competitive careers, integrated multimodal assessment combining ECG with echocardiography and cardiac MRI, and genetic profiling to elucidate heritable contributions to phenotypic heterogeneity (Sharma et al., 2017; Sheikh et al., 2018). Multicentre collaborative studies across various Moroccan institutions are needed to establish nationally representative normative data. International registries that systematically collect standardised data across diverse geographic regions would enable robust comparative epidemiological analyses and inform evidence-based guideline revisions that accommodate global athletic diversity (Egger et al., 2025; Moulson et al., 2021).

## Conclusions

Moroccan amateur collegiate athletes exhibit sport-specific electrocardiographic adaptation patterns, with endurance athletes showing the most pronounced training-related modifications. The markedly lower prevalence of abnormalities (6.0%) compared to sub-Saharan African populations challenges assumptions of continental generalisability and necessitates the development of region-specific regulatory frameworks. These findings support precision medicine approaches in sports cardiology, advocating for ethnically and geographically tailored screening protocols rather than universal application of international criteria. Football/soccer athletes show particularly pronounced bradycardic adaptations, justifying discipline-specific reference ranges for optimal screening accuracy. Future research should employ longitudinal and multimodal designs with genetic profiling to advance understanding of mechanisms and optimise cardiovascular screening efficacy in diverse athletic populations.

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Author affiliations and contributions:

- Younes BROUKI (orcid.org/0000-0002-7906-989X) – Sports Science Research Team, Institute of Sports Science, Hassan I University, Settat, Morocco
- Omar BEN RAKAA (orcid.org/0000-0002-2181-5247) – Multidisciplinary Laboratory in Education Sciences and Training Engineering (LMSEIF), Sport Science Assessment and Physical Activity Didactic, Normal Higher School (ENS-C), Hassan II University of Casablanca, Morocco
- Walid BOUZID (orcid.org/0009-0003-8531-7356) – Sports Science Research Team, Institute of Sports Science, Hassan I University, Settat, Morocco
- Youssef El MACHROUH (orcid.org/0009-0007-1749-1642) – Sports Science Research Team, Institute of Sports Science, Hassan I University, Settat, Morocco
- Mohamed BARKAOUI (orcid.org/0000-0002-5209-1499) – Sports Science Research Team, Institute of Sports Science, Hassan I University, Settat, Morocco
- Abdeljalil ElGOT (orcid.org/0000-0002-2068-7079) – Higher Institute of Health Sciences, Laboratory of Sciences and Health Technologies, Hassan I University of Settat, Morocco
- Aziz ELOIRDI (orcid.org/0000-0003-1061-7787) – Sports Science Research Team, Institute of Sports Science, Hassan I University, Settat, Morocco
- Aziz CHOKRI (orcid.org/0000-0001-8357-3880) – Sports Science Research Team, Institute of Sports Science, Hassan I University, Settat, Morocco

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## Authors and translators' details:


| | | |
|---|---|---|
| Younes Brouki | Younes.brouki@gmail.com | Author/Translator |
| Omar Ben Rakaa | Omarbenrakaa@gmail.com | Author |
| Walid Bouzid | profw.bouzid99@gmail.com | Author |
| Youssef El machrouh | Youssef El machrouh | Author |
| Mohamed Barkaoui | Mohamed.barkaoui@uhp.ac.ma | Author |
| Abdeljalil Elgot | abdeljalil.elgot@uhp.ac.ma | Author |
| Aziz Eloirdi | aziz.eloirdi@uhp.ac.ma | Author |
| Aziz Chokri | Aziz.chokri@uhp.ac.ma | Author |