Assessment of a novel, 22-lead mobile electrocardiogram in elite, adolescent footballers

Harvey Johnson, Nuno Duarte, Diane Ryding, Dave Perry, Steve McNally, A Graham Stuart, Craig A Williams, Guido E Pieles

Abstract

The 12-lead electrocardiogram is a key component of cardiac screening in elite adolescent footballers. Current technology hampers mobile electrocardiogram monitoring that could reduce the time-to-diagnosis in symptomatic athletes. Recently, a 22-lead mobile electrocardiogram monitor, CardioSecur (Personal MedSystems GmbH), has been approved for use in adults. In this study, the differences in parameter accuracy between CardioSecur's 22-lead electrocardiogram and the gold standard 12-lead electrocardiogram were assessed in elite adolescent footballers (n=31) using Bland-Altman and paired *t*-tests/Wilcoxon analysis. Agreement between the two devices was clinically acceptable for heart rate (bias= -0.633 bpm), PR Interval (bias= -1.73 ms), Bazzett's corrected QTc interval (bias= 2.03 ms), T-wave axis (bias= 6.55°), P-wave duration (bias= -0.941 ms), Q-wave amplitude (bias= 0.0195 mV), Q-wave duration (bias= 1.98 ms), rhythm (bias= 0.0333), ST-segment (bias= -0.0629), J-point analysis (bias= -0.01) and extended T wave and QRS duration analysis. Unsatisfactory agreement was observed in QRS axis (bias= -19.4°), P-wave axis (bias= -0.670°), QRS amplitude (bias= -0.660 mV), P-wave amplitude (bias= 0.0400 mV) and T-wave amplitude (bias= -0.0675 mV). CardioSecur's 22-lead electrocardiogram agrees with the gold standard in rhythm, durations, T-wave determination in all leads assessed, permitting its use in adolescent footballers for immediate pitch- or track-side analysis.

Introduction

High levels of athleticism and cardiovascular fitness leads to electrical and structural cardiac adaptations that occasionally exceed the boundaries of normality [1-4]. As a result, specialised ECG screening guidelines have been published to help physicians separate normal physiological adaptation from disease [5]. Professional athletes may show ECG changes such as early repolarisation, T-wave inversion (TWI) without underlying pathology or hypertrophy of the left and right ventricles [5-8]. Some elite adolescent athletes also develop cardiac adaptations, such as ventricular hypertrophy [9]. However, for those with undetected heart disease, exercise may trigger (sometimes fatal) arrhythmias [10, 11]. Cardiomyopathies are a leading cause of sudden cardiac death (SCD) in elite adolescent footballers, however, according to one study, most of these cases would not be detected using ECG alone [12]. It is therefore vital that screening is optimised for these athletes as they are at a greater risk of SCD than their non-athlete peers. Despite this, normative data in the adolescent athlete population are limited and specialised ECG guidelines are not available [13].

The 12-lead ECG is the primary cardiac screening tool in athletes [5]. However, the 10-electrode setup is time consuming and subject to lead misplacement [14, 15]. CardioSecur Pro (*Personal Medsystems GmbH*) is a novel, ECG application (app) for physicians that can extrapolate 12- and 22-lead ECGs from just four electrodes connected to a phone or tablet. CardioSecur is a development of the approved, EASI ECG, negating the requirement for an 'earth'

electrode [16]. This adaptation of the quasi-orthogonal EASI ECG, first described by Dower *et al* [17], uses transformation coefficients to derive 22-leads and 360° of electrical activity**.** Although lacking, comparison studies between CardioSecur and the EASI ECG have been reassuring, >99% agreement in identifying ischaemia was reported in one study [16]. The agreement between the EASI ECG (upon which CardioSecur is based) and the gold standard 12-lead ECG has been verified [18-24]. Electrodes are placed on easily identifiable, bony landmarks, reducing noise and error. This app may offer numerous improvements to the current gold standard 12-lead ECG including portability, efficiency and reduction in lead misplacement. The cost of a CardioSecur Pro account and the physical leads starts from €1510, automated analysis and parameter measurement are optional extras. This device has been approved in Europe for adults as a class IIa medical device, but is yet to be tested in elite adolescent athletes.

It has been argued that the gold standard 12-lead ECG neglects right-sided and posterior aspects of the heart [25, 26]. Additional leads, offered by CardioSecur (V7-V9, VR3-VR9), have been shown to improve detection of posterior myocardial infarcts [27, 28]. It remains unclear if these leads could assist in detection of structural or electrical disease in athletes. The available literature on this device tests its efficacy in adults and, to date, there are no studies directly comparing amplitudes, durations and waveforms in CardioSecur and the gold standard 12-lead ECG in elite adolescent athletes[27, 29]. Therefore, in this study, the agreement in parameter accuracy between CardioSecur's 22-lead mobile ECG and the gold standard 12-lead ECG is investigated in this population.

Methods

Participants

All participants (n=31) were recruited from an English Premier League football club academy and were deemed elite, adolescent athletes by training and competition volumes of approximately 10 hours per week. Male athletes of all ethnicities, between the age of 13 and 16 years were included. Written parental consent and participant assent were obtained. All protocols were approved by the institutional ethics committee and meet the ethical standards of this journal [30]. One participant was excluded due to poor ECG tracing, leaving 30 participants for analysis.

CardioSecur 22-lead mobile ECG

CardioSecur's four electrode, mobile ECG is a modification of Dower's five electrode (four recording, one earth), EASI ECG [17]. CardioSecur uses vector-electrocardiography to mathematically derive 22-lead ECGs (**Fig. 1**). These principles were first described by Frank *et al* [31]. The app is compatible with Apple Inc. (Cupertino, USA) devices (iPhone or iPad) with iOS 10 or higher. In this study, an iPhone was used to collect data using the CardioSecur Pro app that displays a continuous ECG trace with a recording feature, **Fig. 2**.

Figure 1. CardioSecur 22-lead ECG. *This figure is used with permission from Personal MedSystems GmbH (Frankurt, Germany)*

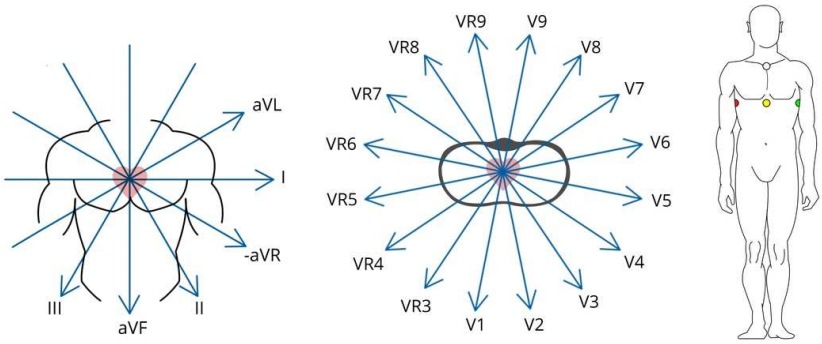
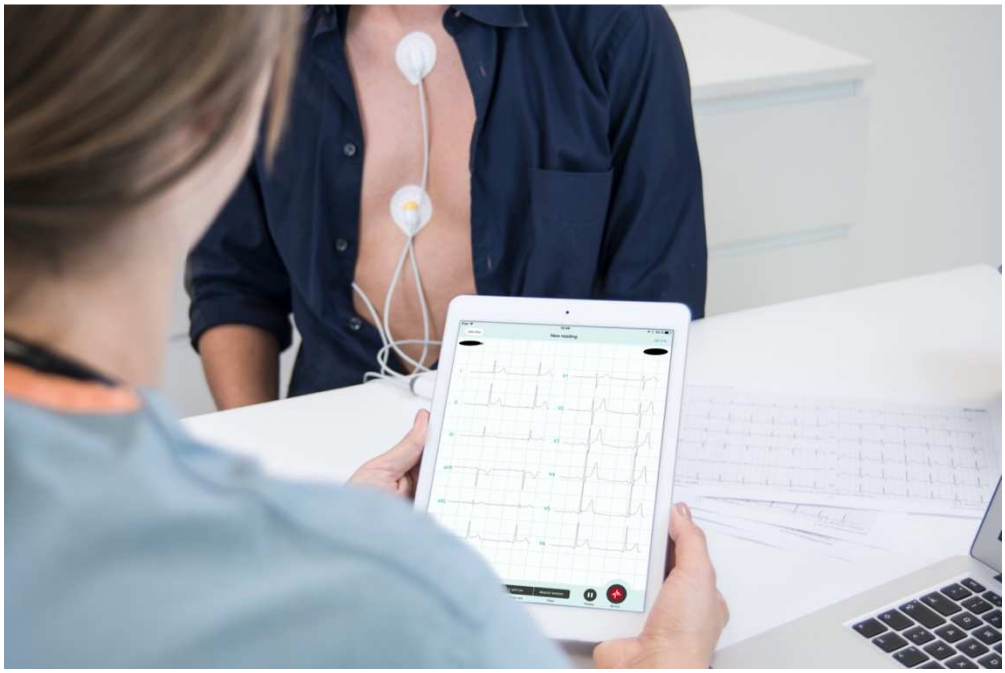


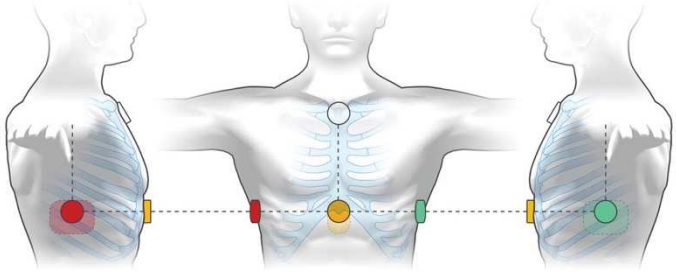
Figure 2. Four chest electrodes connected directly to an iPad showing an ECG trace *This figure is used with permission from Personal MedSystems GmbH (Frankfurt, Germany)*



Data collection

Each participant received a standard, resting, 12-Lead ECG (nECG) followed by a resting 22-Lead Cardiosecur ECG (cECG). The mean sampling duration of nECGs and cECGs was 10 s and 11s, respectively. Data acquisition was part of routine cardiac screening and all nECGs were analysed by the team cardiologist (GEP) present in accordance with FA guidelines. Electrode placement for the nECG followed normal clinical standards (three limb leads, six precordial leads, one earth). The cECG required the attachment of four electrodes as shown in **Fig. 3**. All ECGs were stored as a PDF file for interpretation. ECGs were recorded at an amplitude of 10 mm/mV and a paper speed of 25 mm/s. Filtering on the nECG was set at the standardised frequency of 0.05-150 Hz. The cECG was pre-programmed with a band-stop filter from 40.0-60.0 Hz and high-pass filtering of 0.05 Hz.

Figure 3. Electrode placement in CardioSecur ECG. White, manubriosternal joint in the midline; yellow, xiphoid process in the midline; red, parallel to the xiphoid process at the right mid axillary line (MAL); green, parallel to the xiphoid process at the left MAL. *This figure is used with permission from Personal MedSystems GmbH (Frankfurt, Germany)*



Measures

Parameters selected for comparative analysis were heart rate (V1-V6), PR Interval (V1-V6), QRS duration (Leads I, II, III, aVR, aVL, aVF, V1-V6), Bazzett's corrected QTc interval (Lead II or V5), QRS axis, P-wave axis, T-wave axis, QRS amplitude (V1-V6), P-wave duration (V1-V6), P-wave amplitude (V1-V6), T-wave amplitude (V1-V6), Q-wave amplitude (V1-V6), Q-wave duration (V1-V6). Non-numerical parameters: rhythm, ST-segment (Leads I, II, III, aVR, aVL, aVF, V1-V6), T-waves (Leads I, II, III, aVR, aVL, aVF, V1-V6) and J-point (V1-V6) were recorded as numerical codes (see **Supplementary Table 1S**) and all ECGs were screened for premature ventricular contractions (PVCs). QTc interval was calculated using the 'tangent' method as per adult athlete guidelines [32, 33]. As T wave morphology and QRS duration are particularly relevant in this population, data was reported for each lead separately. Parameters were manually interpreted by a trained medical student (HJ) and re-evaluated by a specialist paediatric and sports cardiologist (GEP).

Statistics

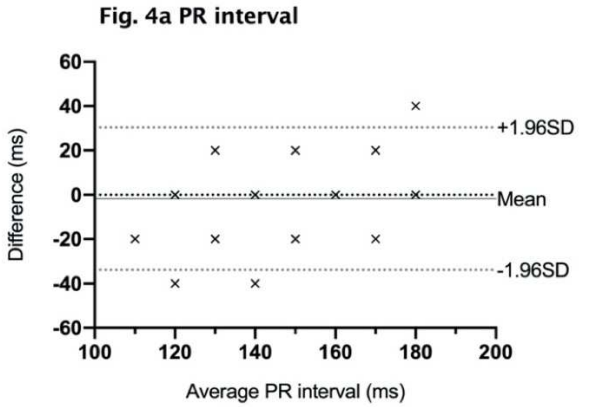
Descriptive data are presented as means ± standard deviation (SD) unless otherwise stated. Normality of ECG parameter distribution was assessed using D'Agostino and Pearson's correlation coefficient (r) tests. Differences in parameter accuracy was assessed using paired *t*-tests (for Gaussian data) or Wilcoxon signed-rank test (for non-Gaussian data) and Bland-Altman's method of assessing agreement [34]. The criteria for statistical agreement was defined as negligible differences in parameter measurement, unlikely to result in misdiagnosis. The 95% limits of agreement (LOA) are indicated by +/-1.96 SD. Statistical significance was defined as $p < 0.05$. Data analysis was performed using Prism 8.0.2 *(GraphPad Software Inc., San Diego, USA).*

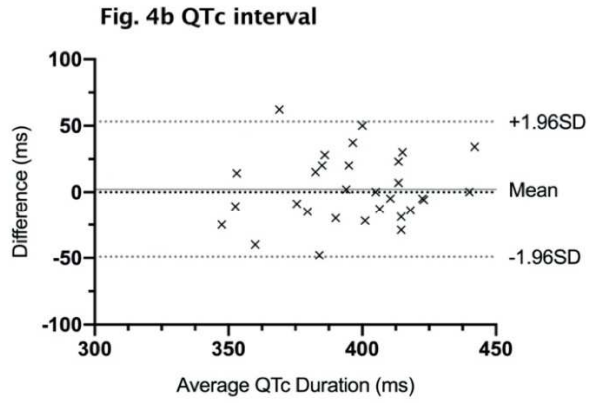
Results

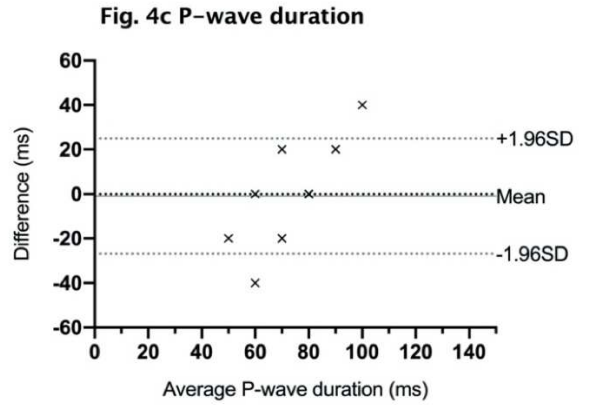
Results from D'Agostino and Pearson's correlation coefficient (r) test for continuous data can be found in **Supplementary Table 2S**. Bland Altman, Wilcoxon signed-rank and paired *t*-test results, assessing differences in parameter accuracy, are summarised in **Tables 1-3**.

All parameters measuring rhythm, rates, intervals and durations agreed satisfactorily. Heart rate had a negligible bias (-0.633 bpm) and paired *t*-test showed no significant difference (p= 0.167). Differences between the devices in PR interval (bias= -1.73 ms, p= 0.166, **Fig. 4a**), QTc interval (bias= 2.03 ms, p= 0.673, **Fig. 4b**), P wave duration (bias= -0.941 ms, p= 0.354, **Fig. 4c**) and rhythm (bias= 0.0333, p> 0.99) were not statistically significant and limits of agreement were narrow. Differences in Q wave duration (bias= 1.98 ms, p < 0.01) tracing was statistically significant.

Figures 4a-c. Bland Altman plots illustrating differences in duration and interval tracing between CardioSecur's 22-lead ECG and the gold standard 12-lead ECG. PR interval (V1-V6) n= 29; QTc interval (V5 or lead II) n= 30; P-wave duration (V1-V6) n= 29.







The two devices did not agree satisfactorily in wave amplitude detection. Analysis of P wave amplitude (bias= 0.0400 mV, p< 0.01, **Fig. 5a**), QRS amplitude (bias= -0.660 mV, p< 0.01, **Fig 5b**) and T wave amplitude (-0.0675 mV, p< 0.01, **Fig. 5c**) identified wide LOA and statistically significant differences. Q wave amplitude analysis (bias= 0.0195 mV, p< 0.01) met our agreement criteria due to low bias and narrow LOA despite a statistically significant difference.

Figures 5a-c. Bland Altman plots illustrating differences in amplitude tracing between CardioSecur's 22-lead ECG and the gold standard 12-lead ECG (V1-V6). P wave amplitude n= 27; QRS amplitude n= 29; T wave amplitude n=28.

Fig. 5a P-wave amplitude

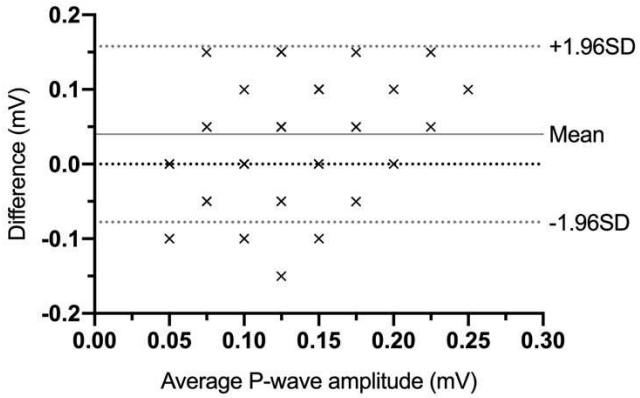


Fig. 5b QRS amplitude

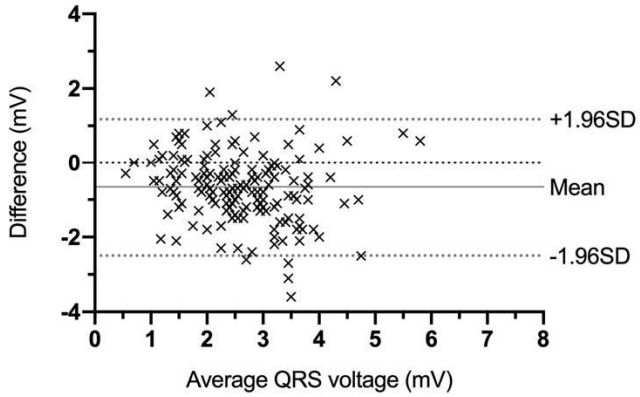
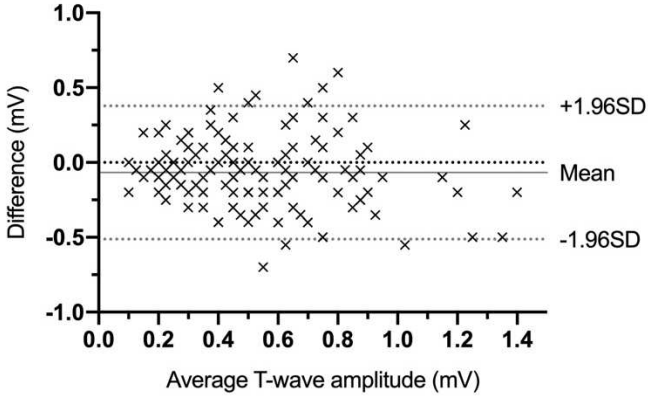
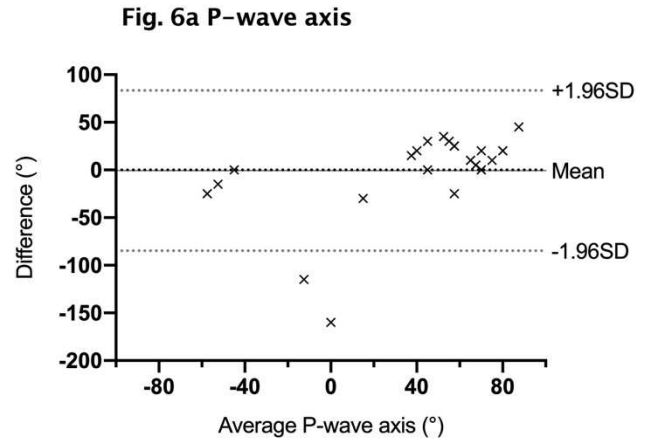


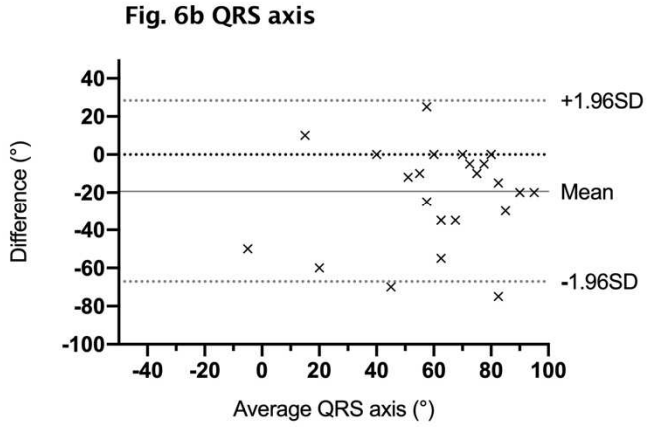
Fig. 5c T-wave amplitude

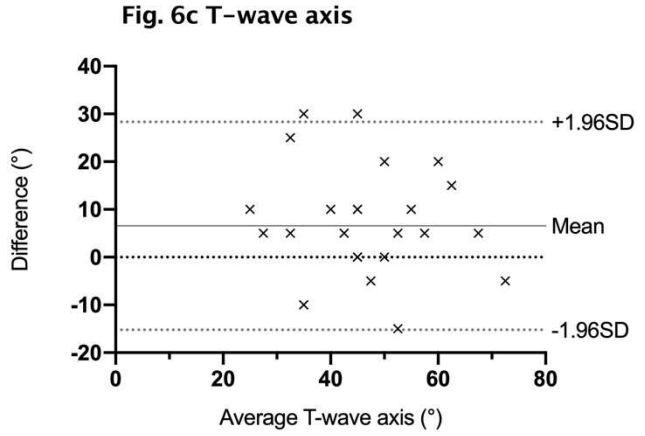


Satisfactory agreement was not found in P wave axis (bias= -0.670°, p= 0.265, **Fig. 6a**) or QRS axis (bias=-19.4°, p< 0.01, **Fig 6b**). T wave axis, however, did meet our agreement criteria (bias= 6.55°, p= 0.004, **Fig. 6c**) given the narrow LOA and negligible bias.

Figures 6a-c. Bland Altman plots illustrating differences in P-wave, QRS and T-wave axis between CardioSecur's 22-lead ECG and the gold standard 12-lead ECG. P wave axis n= 29; QRS axis n= 29; T wave axis n= 29.







All non-numerical parameters agreed sufficiently. J-point (bias= -0.01, p>0.99) and ST segment (bias= -0.0629, p= 0.215) analysis displayed excellent statistical agreement. Additionally, localised T wave analysis (**Table 2**) showed 100% agreement in leads I, II, aVF, V5 and V6 with no significant difference in the remaining leads.

Table 1. Bland Altman analysis and paired *t*-test/Wilcoxon signed-rank test results

		Bland Altman analysis			***t*-Test or Wilcoxon* p values**
Parameter	**n =**	**Bias (SD)**	**Upper LOA (95% CI)**	**Lower LOA (95% CI)**	
Heart rate (bpm)	30	-0.633 (6.12)	11.4 (7.4, 15.3)	-12.6 (-16.6, -8.67)	0.167
PR interval (ms)	29	-1.73 (16.4)	30.4 (26.2, 34.6)	-33.9 (-38.1, -29.7)	0.166
QTc interval (ms)	30	2.03 (26.1)	53.2 (36.5, 69.8)	-49.1 (-65.7, -32.7)	0.673
QRS axis (°)	29	-19.4 (24.4)	28.4 (12.5, 44.1)	-67.1 (-82.9, -51.3)	< 0.01
QRS amplitude (mV)	29	-0.660 (0.937)	1.18 (0.936, 1.42)	-2.50 (-2.74, -2.26)	< 0.01*
P wave axis (°)	29	-0.670 (42.9)	83.4 (55.5, 111)	-84.8 (-113, -56.9)	0.265*
P wave duration (ms)	29	-0.941 (13.2)	24.9 (21.5, 28.3)	-26.8 (-30.2, -23.4)	0.354
P wave amplitude (mV)	27	0.0400 (0.06)	0.158 (0.142, 0.174)	-0.0778 (-0.0938, -0.0617)	<0.01
T wave axis (°)	29	6.55 (11.1)	28.3 (21.1, 35.5)	-15.2 (-22.4, -8.00)	0.004
T wave amplitude (mV)	28	-0.0675 (0.222)	0.378 (0.318, 0.437)	-0.513 (-0.572, -0.453)	< 0.01*
Q wave amplitude (mV)	30	0.0195 (0.0693)	0.155 (0.138, 0.173)	-0.116 (-0.134, -0.0986)	< 0.01*
Q wave duration (ms)	29	1.98 (8.83)	19.3 (18.0, 20.6)	-15.3 (-16.6, 14.0)	< 0.01*
Cardiac rhythm†	30	0.0333 (0.183)	0.391	-0.325	> 0.99*
J-point†	29	-0.01 (0.229)	0.444	-0.455	> 0.99*
ST segments†	29	-0.0629 (0.861)	1.62	-1.75	0.215*

SD = standard deviation; LOA = 95% limits of agreement; CI = 95% confidence interval; QTc interval = Bazett's corrected QT interval; * = Wilcoxon signed-rank test performed. † = Categorical data therefore no units, refer to methods or supplementary table 1S

Localised QRS duration analysis (**Table 3, Fig. 7a-c**) showed no significant difference between the two devices in all leads except V2 (P=0.0312). However, narrow LOA (-8.83 ms, 14.4 ms) and low bias (2.76 ms) satisfied our agreement criteria for V2. In addition, no PVCs were detected in either groups.

Figures 7a-c. Bland Altman plots illustrating differences in QRS duration between CardioSecur's 22-lead ECG and the gold standard 12-lead ECG in leads II (n= 30), III (n= 30) and V2 (n= 29).

Fig. 7a QRS duration Lead II

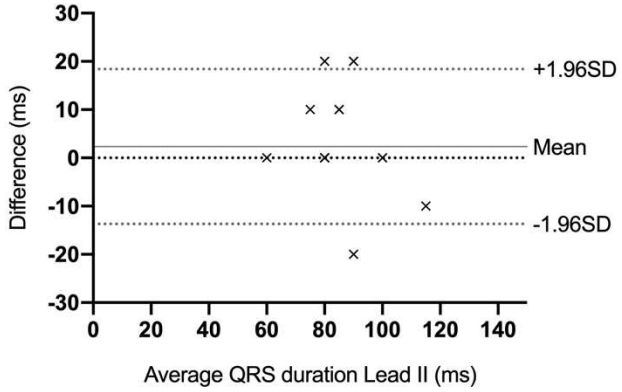


Fig. 7b QRS duration Lead III

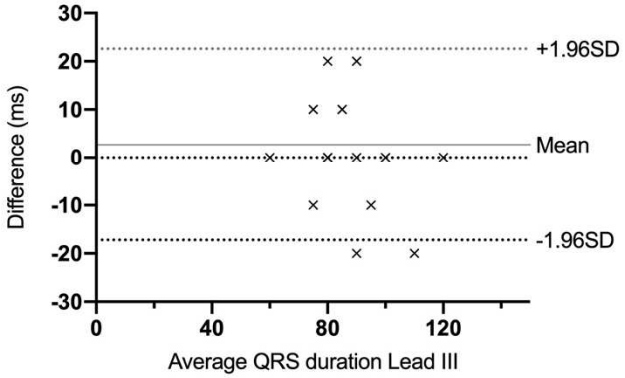


Fig. 7c QRS duration Lead V2

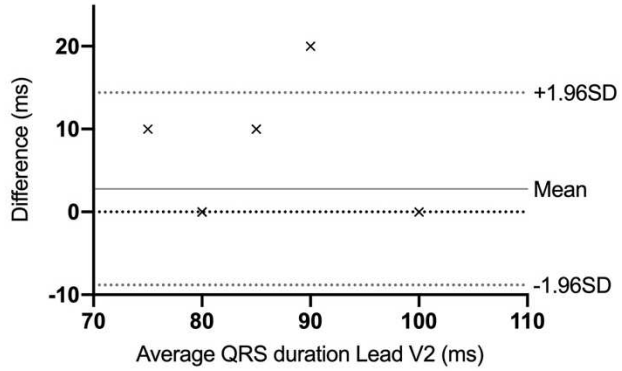


Table 2. Bland Altman analysis and paired *t*-test/Wilcoxon signed-rank test results for localised T-wave morphology

	I	**II**	**III**	**aVL**	**aVR**	**aVF**	**V1**	**V2**	**V3**	**V4**	**V5**	**V6**
***n*=**	29	29	29	29	29	29	29	29	29	29	29	29
Bias (SD)	-	-	0.0345 (0.421)	0.207 (1.4)	-0.138 (0.351)	-	0.172 (2.14)	-0.0345 (2.68)	0.345 (1.01)	-0.448 (1.33)	-	-
Lower LOA (CI)	-	-	-0.791 (-1.07, -0.514)	-2.53 (-3.64, -1.43)	-0.826 (-1.10, -0.548)	-	-4.02 (-5.72, -2.32)	-5.29 (-7.41, -3.20)	-2.32 (-3.13, -1.52)	-3.05 (-4.10, -2.00)	-	-
Upper LOA (CI)	-	-	0.860 (0.583, 1.13)	2.95 (1.84, 4.05)	0.550 (0.272, 0.828)	-	4.37 (2.66, 6.07)	5.22 (3.09, 7.34)	1.63 (0.831, 2.44)	2.15 (1.10, 3.20)	-	-
Wilcoxon P value	-	-	>0.999	0.570	0.125	-	0.535	0.921	0.0625	0.125	-	-
Interpretation	100% agreement	100% agreement	N.S.	N.S.	N.S.	100% agreement	N.S.	N.S.	N.S.	N.S.	100% agreement	100% agreement
N.S. = Not significant. SD = standard deviation. LOA = Limit of agreement. CI = confidence interval. Categorical data therefore no units, refer to methods or supplementary Table 1S												

Table 3. Bland Altman analysis and paired *t*-test/Wilcoxon signed-rank test results for localised QRS duration

	I	**II**	**III**	**aVL**	**aVR**	**aVF**	**V1**	**V2**	**V3**	**V4**	**V5**	**V6**
***n*=**	29	30	30	30	30	30	29	29	29	29	29	29
Bias (SD) (ms)	1.72 (5.39)	2.33 (8.17)	2.67 (10.2)	2.33 (9.35)	2.00 (8.87)	1.33 (7.76)	1.38 (4.41)	2.76 (5.91)	1.72 (5.39)	1.72 (4.68)	1.38 (4.41)	2.76 (6.49)
Lower LOA (CI) (ms)	-8.84 (-13.1, -4.57)	-13.7 (-18.9, -8.41)	-17.2 (-23.8, -10.7)	-16.0 (-22.0, -9.96)	-15.4 (-21.1, -9.66)	-13.9 (-18.9, -8.87)	-7.27 (-10.2, -4.37)	-8.83 (-12.7, -4.95)	-8.84 (-12.4, -5.30)	-7.45 (-10.5, -4.38)	-7.27 (-10.2, -4.37)	-9.96 (-14.2, -5.70)
Upper LOA (CI) (ms)	12.3 (8.00, 16.6)	18.4 (13.1, 23.6)	22.6 (16.0, 29.1)	20.7 (14.6, 26.7)	19.4 (13.7, 25.1)	16.5 (11.5, 21.5)	10.0 (7.13, 12.9)	14.4 (10.5, 18.2)	12.3 (8.75, 15.8)	10.9 (7.83, 14.0)	10.0 (7.13, 12.9)	15.5 (11.2, 19.7)
Wilcoxon P value	0.188	0.195	0.218	0.220	0.277	0.484	0.250	0.0312	0.250	0.125	0.250	0.0625
Interpretation	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	N.S.	*	N.S.	N.S.	N.S.	N.S.

N.S. = Not significant. SD = standard deviation. LOA = Limit of agreement. CI = confidence interval.

Discussion

This purpose of this study was to analyse differences in parameter accuracy between CardioSecur's 22-lead mobile ECG and the gold standard 12-lead ECG in elite adolescent athletes. A priori LOA were not proposed as specialised ECG guidelines for elite adolescent athletes, currently, do not exist. CardioSecur's tracing of Heart rate, PR interval, QRS duration, QTc interval, T wave axis, P wave duration, Q wave amplitude, Q wave duration, rhythm, T waves, ST segment and J-point agreed sufficiently with the gold standard, demonstrated by low bias', narrow LOA and largely insignificant differences. Five parameters did not demonstrate satisfactory agreement, these were QRS axis, P-wave axis, QRS amplitude, P-wave amplitude and T-wave amplitude.

Statistically significant differences in P wave, QRS complex and T-wave amplitudes (all $p < 0.01$) were identified, highlighting the need for improvement in amplitude detection. Previous validation studies on CardioSecur also reported differences in amplitude readings which was attributed to different filter settings [35]. However, our data also highlighted significant outliers in P wave and QRS axis, contributing to wide LOA as demonstrated in the Bland Altman analysis. CardioSecur underestimated the mean QRS axis compared to the gold standard, resulting in a bias of -19.4°. Axis measurements largely agreed, resulting in a low bias. However, significant outliers resulted in wide LOA, thus, determining unsatisfactory agreement. This highlights CardioSecur's accuracy but relatively weak precision in amplitude and axis parameters. In practice, incorrect axis determination and QRS amplitude readings could lead to incorrect suspicion of electrical or structural cardiac disease, such as left ventricular hypertrophy. For the player and team, this is a costly mistake and may lead to suspension of playing time before further investigations have taken place.

In contrast, CardioSecur was consistently reliable in measuring rhythm, durations and intervals in all leads when compared to the gold standard ECG. Low bias and narrow LOA were found for PR interval, QRS duration and QTc interval. Additionally, CardioSecur showed >96% agreement with the gold standard 12-lead ECG in measuring cardiac rhythm. The exception was due to an error in P wave axis in lead II, diagnosing a low atrial rhythm – not a significant pathology and a common finding in the healthy adolescent population. Results from T wave axis and Q-wave duration highlighted significant differences (all $p < 0.01$). However, correlating the results with Bland Altman analysis, it was concluded that these were of low clinical impact. Differences of this magnitude are unlikely to result in misdiagnosis.

T wave morphology assessment is a core parameter in athletes, as TWI could be the only observable ECG sign pointing to underlying cardiac pathology, such as cardiomyopathy [5]. Therefore, it is vital that any novel ECG device agrees sufficiently with the gold standard ECG. CardioSecur and the gold standard ECG agreed sufficiently in T wave axis, conveyed by the low bias and narrow LOA. Additionally, extensive analysis of localised T wave morphology exposed 100% agreement in leads I, II, aVF, V5 and V6, with no significant difference in the remaining leads. In contrast, our data did not support the use of CardioSecur for T wave amplitude detection. However, this parameter is of little diagnostic use in this population. On this basis, it is concluded that CardioSecur agrees with the gold standard 12-lead ECG sufficiently in T wave analyses, a key parameter when differentiating training-related changes and cardiac disease in adolescent athletes.

QRS duration is an important parameter in young athletes as prolongation can signify underlying conduction abnormalities, such as ventricular pre-excitation[5]. Therefore, it is paramount that novel ECG devices agree with the gold standard. CardioSecur agreed sufficiently in all 12 leads with narrow limits of agreement and negligible bias. Differences were not statistically significant in all leads except in V2. When correlating V2 with Bland-Altman analysis, the difference was clinically insignificant. Therefore, CardioSecur was reliable in measuring QRS duration in all leads. Current guidance advises detection of PVCs using 24hr ambulatory monitoring or exercise stress testing [36]. We did not detect any PVCs in either groups. A larger sample is required to determine if CardioSecur can identify this relevant parameter in athletes.

Internal validation studies have pertained that CardioSecur is highly comparable to the EASI-ECG, despite discrepancies in amplitude measurements [17, 35]. Our data shows that differences in amplitude recording are present when comparing CardioSecur to the gold standard 12-lead ECG. However, we have additionally identified clinically significant differences in P wave and QRS axis determination that will need to be re-evaluated in larger populations. However, CardioSecur agreed with the gold standard in rhythm, durations, ST segment and T wave determination making it suitable for the detection of the majority of cardiac pathologies effecting young athletes. CardioSecur offers academies and athletic institutions a potential tool to detect and assess cardiac disease in addition to pre-participation screening. The simplicity of setup, designed for patient use, would allow all medical staff to accurately position electrodes and record ECGs on symptomatic athletes for cardiology assessment. This may improve the detection of arrhythmia's, leading to further tests and improved identification of underlying cardiac disease. Additionally, in the rare but emergency event of collapse during participation, CardioSecur offers fast, portable ECG monitoring for sports physicians during competition [27, 37].

Limitations

Our small study population will limit the external validity of these results. Future validity and reliability studies on CardioSecur should employ blinding when analysing ECGs, adjust for intra- and inter-observer variation and correlate ECG findings with echocardiography to better characterise heart pathology. To obtain the definitive technical error, ECG signals could be compared based on identical, artificial electrical stimulation, eliminating human error. Further research in this field should assess additional relevant parameters such as S-wave upstroke and compare CardioSecur with an approved 22-lead ECG in V7-V9, VR3-VR9 to assess accuracy in these leads and correlate this with clinical findings.

Conclusions

CardioSecur's 22-lead mobile ECG app agrees with the gold-standard 12-lead ECG sufficiently for on-field use in adolescent footballers. Whilst our data highlighted differences in amplitudes and axis, this novel app was highly comparable to the current gold standard in rhythm, durations, intervals, ST segment and J-point determination. The two devices were also highly comparable in T wave and QRS duration tracing in all leads, vital parameters in this youth population. Our data supports the use of CardioSecur for fast, pitch-side monitoring in training and competition settings. However, more studies are required, in larger populations, before this device replaces the gold standard method.

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Supplementary material: Assessment of a novel, 22-lead mobile electrocardiogram in elite, adolescent footballers

Table 1S. Non-numerical parameters were coded as shown below when analysing ECGs

Non-Numerical Parameters+	0=	1=	2=	3=	4=	5=
Rhythm	Sinus	Not sinus	-	-	-	-
ST-Segment	Isoelectric	Depression	Elevation	-	-	-
T-wave	Normal	Inversion <0.2mV	Inversion ≥0.2mV	Isoelectric	Biphasic	Notched
J-point Elevation (JPE)	Normal	JPE ≥0.1mV				

Table 2S. D'Agostino and Pearson's correlation coefficient (r) test

Parameter	**(P)assed or (F)ailed**	**P value**
Heart Rate	P	0.257
PR interval	P	0.244
QTc interval	P	0.699
QRS axis	P	0.209
QRS duration	F	0.0110
QRS amplitude	F	0.045
P-wave axis	F	<0.01
P-wave duration	P	0.443
P-wave amplitude	P	0.180
T-wave axis	P	0.583
T-wave amplitude	F	0.0142
Q-wave amplitude	F	<0.01
Q-wave duration	F	<0.01