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Sex-specific electrocardiographic criteria for left ventricular hypertrophy in young athletes

Samuel Montalvo, PhD,[1,2] Jason V. Tso, MD,[1,2] Jeffrey W. Christle, PhD,[1,2] David Hadley, PhD,[3] Matthew Wheeler, MD, PhD,[1,2] Marco Perez, MD,[1,2] Jonathan Myers, PhD,[1,2,4] Euan Ashley, DPhil, MBChB,[1,2] Victor Froelicher, MD[1,3]

ABSTRACT

BACKGROUND Left ventricular hypertrophy is a common electrocardiographic (ECG) finding in athletes, but existing amplitude-based criteria often generate false positives.

OBJECTIVE The purpose of this study was to reevaluate ECG criteria for screening athletes for left ventricular hypertrophy by considering QRS amplitude measurements and demographic factors, using data from an extensive digital ECG database.

METHODS A retrospective analysis of digitized ECG records from 9254 young athletes aged 12–35 years underwent a preparticipation examination between 2010 and 2021. Univariate and multivariate analyses assessed R- and S-wave amplitudes by applying the 99th percentile for R waves and the 1st percentile for S waves and examined the Sokolow-Lyon (SL) precordial lead score and the limb lead (LL) score, adjusting for sex, sport, age, class (athlete classification [college, grade school, high school, and professional]), body mass index, and heart rate.

RESULTS Our findings demonstrate significant sex differences in R- and S-wave voltages, with the highest R-wave voltages observed at the 99th percentile in lead V_4, V_5, or V_6 (4.4 mV for males and 3.3 mV for females). Multivariate analyses demonstrated that male athletes had significantly higher SL and LL scores than did females. While age, sport, ethnicity, and body mass index influenced SL and LL scores, their effect was much weaker than those of sex and impractical for general use.

CONCLUSION Our findings demonstrate that the 99th percentile values for sex-specific QRS voltage criteria (SL score of >6.8 mV for males and >4.7 for females; LL score of >2.3 mV for males and >1.9 mV for females) can enhance ECG criteria in athletes by increasing sensitivity for pathological hypertrophy with modest decreases in specificity.

KEYWORDS Athletic screening; Electrocardiography (ECG); Hypertrophic cardiomyopathy (HCM); Left ventricular hypertrophy (LVH); QRS voltage criteria

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Introduction

The most important factor in lowering the false-positive rate of electrocardiographic (ECG) criteria for screening young athletes has been the concept that large ECG QRS voltages, without repolarization abnormalities, are due to physiological hypertrophy rather than hypertrophic cardiomyopathy (HCM). This lowered the false-positive rate from roughly 20% to 2%–3% and led to a wide acceptance of the ECG as perhaps the major tool for screening young athletes for cardiovascular risk.[1–4] However, recent findings caused us to reexamine this assumption. First, the pathophysiology of HCM involves a first stage of myocyte hypertrophy (with QRS voltage increases) followed by lipid and fibrosis replacing myocytes, further increasing myocardial mass and causing repolarization abnormalities.[5] Second, the most thorough ECG study of HCM in adolescents documented that in 25%, excessive QRS voltages were the first ECG finding.[6] Third, our studies of digital QRS measurements and cardiac imaging failed to find a strong relationship between R- and S-wave amplitudes and myocardial mass.[7]

From the [1]Division of Cardiovascular Medicine, Stanford University School of Medicine, Stanford University, Palo Alto, California, [2]Wu Tsai Human Performance Alliance, Stanford University, Stanford, California, [3]Cardiac Insight Inc, Seattle, Washington, and [4]Palo Alto VA Medical Center, Palo Alto, California.

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These findings led to our present study examining the QRS voltage criteria for left ventricular hypertrophy (LVH) using a standard technique of biostatistics. Norms of many biological measures have considered that the extremes associated with pathology examples are obesity and cachexia for body weight and polycythemia and anemia for hematocrit. Cardiology examples include corrected QT interval in neonates,[8] low QRS voltage,[9] and ECG-LVH.[10] Thus, the study of QRS voltage norms could provide cut points that would increase the sensitivity for HCM in the young. As has been shown by Marshall et al,[6] 25% of youngsters with HCM have high QRS voltage as the only abnormality on their initial ECGs. Percentiles have been used to identify abnormalities, with the chosen values limiting the percentage of false positives. For instance, values such as the 1st or 99th percentile mean that the false-positive rate cannot increase >1% while acknowledging that sensitivity is reciprocal to specificity. Our first study of low QRS voltages encouraged us to turn our attention to quantify excessive QRS voltages in young athletes with the hope of identifying those with early HCM for additional studies.[3]

Methods

We performed a retrospective analysis on a data set encompassing ECG records from healthy asymptomatic athletes collected between 2010 and 2021,[11] using Cardea 20/20 ECG (Cardiac Insight Inc., Bellevue, WA) system to ensure consistent ECG digital data standards across the study. The data set included 10,728 athletes (4553 female [42.5%]; 6175 male [57.5%]; mean age 18.1 ± 4.3 years) who underwent ECG screening before participation in sports, with mass screenings conducted between 2014 and 2021 at multiple sites across the United States, including grade schools (11%), high schools (32%), colleges (50%), and professional athletic teams (6%). Exclusion criteria encompassed athletes with the Wolff-Parkinson-White pattern (n=26), right or left bundle branch block (n=77), and reversed leads (n=35). After applying these criteria, 9254 athletes (5400 male [58%]; 3854 female [42%]) remained eligible for analysis. QRS voltage was analyzed for each ECG lead, and traditional voltage criteria were applied and stratified by sex. This study was approved by the Stanford University Institutional Review Board (#12245), but follow-up was not permitted and the board specified that the data be de-identified.

Abbreviations

BMI: body mass index

CCC: cross-country and cycling

ECG: electrocardiographic

HCM: hypertrophic cardiomyopathy

HR: heart rate

LL: lower limb

LVH: left ventricular hypertrophy

SL: Sokolow-Lyon

ECG analysis

Digital ECG records from the athlete's prescreening sport participation were used. The Sokolow-Lyon (SL) precordial lead score was computed as the maximum absolute magnitude of the S wave in lead V_1 or V_2 and the maximum amplitude of the R wave in lead V_5 or V_6. The lower limb (LL) score was computed as the magnitude of the R wave in lead I and the absolute magnitude of the S wave in lead III. These scores were used as they represent the most widely used clinical score (SL score) for ECG-LVH screening, while the LL score offers a complementary perspective from the limb leads.

Sport classification

A sport classification was created to group the multiple sports into 14 major categories on the basis of the hemodynamic challenges of each sport type and the number of athletes participating. The categories include baseball and softball, basketball and volleyball, cross-country and cycling (CCC), fencing and golf, soccer, football linemen, football (other), gymnastics, swimming and diving, tennis and squash, crew and rowing, sailing, track and field, and water polo and wrestling.

Statistical analysis

Digitized ECG data were statistically analyzed using the R statistical programming language in RStudio: Integrated Development for R (version 4.5.0).[12] Descriptive statistics were calculated to assess the distribution of R- and S-wave amplitudes across various leads. We applied the 99th percentile for R waves and the 1st percentile for S waves to identify potential indicators of LVH. We selected the 99th percentile to capture the extreme tail of the distribution, ensuring a maximal theoretical false-positive rate of 1%. This choice is in line with prior literature using extreme cutoff points to detect outliers that may represent early pathological changes.[13] Two independent multivariate linear models (ordinary least squares) were constructed to compare the SL precordial lead score and the LL lead score. The models included the following independent variables: sex, type of sport, age, age class, body mass index (BMI), and resting heart rate (HR). A post hoc contrast test with Bonferroni correction (P-adjusted) was conducted when appropriate to determine sport-specific differences across both sexes. Linear models were evaluated through residual analysis and diagnostic plots to ensure that the assumptions of linearity, homoscedasticity, and normality of residuals were met. Statistical significance was set at a threshold of $P < .05$.

Results

Participant demographics

Overall, the study included 3854 female participants and 5400 male participants (Table 1). The median age was 18.1 years for women and 18.3 years for men. There were significant differences noted across various characteristics such as weight, height, BMI, and resting HR, all showing P values <.001. In terms of race/ethnicity, the distribution included African American, Asian, Caucasian (white/European descent), Hispanic (Latin American descent), and others, with differences between sexes ($P < .001$).

Sport participation varied significantly between males and females ($P < .001$) (Online Supplemental Table 1). Greater

Table 1 Characteristics of our athletes undergoing a preparticipation examination

Characteristic	Female (n = 3854)	Male (n = 5400)	P*
Age (y)	18.1 (12.0–33.3)	18.3 (12.0–34.8)	<.001
Weight (kg)	61 (15–143)	76 (26–170)	<.001
Height (cm)	165.1 (125.7–190.5)	180.3 (134.6–210.8)	<.001
BMI (kg/m^2)	21.7 (13.3–39.9)	23.4 (13.0–40.0)	<.001
Resting HR (beats/min)	66 (32–130)	64 (36–134)	<.001
Race/ethnicity			<.001
African American	316 (8.2)	915 (17)	
Asian	389 (10)	446 (8.3)	
Caucasian (white/European descent)	2511 (65)	3233 (60)	
Hispanic (Latin American descent)	335 (8.7)	453 (8.4)	
Other	303 (7.9)	353 (6.5)	
Class			<.001
College	2276 (59)	2727 (51)	
Grade school	332 (8.6)	439 (8.1)	
High school	1228 (32)	1726 (32)	
Professional	16 (0.4)	504 (9.3)	

Values are presented as median (minimum–maximum) or n (%).
BMI = body mass index; class = athlete classification (college, grade school, high school, and professional); HR = heart rate.
*Wilcoxon rank sum test; Pearson χ^2 test.

sport participation among females was observed in sports such as basketball and volleyball (21%) and field events such as soccer (20%). In contrast, males showed higher participation in sports such as baseball and softball (12%), football (16%), and basketball and volleyball (13%). Other differences include higher female participation in rowing (9.7%) compared with males (3.2%) and higher male participation in water polo and wrestling (5.4%) compared with females (3.4%). Females also had higher participation in gymnastics (4.5% vs 1.3%) and swimming/diving (6.6% vs 3.6%) than did males.

Percentile thresholds

For R waves, the highest voltage at the 99th percentile was observed when selecting the highest value from all leads V_4, V_5, and V_6, with males showing 4.3 mV (43 mm when the ECG was recorded with the standard scale of 1 mV/10 mm) and females 3.2 mV (32 mm). Closely following this, lead V_4 showed a 99th percentile of 4.2 mV (42 mm) for males and 3.1 mV (31 mm) for females. Similarly, the S wave in the minimum value from leads V_1, V_2, and V_3 showed larger absolute voltages, with males at −3.9 mV (−39 mm) and females at −2.7 mV (−27 mm). Lastly, in a single lead for the S wave, lead V_2 showed the 1st percentile of −3.8 mV (−38 mm) for males and −2.6 mV (−26 mm) for females. For the SL and LL scores, the 99th percentile values were significantly higher in males than in females, with the SL score at 6.6 mV (66 mm) for males and 4.8 mV (48 mm) for females and the LL score at 2.3 mV (23 mm) for males and 1.9 mV (19 mm) for females (Table 2; Figures 1 and 2). These findings highlight significant sex differences in ECG wave voltages, particularly in the precordial leads, underscoring the importance of considering sex-specific reference values in clinical evaluations of athletes.

Multivariate analysis

SL score analysis

The regression analysis revealed significant predictors of the SL score in athletes. The SL intercept was 4.25 mV (P < .001). Resting HR negatively influenced SL scores, with each unit increase in HR decreasing SL scores by 0.01 mV (P < .001). Male athletes had significantly higher SL scores than did female athletes, with a difference of 1.30 mV (P < .001). Age reduced SL scores by 0.03 mV per year (P < .001). Although BMI was statistically significant, its effect was minimal, reducing SL scores by just 0.01 mV per unit increase (P < .001), indicating that BMI had a relatively small effect on SL scores compared with the effects of sex, age, and resting HR. The impact of sport discipline varied, with sports such as basketball and volleyball and cross-country significantly increasing SL scores by 0.21 and 0.47 mV, respectively (P < .001 for both), while football linemen and gymnastics decreased SL scores by 0.27 and 0.25 mV, respectively (P < .001 for both). A post hoc contrast test also revealed a substantial influence of sex over sport. Specifically, male athletes had higher SL scores than did all athletes involved in cross-country (estimate 0.185 mV; P < .01), further supporting the hypothesis that sex may play a more crucial role than sport participation in determining SL scores. Note that the abnormal 3.5 mV traditional criterion for abnormal SL scores was achieved by 62% of our male athletes (n=3323) and 15% of our female athletes (n=572). These findings are summarized in Table 3.

Table 2 Percentiles for the Sokolow-Lyon and lower limb scores stratified by sex (in millimeters): 99th and 97.5th percentiles for the R wave, and 1st and 2.5th percentiles for the S wave

	Male		Female	
Lead	99th	97.5th	1st	2.5th
S wave V_1 (mm)*	−27	−24	−19	−17
S wave V_2 (mm)*	−38	−35	−27	−23
S wave V3 (mm)*	-34	-29	-23	-20
S wave min (V1,V2,V3) (mm)*	-39	-35	-28	-24
R wave V_4 (mm)*	42	39	31	28
R wave V_5 (mm)*	39	35	30	27
R wave V_6 (mm)*	30	26	24	22
R wave maximum (V_4, V_5, V_6) (mm)*	44	40	33	29
R wave aVF (mm)*	26	27	23	23
R wave I (mm)*	14	14	12	13
Sokolow-Lyon score	67	62.1	48	44.7
Lower limb score	23	18.1	19	15.4

*Electrocardiographic recording scale setting: 1 mV = 10 mm (ie, 1 mm = 0.1 mV).

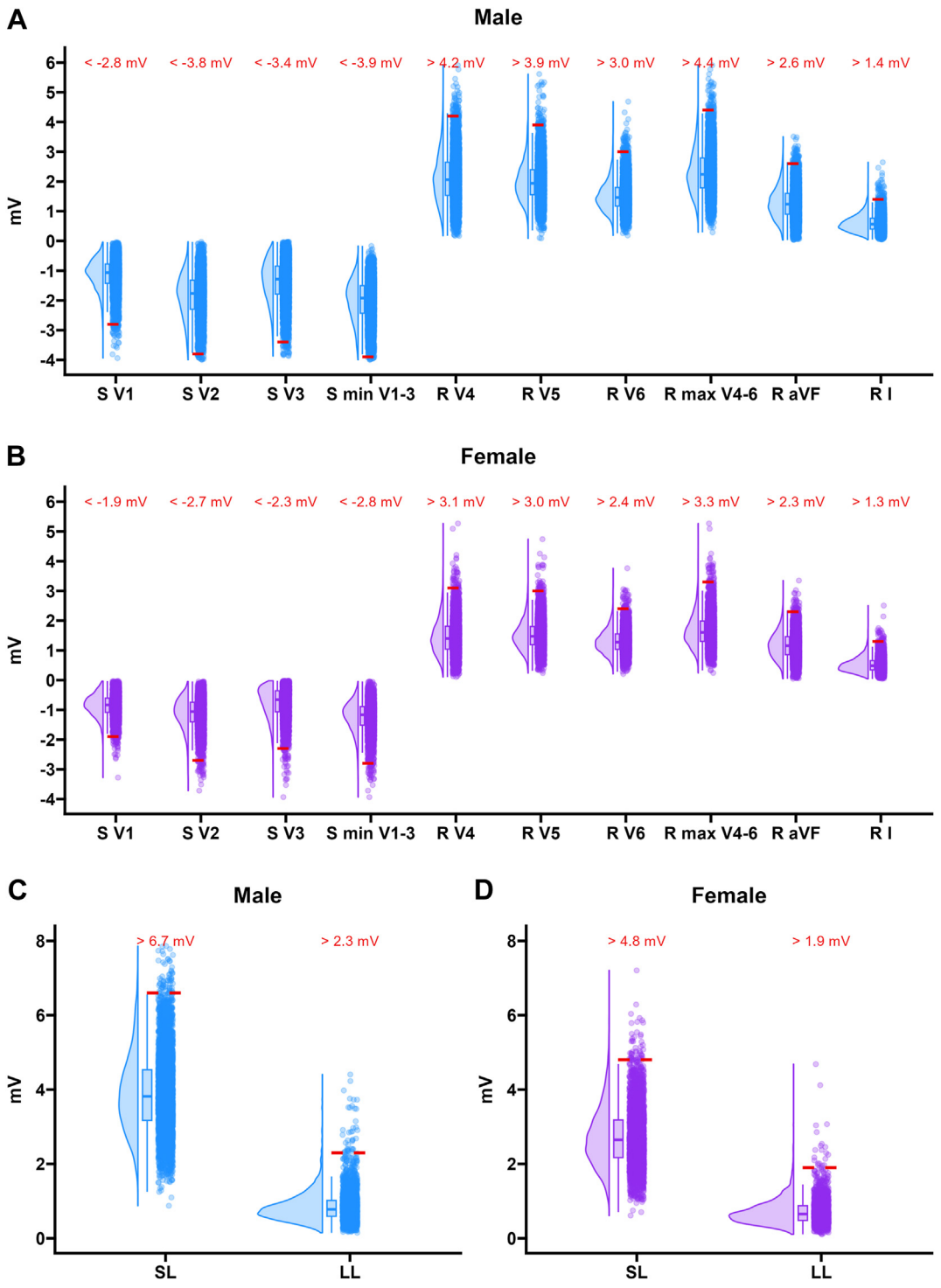

Figure 1

A and B: Precordial R- and S-wave measurements, stratified by sex (panel A: male; panel B: female), with group-specific 1st and 99th percentile cutoff values (in millivolts) indicated by the *dashed red lines*. **C and D:** Sokolow-Lyon (SL) score and lower limb (LL) score, also stratified by sex (panel C: male; panel D: female), with corresponding 1st and 99th percentile cutoff values shown.

LL score analysis

The LL score, calculated as the magnitude of the R wave in lead I and the absolute value of the S wave in lead III, was also analyzed. As expected, the LL amplitudes were significantly lower than the SL ones because of the placement of the electrodes further from the heart. The intercept LL score was 0.26 mV ($P < .001$). HR had no significant effect on LL scores ($P = .200$). Male athletes had significantly higher LL values than did female athletes, with a difference of 0.09 mV ($P < .001$). Age reduced LL scores by 0.01 mV per year ($P < .001$). Although BMI increased LL scores slightly by 0.03 mV per unit increase ($P < .001$), this effect was relatively

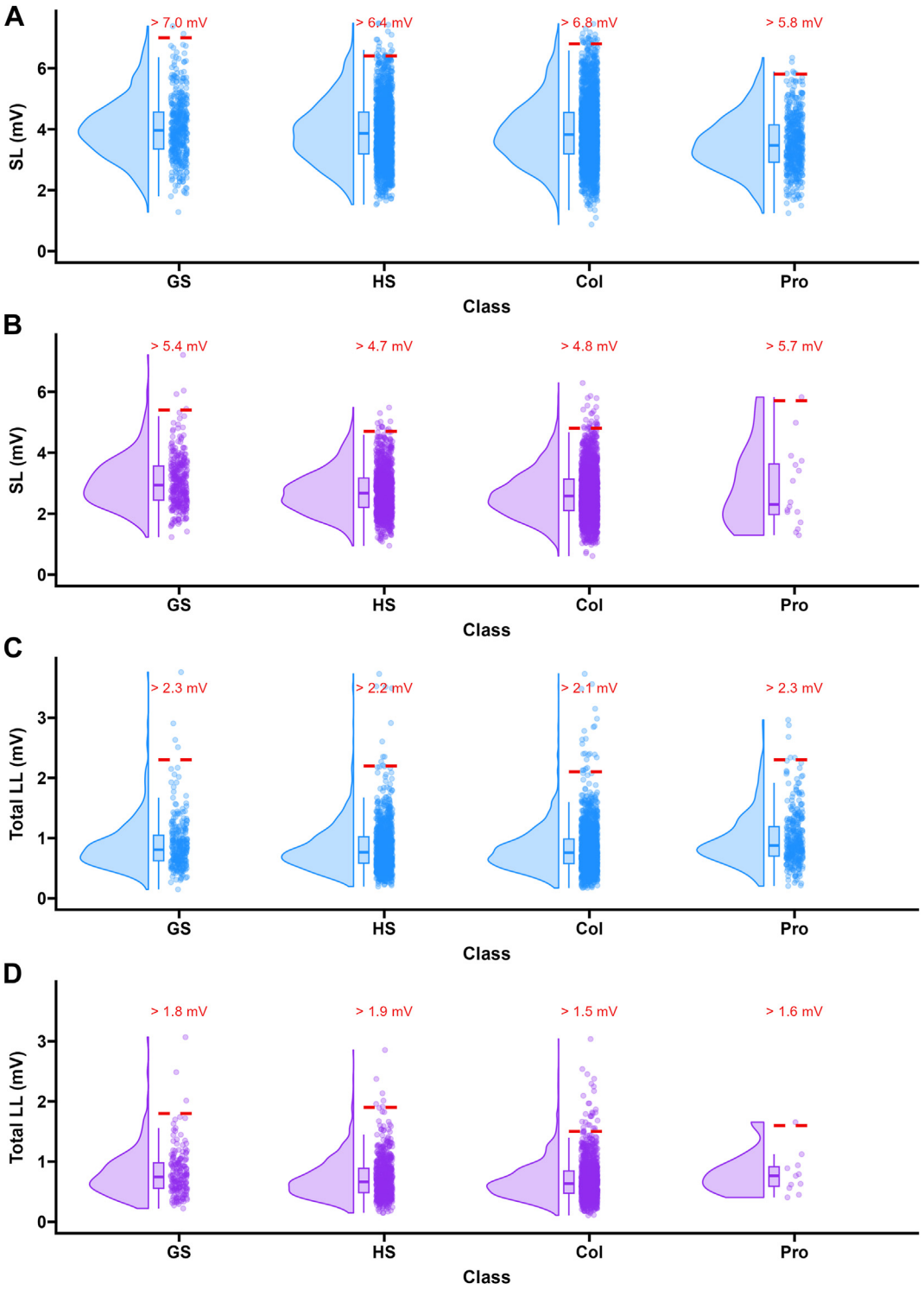

Figure 2
Panels (**A**) and (**B**) show the Sokolow–Lyon Index (SL) in male and female participants, respectively, while (**C**) and (**D**) present the total Lower-Limb (LL) score in male and female participants, respectively—all stratified by athletic class (GS, HS, Col, Pro) and annotated with group-specific 99th percentile cutoff values (in mV) above the box plots. Col = college; GS = graduate school; HS = high school; Pro = professional athlete.

small, suggesting that BMI plays a minor role in influencing LL scores compared with other factors. Participation in sports such as basketball and volleyball and cross-country significantly increased LL scores by 0.09 and 0.14 mV, respectively ($P < .001$ for both).

A post hoc contrast test revealed mixed results for LL scores with CCC. While CCC had significantly higher LL scores compared with some sports, such as basketball and track and field ($P < .01$), it did not show significant differences compared with others such as basketball and volleyball, gymnastics, and

racquet sports, emphasizing a more nuanced effect of sport history on LL scores. These findings highlight that the influence of sport on LL scores is not uniform and varies depending on the specific sports being compared. These findings are summarized in Table 4.

In addition to multivariate analysis, we conducted univariate correlations and regressions between LL and SL scores with age, weight, and BMI by sex. Although we observed significant correlation, these were poor and may offer little clinical significance (see Online Supplemental Figure 3).

Discussion

Our study underscores the complexity and nuances involved in developing ECG criteria for LVH in athletes. The multivariate analysis revealed significant differences in both the precordial and limb lead scores across demographic and physiological factors; however, the clinical importance of these was minimal except for sex. However, to make the limitations of our data obvious, we present our percentile cut points divided by athletic class (grade school, high school, collegiate, and professional). Class combines age and body size without resorting to a complex multivariate equation. However, because our study did not include echocardiographic or magnetic resonance imaging evaluations, we cannot directly confirm whether the elevated QRS amplitudes we observed truly reflect pathological LVH rather than benign physiological adaptation. This limitation precludes establishing formal sensitivity and specificity values for our proposed cut points. Accordingly, these data should be regarded as exploratory reference thresholds that warrant further validation in prospective cohorts—ideally incorporating imaging—to ascertain whether these high ECG voltages indeed serve as early markers of HCM.

Figure 3 is an example from our athletes of abnormal voltage as the only ECG abnormality present. This is the situation to be found in 25% of adolescents with HCM, stressing the importance of adding voltage criteria to the current recommendations.[6]

Furthermore, when developing norms, the electrocardiologist must first deal with 6 stages of pediatric growth with rapid changes in body size, then the onset of sexual maturation, which is key to survival of any species, and finally the relentless impact of aging. For example, population norms for HR begin in the hundreds for neonates and gradually decrease to ~70 beats/min throughout adolescence and adulthood. Another example is that differences in precordial R-wave measurements were noted between sex in older and not younger children. Boys had taller precordial R waves than did girls in lead V_6 only for ages ≥12 years and not before, with a mean difference of 0.415–0.349 mV for boys vs girls in age groups 12–<16 and 16–18 years.[10] In our population, African American athletes did not exhibit larger LVH scores than did other ethnicities. While some previous studies have demonstrated higher QRS voltages in African Americans,[14] this has not been a consistent finding nor documented in young African American athletes.[15,16] Thus, while most studies show more repolarization changes in black athletes than in those of other ethnicities, we conclude that black race is not associated with QRS voltage differences.

One of our most intriguing observations regarding QRS voltages has been higher QRS voltages in certain sports, particularly those requiring high amounts of volumes and/or intensities of aerobic training. This is obvious in our athletes who self-selected for cycling and cross-country running who exhibited higher voltages than other athletes in the 14 sport classification we used (see Online Supplemental Figure 1). We feel that larger studies of specific sports may lead to sport-specific criteria. In addition, we observed little difference in race (see Online Supplemental Figure 2).

When dealing with the prevalent cardiac diseases affecting athletes, they first encounter HCM, which initially exhibits enlargement of myocytes (and increases in QRS voltage) followed by myocardial infiltration of fibrosis and lipid deposits associated with myocardial damage (QRS prolongation and repolarization abnormalities). Next comes atherosclerosis that starts with decreasing vascular compliance and then calcification, occlusion, and myocardial damage (repolarization abnormalities and Q waves). It is important to note that physical activity does not typically lead to significant increases in QRS amplitude norms, despite the average resting HR decreasing by ~10 beats/min in young athletes.[16] Note that body size or ethnicity has little effect on QRS norms in a population with healthy nutrition and multiracial identities.

The sex-based differences in QRS amplitude among young athletes are surprising, as they appear more clinically

Table 3 Multivariate analysis of Sokolow-Lyon scores

Variable	R	R^2	New variance explained (%)	*P*
Sex	0.52	0.27	–	<.001
Sport	0.55	0.30	3.16	<.001
Race	0.56	0.31	0.93	<.001
Class	0.56	0.32	0.38	<.001
Resting heart rate	0.57	0.33	1.28	<.001
Age	0.58	0.33	0.25	<.001
Body mass index	0.58	0.34	0.33	<.001

Class = athlete classification (college, grade school, high school, and professional).

Table 4 Multivariate analysis of lower limb lead scores (R wave in lead I, S wave in lead III, and Lower Limb score, in millivolts)

Variable	R	R2	New variance explained (%)	*P*
Sex	0.13	0.016	–	<.001
Sport	0.18	0.031	1.486	<.001
Race	0.19	0.037	0.591	<.001
Class	0.22	0.047	1.018	<.001
Resting heart rate	0.22	0.047	0.014	<.001
Age	0.22	0.049	0.207	<.001
Body mass index	0.32	0.105	5.563	<.001

Class = athlete classification (college, grade school, high school, and professional).

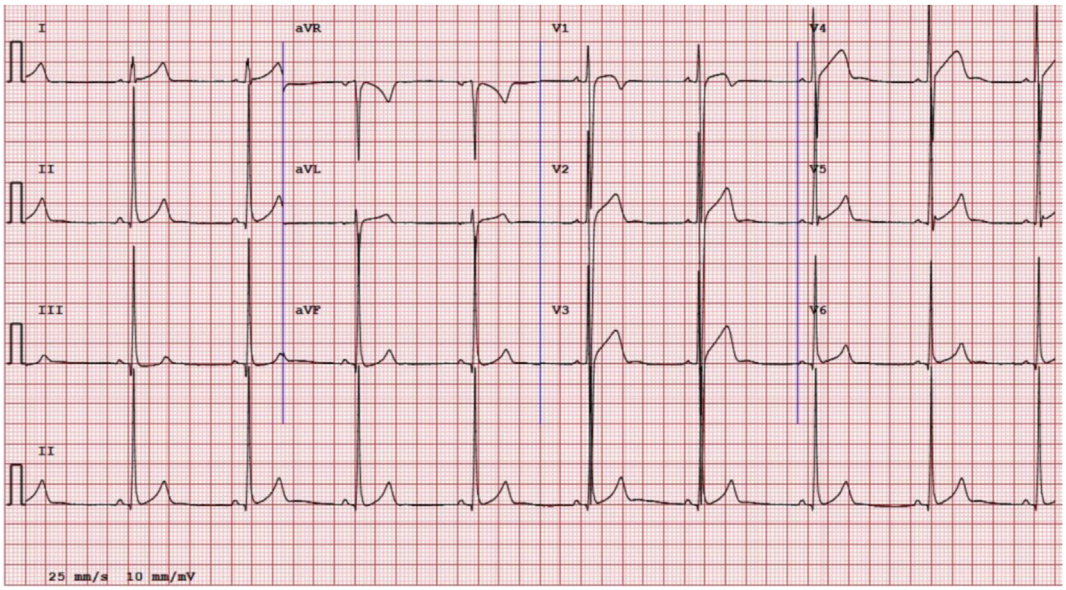

Figure 3
Example of high QRS voltage only (without other ECG abnormalities) in one of the athletes undergoing a preparticipation examination (note the square wave amplitude scale marker of 1 mV/10 mm along the left border of the recording).

meaningful than other parameters and they require setting norms after making the male/female classification. Whether this applies to transgender individuals remains to be determined.

The ability to accurately interpret ECG patterns in athletes is essential, as distinguishing physiological adaptations from pathological conditions is crucial to prevent unnecessary further testing and potential disqualification from sports.[17,18] Current recommendations assume that physiological and pathological ECG-LVH cannot be distinguished by QRS voltage criteria. The present research aims to reevaluate the ECG-LVH criteria for athlete screening, with a particular focus on the application of R- and S-wave amplitudes in young athletes. The current ECG interpretation guidelines for athletes suggest that some common ECG changes, including voltage criteria for LVH, are often physiological adaptations to regular exercise and do not necessarily indicate an underlying pathological condition.[1–4] However, the appropriate differentiation between physiological and pathological ECG changes in this population remains a challenge, as incomplete penetrance of inherited cardiovascular conditions can confound the interpretation.[19]

Limitations

Our institutional review board and resources did not permit follow-up for other than clinical reasons, nor mandated additional studies for all young athletes undergoing a preparticipation examination. Much of the data were de-identified for research purposes. Because we did not obtain systematic echocardiograms or include participants with known HCM, we cannot conclusively determine whether elevated QRS voltages reflect benign remodeling or undiagnosed pathological LVH. A confounding finding has been the poor correlation with imaging estimates of left ventricular mass and QRS voltage in athletes[7] in subsets of our study group. Furthermore, as a retrospective analysis, our population distribution was based on individual choices of sport, so many interactions with demographics likely caused unappreciated biases. A more tailored approach to ECG interpretation in athletes may require larger studies with an even distribution of races and sports, with sex considered separately. Sex-specific multivariate scores could be developed including all the significant non-ECG variables or tables with results for all the variables, but they would not be convenient. Furthermore, all the other variables have a weak effect compared with sex. It is unlikely that studies randomizing sexes separately matched by ethnicity, sport, and body size will be feasible, so studies such as ours will remain the only way to define QRS voltage amplitude criteria.

Conclusion

This study provides a comprehensive reevaluation of ECG criteria for LVH in male and female athletes, providing practical cut points for identifying young athletes who may warrant evaluation for HCM. We recommend including sex-specific SL score thresholds to improve sensitivity for detecting early HCM. We favor the SL score over the LL score since the SL score provides a wider normal range and the LL score is known to be lower in amplitude than the SL score because the electrodes are placed further from the heart.[20] These sex-specific criteria are intended as an adjunct to current screening recommendations, rather than a stand-alone diagnostic tool. Prospective, imaging-based studies will be necessary to confirm their validity and determine their practical impact on clinical outcomes. Future research should focus on longitudinal studies to validate these findings and refine ECG screening protocols, ensuring they are both sensitive and specific for the athletic population. The ultimate goal is to prevent unnecessary interventions and

safeguard the health and careers of athletes through more discriminate and personalized diagnostic practices.

While further validation is required, our criteria can be applied immediately and assessed using modern "instant epidemiology" methods, such as genetic testing, detailed family history screening, and imaging. The potential increase in sensitivity justifies the added screening burden. To facilitate further exploration, we have developed an interactive calculator available at https://samuelmontalvo.shinyapps.io/ecg_shinyapp/

Appendix

Supplementary Data

Supplementary data associated with this article can be found in the online version at https://doi.org/10.1016/j.hrthm.2025.03.162.

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Address reprint requests and correspondence: Dr Samuel Montalvo, Division of Cardiovascular Medicine, Stanford University School of Medicine, 450 Jane Stanford Way, Stanford, CA 94305. E-mail address: smontal@stanford.edu

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