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Research article

Predictive Effect of Echocardiographic Assessment of Myocardial Efficiency on Martial Arts Performance

Honghong Song ✉
Martial Arts Academy, Shandong Sport University, Jinan, Shandong, China

Abstract

Cardiac strain and myocardial work indices may provide additional information for performance stratification beyond traditional physiological assessments in martial arts, but their relevance to anaerobic and neuromotor performance remains insufficiently defined. This cross-sectional observational predictive modeling study assessed whether echocardiographic myocardial efficiency indices were associated with performance classification among national-level martial artists. A total of 180 athletes were assessed, and the primary comparative analysis used the top and bottom tertiles of a composite performance score to define higher-performance athletes and a lower-performance internal reference group, respectively, rather than a non-athlete control group. Echocardiographic indices included global longitudinal strain (GLS), global work efficiency (GWE), global wasted work (GWW), and myocardial performance index (MPI). Performance outcomes included Wingate anaerobic power, agility time, reaction time, Balance Error Scoring System (BESS) errors, and Finger-to-Nose Alternation Test (FTNAT) coordination. Higher-performance athletes showed greater peak power than the lower-performance reference group (11.7 ± 1.3 vs. 9.3 ± 1.2 W/kg, p = 0.002), faster agility time (9.0 ± 0.7 vs. 10.6 ± 0.9 s, p = 0.001), and higher technical execution scores (8.4 ± 1.0 vs. 5.6 ± 1.4, p = 0.001). GLS magnitude was greater across myocardial segments, GWE was higher (96.8% vs. 92.1%, p = 0.002), and GWW was lower (9.4% vs. 13.2%, p = 0.003). GLS and GWE were associated with group classification in regression models, while lower MPI values were associated with shorter agility times and fewer balance errors, indicating better performance direction for both outcomes. These findings suggest that cardiac strain and myocardial work indices are associated with anaerobic and neuromotor performance in martial artists; however, longitudinal validation is required before these measures can be considered predictive markers for talent identification or training decisions.

Key words: Martial arts, Echocardiography, Global longitudinal strain, Myocardial work, Anaerobic power, Neuromotor performance.

Introduction

In high-performance sport, cardiac assessment increasingly extends beyond chamber size and volumetric pump output to indices that describe how myocardial deformation is converted into effective ventricular work. Myocardial efficiency refers to the capacity of the heart to transform metabolic energy into useful mechanical work during each cardiac cycle (Liu et al., 2025). In contemporary echocardiography, this construct is estimated through non-invasive pressure-strain loop analysis derived from speckle-tracking echocardiography and brachial blood pressure calibration (Wang and Yin, 2024). Global Work Efficiency (GWE) is defined as the ratio of constructive myocardial work to total myocardial work, whereas Global Wasted Work (GWW) represents myocardial work that does not contribute to effective ventricular ejection. In contrast, traditional parameters such as Left Ventricular Ejection Fraction (LVEF) represent volumetric output without capturing contractile or metabolic efficiency (Yang et al., 2024). By directly reflecting the energetic economy of the myocardium, measures such as Global Longitudinal Strain (GLS), GWE, and the Myocardial Performance Index (MPI) allow for earlier detection of subclinical dysfunction and functional reserve capacity (Jang et al., 2024; Tyurina et al., 2024).

Martial arts are high-intensity combat disciplines in which performance depends on repeated explosive actions, rapid directional changes, reactive decision-making, balance recovery, and short recovery intervals between offensive and defensive exchanges. These demands place substantial load on anaerobic alactic and lactic pathways during striking, grappling entries, throws, evasive movements, and repeated acceleration-deceleration sequences, while aerobic recovery supports phosphocreatine resynthesis and repeated high-intensity output across rounds (Martinez et al., 2021). Because these sport-specific demands combine neuromotor precision with intermittent cardiovascular stress, athlete evaluation requires markers that extend beyond chamber size and resting volumetric output alone (Palermi et al., 2023). Resting myocardial strain and myocardial work indices do not directly measure combat skill, but they characterize cardiac deformation, systolic timing, and pressure-adjusted mechanical work capacity that may accompany the wider physiological profile of highly trained martial artists. Multimodal athlete-assessment models similarly support the combined interpretation of cardiovascular, neuromotor, and performance outputs when evaluating complex athletic capacity (Spanakis et al., 2024).

Echocardiographic advancements now permit stratified assessment of cardiac function through three core modalities: (i) structural deformation (GLS), which reflects longitudinal myocardial shortening; (ii) functional energy efficiency (GWE and GWW), which quantify contractile economy; and (iii) composite temporal indices (MPI), which integrate systolic and diastolic timing (Erevik et al., 2024; Yasheng et al., 2025). While these indices have demonstrated prognostic utility in disease contexts such as heart failure, myocardial infarction, and cardiac amyloidosis (Randazzo et al., 2024), their application to athletic performance evaluation especially in anaerobic disciplines has not been systematically explored. Current studies primarily

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focus on clinical outcomes (mortality, hospitalization, or remodeling) rather than peak physiological output under sport-specific stress. Growing interest has emerged in using myocardial efficiency to understand athletic capacity.

Erevik et al. (2024) reported that GWE was positively correlated with maximal oxygen uptake (VO_2max; r = 0.61) and treadmill exercise duration in trained male athletes. In that context, treadmill duration referred to the time sustained during graded exercise testing before volitional exhaustion or test termination, and the positive correlation indicates that athletes with higher GWE tended to maintain incremental treadmill exercise for longer periods. This finding supports the relevance of myocardial work indices to general cardiorespiratory performance, although treadmill duration reflects endurance tolerance rather than martial arts-specific anaerobic power, agility, or technical execution. Similarly, Colombo et al. (2024) demonstrated sex-dependent adaptations in myocardial strain among adolescent basketball players, suggesting training-induced remodeling. However, these findings are population-specific and lack direct linkage to actual competition or skill-based outputs. Large-scale studies (Martinez et al., 2021; Lau et al., 2023; Wang et al., 2024) have associated strain and GWE with general cardiorespiratory fitness rather than anaerobic competition metrics. This distinction is important because martial arts performance is not captured adequately by endurance tolerance alone. Competitive success requires the integration of explosive power, acceleration, deceleration, balance recovery, visual-motor response, and technical execution under intermittent load. Consequently, myocardial work indices require evaluation against sport-specific outputs such as Wingate anaerobic power, T-test agility time, balance errors, reaction time, and competition-index scores before their value for martial arts performance stratification can be inferred.

Moreover, no current study has comprehensively evaluated how myocardial efficiency correlates with agility, peak anaerobic output, or competition score indices in martial artists. While some indices have been incidentally linked to fatigue or exercise intolerance, direct performance correlations in anaerobic sports remain hypothetical. Liu et al. (2025) recommended incorporating myocardial efficiency into athlete screening frameworks, yet no predictive models or thresholds have been validated in martial arts. Despite recent advances in echocardiographic imaging and myocardial work analysis, the predictive role of myocardial efficiency in martial arts performance specifically regarding anaerobic output, agility, and competitive success remains insufficiently studied.

Global Longitudinal Strain (GLS) and Myocardial Performance Index (MPI) in combat athletes

Studies evaluating GLS as a predictor of performance have primarily focused on endurance contexts, limiting their relevance to anaerobic sports. Murray et al. (2022) conducted a meta-analysis of 39 exercise trials and found that while clinical populations demonstrated significant improvement in GLS post-intervention, healthy and athletic cohorts showed minimal change. This pattern suggests that GLS may show limited responsiveness in already-trained cohorts when measured at rest, particularly when the outcome of interest is short-duration anaerobic performance rather than clinical recovery or endurance adaptation. Similarly, D'Andrea et al. (2022) compared myocardial efficiency markers and found reduced resting GLS in endurance athletes but preserved contractile reserve, indicating that MWE, not GLS, predicted functional sustainability under load. These findings support GLS's diagnostic value but highlight its limited dynamic responsiveness in elite athletes. Notably, Kandels et al. (2023) observed unchanged GLS post-cardiopulmonary exercise testing (CPET) in handball and football players, with only Global Work Index (GWI) correlating with VO_2max, suggesting that pressure-adjusted myocardial work indices may be more sensitive than resting strain alone for exercise-related functional differentiation.

Combat-sport specific evidence remains absent in the existing literature. Similarly, Zhao et al. (2022) used pressure-strain loop metrics to correlate myocardial function with VO_2max in youth basketball players, indicating aerobic relevance but no translation to alactic or lactic output. Palermi et al. (2023), in a narrative review, emphasized GLS's utility for screening but not performance prediction. The current literature affirms GLS's utility in endurance screening but offers no tested framework linking GLS to peak power or short-duration anaerobic capacity in martial arts. This limits its validity as a standalone predictor for explosive sport performance. Collectively, these studies reveal that while GLS holds diagnostic potential, its role in predicting anaerobic power in combat athletes remains under-investigated and empirically unvalidated. The direction of GLS magnitude also requires careful handling in athlete studies because GLS is conventionally reported as a negative percentage. More negative GLS values generally indicate greater longitudinal myocardial shortening, whereas statistical models may use either signed values or absolute magnitude values. This distinction affects whether correlations appear positive or inverse and should be specified when GLS is linked to performance outcomes such as peak power, agility time, or reaction time.

MPI has been validated as a composite marker of systolic and diastolic timing, but evidence supporting its use in agility, coordination, or skill-specific performance evaluation remains limited. Hidayat et al. (2024) conducted a meta-analysis in autoimmune populations and demonstrated that elevated MPI reflected myocardial inefficiency, even with preserved ejection fraction. The review emphasized TDI-derived MPI's reliability but did not explore any performance-based endpoints. Kaya et al. (2022) confirmed similar findings in post-COVID individuals, with higher MPI values predicting persistent symptoms, despite normal GLS and LVEF. These results reinforce MPI's diagnostic relevance, but neither study addresses its translation to physical performance metrics such as agility, acceleration, or reactive response time in athletes.

Alsafi et al. (2017) provided the only direct comparison of MPI in athletes versus sedentary controls, finding no significant differences across groups. However, methodological inconsistency in Doppler techniques and exclusive focus on female athletes reduce generalizability. Zholshybek et al. (2023) advocated integrating MPI into athlete monitoring but acknowledged that no study has linked MPI to agility-based outputs. The current body of work supports MPI's cardiological precision but fails to extend its application to movement-based performance markers in combat sports. Overall, current studies highlight MPI's diagnostic value but do not establish its utility as a predictor of agility or multidimensional skills in martial arts.

Echocardiographic biomarkers and cardiac function measures

The use of echocardiographic markers for athlete performance stratification remains conceptually relevant but empirically underdeveloped, particularly for anaerobic and skill-dominant sports. Oxborough et al. (2025) provided practical guidelines for echocardiographic screening in youth athletes, emphasizing strain imaging and volumetric thresholds. While it recommended GLS thresholds for trained populations, the review did not address how these markers relate to sport-specific talent or anaerobic skill profiles. Similarly, Flanagan et al. (2023) normative data for GLS and MPI in athletes but refrained from proposing predictive cutoffs for talent identification, acknowledging the lack of performance-linked studies. These reviews confirm the feasibility of echocardiography for general monitoring but do not validate its use for scouting or selection.

Spanakis et al. (2024) advanced this discourse by proposing a multi-modal athlete profiling model integrating echo data, omics, and neuromuscular markers. Though theoretically rich, the model remains untested and lacks data from anaerobic sports. Lee et al. (2022) outlined structural adaptations across sport types and questioned whether echo values could predict "trainability," but stopped short of performance validation. Jouffroy et al. (2022) tracked GLS changes post-endurance events, correlating reductions with training age, but again provided no insight into explosive performance. Similarly, Mukhopadhyay (2024) reviewed cardiac remodeling in sprinters and jumpers, noting reduced GLS and thicker LV walls, but offered no performance outcome correlations. Taken together, these sources confirm the theoretical appeal of echocardiographic stratification but reveal a clear absence of validated models or empirical links between echo indices and anaerobic talent identification in martial arts.

Several studies affirm the superiority of GLS and MPI over LVEF in detecting cardiac adaptation and subclinical dysfunction. Schellenberg et al. (2023a; 2023b) followed recreational athletes post-COVID and found no significant change in LVEF, while GLS improved, indicating greater sensitivity of deformation-based indices to subtle functional recovery than conventional volumetric measures. Furthermore, they demonstrated that GLS, not LVEF, revealed lingering myocardial inefficiency in recovered athletes, emphasizing the limitations of relying on volumetric output alone. These studies confirm that GLS can identify abnormalities even when LVEF is within normal ranges, especially during recovery from stress or illness. However, none evaluated performance metrics.

MacIver et al. (2024) compared LVEF, GLS, and GLASED (a newer strain-derived technique) in younger versus older athletes and showed that GLASED revealed structural differences not captured by traditional indices. Abibillaev et al. (2025) further stratified athletes by sport and found that LVEF remained constant across resistance, endurance, and mixed athletes, while GLS varied significantly. However, the study did not extend findings to skill-based outputs. Claessen et al. (2024) emphasized that even athletes with low LVEF might show no functional deficit, reinforcing the need for adjunctive imaging. Huang et al. (2023) compared GLS with PET imaging and found both to be complementary, though tested only in clinical populations. Across these investigations, LVEF consistently underperforms in detecting nuanced adaptation, but its replacement with GLS or MPI in performance profiling remains largely untested. While these studies validate advanced echocardiographic measures over conventional LVEF, none demonstrate direct predictive power for sport-specific performance outcomes in anaerobic disciplines.

Conceptual model

This study proposes a predictive stratification model that integrates myocardial efficiency markers specifically GLS, MPI, and GWE into a three-layered martial arts performance framework (see Figure 1). Layer one quantifies resting myocardial work capacity using echocardiographic strain and timing indices. Layer two overlays athlete-specific metrics such as anaerobic power and agility scores to examine predictive relationships. Layer three incorporates competition scoring to establish functional thresholds. By correlating each echocardiographic marker with domain-specific outputs, the model evaluates whether resting myocardial strain, myocardial work, and timing indices are associated with higher performance classification, while recognizing that longitudinal validation is required before these indices can be used for talent identification, selection policy, or individualized training decisions.

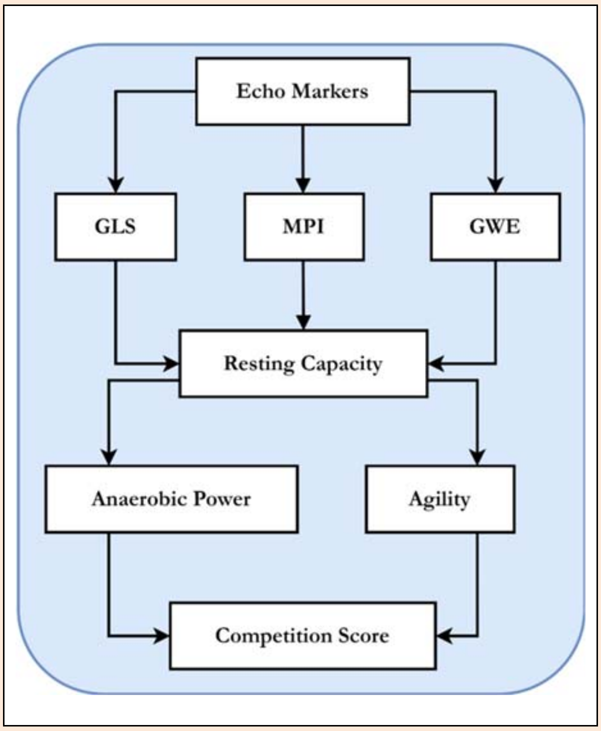


Figure 1. Three-layered martial arts performance framework linking echocardiographic markers, capacity, and outcomes.

Objectives

This study aims to (i) assess the association between echocardiographic myocardial indices, including GLS, GWE, GWW, and MPI, and multidimensional martial arts performance outcomes; (ii) determine whether these indices are associated with peak anaerobic power, agility, balance, reaction time, coordination, and competition-index scores; and (iii) evaluate whether myocardial indices provide additional information for internal performance stratification among national-level martial artists. The study addresses three research questions (RQs): RQ1: How are GLS, GWE, GWW, and MPI associated with anaerobic, agility, neuromotor, and competition-related outcomes in national-level martial artists? RQ2: Do GLS and GWE explain variation in performance outcomes beyond anthropometric characteristics and training covariates? RQ3: Does a combined GLS plus GWE model improve internal classification of higher-performance and lower-performance martial artists compared with covariate-only or single-index models? The study tests three hypotheses: H1: More favorable myocardial deformation, myocardial work, and timing indices are associated with higher anaerobic power, shorter agility time, fewer balance errors, faster reaction time, greater coordination output, and higher competition-index scores. H2: GLS and GWE provide independent explanatory information after adjustment for age, sex, discipline, training age, weekly training load, body fat percentage, and skeletal muscle mass. H3: A combined GLS plus GWE model improves internal performance classification compared with covariate-only, GLS-only, and GWE-only models.

Methods

Study design

This cross-sectional observational study, conducted per STROBE guidelines, examined physiological predictors of performance among trained adult martial artists without interventions or randomization. All exposures and outcomes were measured during a single assessment period; therefore, the design was restricted to association and classification analyses. The study did not test causal effects of training, longitudinal cardiac remodeling, or chronic adaptation. Training age, weekly training frequency, weekly training load, and discipline type were recorded as contextual covariates to account for between-athlete variation in long-term training exposure, but these variables were not interpreted as experimentally manipulated determinants of myocardial work or performance. Ethical approval was granted by the University (Approval No. AD-2025 - 148), and all participating athletes provided written informed consent. The study complied with the Declaration of Helsinki. Data collection occurred at a national high-performance institute with on-site cardiopulmonary imaging and standardized athletic testing, ensuring procedural consistency and minimal variability across assessments.

Participants

Recruitment

Participants were recruited through federation lists and briefings at three national training centers. Coaches and sport science officers distributed study invitations, and eligibility was confirmed during pre-screening. Recruitment was based on federation and training-center access rather than random population sampling. This procedure increased feasibility in a national-level athlete cohort but may have introduced selection bias toward athletes already retained in formal training systems, athletes with coach endorsement, and athletes available during scheduled testing periods. Recruitment source, discipline, sex, training age, and weekly training load were therefore documented for descriptive comparison and bias modeling. Written consent was obtained. A priori sample-size estimation was performed in G*Power 3.1.9.7 using a two-tailed independent-samples t test for the primary comparison of myocardial work indices between the upper and lower performance tertiles. Assuming a moderate-to-large standardized effect size of d = 0.60 for GWE, α = 0.05, power = 0.90, and equal allocation between the two extreme tertiles, the required minimum sample was 120 athletes, corresponding to 60 athletes in the lower-performance internal reference group and 60 athletes in the higher-performance group. A total recruitment target of 180 athletes was therefore used to permit tertile classification across the full performance distribution, retain the middle tertile for continuous regression and sensitivity analyses, and allow exclusion for incomplete testing or inadequate echocardiographic tracking quality.

Eligibility

Inclusion criteria were: (i) age between 18 and 30 years, (ii) at least 5 years of continuous formal training in a recognized martial art (taekwondo, sanda, or Brazilian jiu-jitsu), and (iii) an average weekly training frequency of ≥ 4 sessions sustained over the past 6 months. Exclusion criteria were: (i) any diagnosed cardiovascular, metabolic, or neurological disorder as confirmed by physician-supervised medical clearance using the American College of Sports Medicine Pre-Participation Screening algorithm; (ii) musculoskeletal injury within the prior 3 months that could impair performance testing; (iii) any use of medications influencing cardiovascular output, including beta-blockers or stimulants; and (iv) inability to complete all required testing procedures. Cardiovascular exclusion was additionally confirmed by a resting ECG and blood pressure screening using an automated sphygmomanometer (Omron HEM-7120, Japan), with exclusion enforced for systolic pressure ≥ 140 mmHg or diastolic ≥ 90 mmHg. Anthropometric data were recorded using a bioelectrical impedance analyzer (InBody 770, South Korea), including (i) total body fat percentage, (ii) skeletal muscle mass, and (iii) segmental lean mass distribution. These metrics were used to ensure consistency in interpreting training load responses and to verify athlete classification status.

Stratification and bias

Participants were stratified after data collection into three tertiles using a composite performance score. The bottom tertile was classified as the lower-performance internal reference group, the middle tertile was retained for continuous regression and sensitivity analyses, and the top tertile was classified as the higher-performance group.

The composite performance score was adapted from the Total Score of Athleticism approach, in which heterogeneous physical-performance tests are converted into standardized z scores and combined into a single athlete-profile score (Turner, 2014). This approach is suitable for the present study because anaerobic power, agility time, and competition performance are measured on different scales and cannot be directly averaged in raw units. For each athlete i, each performance domain k was first standardized as:

$$z_{i,k} = \frac{X_{i,k} - \bar{X}_k}{SD_k}$$

where $X_{i,k}$ represents the athlete's raw score in domain k, $\bar{X}_k$ represents the sample mean for that domain, and SD_k represents the sample standard deviation. Peak anaerobic power and competition index were coded so that higher values indicated better performance. T-test agility time was reverse-coded before aggregation because shorter completion time indicated better performance. The final composite performance score was calculated as:

$$\text{Composite Performance Score}_i = \frac{z(\text{Peak Power}_i) - z(\text{T-test Time}_i) + z(\text{Competition Index}_i)}{3}$$

This score represented each athlete's multidimensional performance position relative to the study cohort. The top and bottom tertiles were used for the primary internal performance comparison, consistent with prior z-score-derived athlete profiling work that applied tertile-based interpretation of composite athleticism scores (Maestroni et al., 2023). The middle tertile was retained for continuous regression and sensitivity analyses.

All groups consisted of trained national-level martial artists, and stratification was based on observed performance distribution across anaerobic power, agility, and competition-index domains. All echocardiographic assessors were blinded to group assignment and performance outcomes. To mitigate selection and confirmation bias, stratification was performed post hoc based on raw score distributions without investigator knowledge of echo results. Demographic variables, training age, and sport discipline were recorded for bias modeling. Additionally, observer expectancy bias was minimized by automated scoring of performance metrics wherever possible.

Echocardiographic Imaging

Resting echocardiography standardization

Resting echocardiography followed the same acquisition protocol for the lower-performance internal reference group and the higher-performance group. Athletes arrived between 07:30 and 09:30 after an overnight fast of at least eight hours, with testing completed between 08:00 and 10:30 in a controlled imaging room maintained at 22 - 24°C and 40 - 60% relative humidity. A 10-minute seated stabilization period preceded all measurements. Resting systolic blood pressure, diastolic blood pressure, heart rate, and peripheral oxygen saturation were recorded using an Omron HEM-7120 automated sphygmomanometer and fingertip pulse oximetry before image acquisition. Athletes avoided caffeine and alcohol for 24 hours and strenuous exercise, sparring, resistance training, and high-intensity conditioning for 48 hours before testing. Compliance was documented on a pre-test screening form that recorded last meal time, caffeine intake, alcohol intake, medication use, training activity during the previous 48 hours, and acute symptoms. Athletes who did not meet these pre-test conditions were rescheduled within the same testing week.

Timing and order of cardiac and performance testing

Cardiac and performance assessments were completed within a fixed 48-hour testing window for each athlete. Resting echocardiography was performed first to prevent acute fatigue from affecting GLS, GWE, GWW, or MPI measurements. Neuromotor testing was completed three hours after echocardiography on the same day, following a standardized light meal and seated recovery. Reaction time testing was performed first, followed by the Balance Error Scoring System, the Finger-to-Nose Alternation Test, and the T-test. The Wingate Anaerobic Test was completed 24 hours after echocardiography to separate maximal anaerobic exertion from resting myocardial imaging. Athletes were instructed to avoid competition, sparring, resistance training, and high-intensity conditioning between cardiac imaging and performance testing.

Imaging procedure

Echocardiographic imaging was conducted using the Vivid E95 ultrasound platform (GE Healthcare, United States) equipped with an M5Sc-D sector array transducer (see Figure S1). Each participant was positioned in the left lateral decubitus orientation and attached to electrocardiographic leads to synchronize imaging with cardiac electrical activity. Standard apical 4-chamber, 2-chamber, and long-axis views were obtained under continuous visualization. Frame rate was adjusted to remain within 55 to 80 frames per second depending on heart rate and thoracic window clarity. Depth, gain, and sector width were optimized manually for each participant. Once three stable cardiac cycles were confirmed, recordings were stored for offline processing. All imaging was performed by a certified echocardiographic technologist with more than eight years of clinical experience and with no access to athlete grouping data. Offline analysis was conducted using EchoPAC clinical software (version 204, GE Healthcare, United States), a medically certified platform designed specifically for myocardial strain and work quantification. All cine loops were exported from the Vivid E95 platform to EchoPAC version 204 for offline analysis after removal of group labels, performance scores, competition-index values, and training-history variables from the analyst-facing dataset. Offline tracing, segment tracking, and myocardial work analysis were performed by a certified echocardiography analyst blinded to athlete performance classification. Reliability testing used 36 randomly selected scans, representing 20% of the full sample. A second certified analyst independently repeated GLS, GWE, GWW, and MPI measurements for the same scans, and the primary analyst repeated the measurements after a two-week interval. Inter-observer reliability was high for GLS (ICC = 0.93, CV = 4.8%), GWE (ICC = 0.91, CV = 3.9%), GWW (ICC = 0.89, CV = 7.6%), and MPI (ICC = 0.87, CV = 6.2%). Intra-observer reliability was similarly strong for GLS (ICC = 0.96, CV = 3.6%), GWE (ICC = 0.94, CV = 3.2%), GWW (ICC = 0.92, CV =

6.4%), and MPI (ICC = 0.90, CV = 5.7%). These values supported retention of strain-derived, myocardial work, and Doppler-derived indices in the final analysis.

Global Longitudinal Strain (GLS)

GLS was measured through two-dimensional speckle-tracking echocardiography following the American Society of Echocardiography consensus protocol. The apical 4-chamber, 2-chamber, and long-axis views were imported into EchoPAC and the endocardial border was manually traced at end-diastole using the software's integrated region-of-interest tool. The software's clinical algorithm then tracked acoustic speckles frame by frame across the 17-segment left ventricular model throughout the cardiac cycle. The tracking accuracy was visually verified for each segment and adjusted when deviation exceeded 10 percent. Tracking quality was required to exceed 85 percent across segments for the data to be accepted. End-systole was automatically identified by the software using aortic valve closure timing derived from Doppler inputs. Global longitudinal strain was defined as the average peak negative strain value from all 17 segments, expressed as a percentage, and calculated as the mean of three validated cardiac cycles per view.

Myocardial Work Indices (GWE and GWW)

Myocardial work analysis was performed within EchoPAC using pressure-strain loop modeling derived from noninvasive blood pressure inputs. Immediately prior to imaging, brachial systolic and diastolic blood pressures were recorded using an automated monitor and entered into the software to generate an individualized reference pressure curve. Brachial blood pressure was measured twice at one-minute intervals after seated rest using the Omron HEM-7120 device. When systolic or diastolic values differed by more than 5 mmHg between readings, a third measurement was obtained, and the mean of the two closest readings was entered into EchoPAC. GWE and GWW were interpreted as pressure-adjusted myocardial work indices derived from non-invasive pressure-strain loop modeling. These indices were not treated as direct measurements of whole-body metabolic energy efficiency, because their calculation depends on cuff-derived blood pressure calibration, stable loading conditions, and adequate speckle-tracking quality during the analyzed cardiac cycles. This curve was temporally aligned with the longitudinal strain data obtained from speckle-tracking. The software integrated the pressure and deformation signals to compute segmental myocardial work throughout systole. Global work efficiency was defined as the ratio of constructive work to the sum of constructive and wasted work, expressed as a percentage, while global wasted work reflected energy expenditure during myocardial lengthening in systole and shortening in isovolumic relaxation. Both indices were calculated using segmental data from all 17 left ventricular segments and averaged across three validated cardiac cycles. Tracking quality criteria were applied identically as in the GLS protocol.

Myocardial Performance Index (MPI)

The myocardial performance index was calculated using pulsed-wave tissue Doppler imaging of the lateral mitral annulus in the apical 4-chamber view. Doppler sample volume was positioned 1 centimeter below the lateral annular plane and Doppler settings were adjusted to maintain a sweep speed of 100 millimeters per second for precise time interval measurement. Three cardiac cycles were analyzed per subject. Isovolumic contraction time was measured from the end of the A-wave to the onset of the systolic S-wave, isovolumic relaxation time from the end of the S-wave to the beginning of the early diastolic E-wave, and ejection time was measured as the duration of the S-wave. MPI was calculated using the formula: $\text{MPI} = (\text{IVCT} + \text{IVRT}) \div \text{ET}$. All measurements were performed manually using caliper tools within EchoPAC and were reviewed by a second blinded investigator in 20 percent of the cases to assess inter-rater reliability. Both left and right ventricular MPI were calculated where Doppler alignment permitted.

Instruments

Primary outcomes

Anaerobic power was assessed using the Wingate Anaerobic Test (WAnT), administered on a Monark 894E Peak Bike Ergometer (Monark Exercise AB, Sweden), a validated platform for high-intensity anaerobic testing in athletic populations. The WAnT followed the standard 30-second protocol originally established by Bar-Or (1987), with resistance set at 0.075 kg per kg of body mass. Output variables included (i) peak power (W/kg), (ii) mean power over 30 seconds (W), (iii) fatigue index (% drop from peak to final 5 seconds), and (iv) time to peak power (s). All raw torque and RPM data were captured digitally and analyzed using Monark Anaerobic Test Software. Validity of the WAnT has been established in both youth and elite adult athletes, with intraclass correlation coefficients exceeding 0.95 for peak power and mean power. Day-to-day test-retest reliability in trained populations has been reported with a coefficient of variation below 5%.

Agility was assessed using the T-Test, a four-directional change-of-direction protocol standardized in athletic performance research. The layout consisted of four cones arranged in a T-formation over a 10-yard by 10-yard configuration. Athletes sprinted forward, shuffled laterally, and backpedaled in sequence, with timing captured via electronic timing gates (Brower TCi, Brower Timing Systems, United States). Only fully completed trials without cone dislodgment were scored. Each athlete completed two familiarization trials and two timed attempts; the best trial was retained for analysis. The T-Test is a publicly available field protocol and has been validated in competitive sport settings with test-retest reliability exceeding ICC = 0.89 and concurrent validity with multidirectional speed tests ranging from r = 0.82 to 0.91 (Sassi et al., 2009).

Competition performance was quantified using a 10-point competition index derived from each athlete's five most recent official sanctioned matches within the 12 months preceding echocardiographic assessment. Matches were eligible if they were recorded in federation logs and occurred at regional, national, or international level. Each match score combined three components: event tier, match outcome, and technical margin. Event tier contributed 1 point for regional competition, 2 points for national competition, and 3 points for international competition. Match outcome contributed 0 points for loss, 1 point for draw or no-decision, and 3 points for win. Technical margin contributed 0 points for dominant loss, 1 point for narrow point loss, 2 points for point-based win, and 4 points for technical superiority, submission, stoppage, or knockout win. The maximum score per match was therefore 10 points. The five match scores were averaged to produce the final competition index. When more than five official sanctioned matches were available, the five matches closest to the echocardiographic assessment date were used. Competition records were verified against federation records and coach-confirmed match sheets.

Secondary outcomes

Neuromotor performance was assessed using three validated public-domain instruments. (i) Simple reaction time was measured via the Human Benchmark online test (https://humanbenchmark.com/tests/reactiontime), where athletes completed five trials in response to a visual cue, with median latency (ms) recorded. The tool shows ICC > 0.86 (Welford, 1986). (ii) Balance was assessed using the Balance Error Scoring System (BESS), a 6-condition, 20-second stance protocol with errors summed across all stances (0 - 60). Reported ICC = 0.87 - 0.91 (Bell et al., 2011). (iii) The Finger-to-Nose Alternation Test (FTNAT) evaluated sensorimotor coordination using six paced trials, ICC = 0.89 in prior validation.

Statistical analysis

All analyses were conducted in R version 4.3.2 (R Foundation for Statistical Computing, Vienna, Austria), with statistical significance set at two-tailed $p < 0.05$. The primary group comparison used athletes in the bottom and top tertiles of the composite performance score, classified as the lower-performance internal reference group and the higher-performance group, respectively. The full sample of 180 athletes was retained for continuous regression, moderation, and sensitivity analyses. Distributional assumptions were examined using histograms, Q-Q plots, and Shapiro-Wilk tests, and variance equality was assessed using Levene's test. Between-group comparisons used independent-samples t tests for normally distributed variables with equal variances, Welch-corrected t tests for unequal variances, and Mann-Whitney U tests for markedly non-normal variables. Cohen's d with 95% confidence intervals was reported for all main between-group comparisons.

Associations between myocardial indices and performance outcomes were examined using linear regression for continuous outcomes and logistic regression for higher-performance versus lower-performance classification. The base covariate model included age, sex, discipline, training age, weekly training load, body fat percentage, and skeletal muscle mass. Myocardial indices were then entered hierarchically as GLS, GWE, GLS plus GWE, MPI, and GWW to assess their incremental contribution beyond anthropometric and training variables. Multicollinearity was assessed using variance inflation factors, with values < 5.0 considered acceptable. Logistic model discrimination was evaluated using area under the receiver operating characteristic curve, sensitivity, specificity, and 95% confidence intervals generated from 1, 000 bootstrap resamples.

Sex and discipline moderation were tested in full-sample regression models using interaction terms between each myocardial index and the moderator variable. These analyses were treated as exploratory and interpreted only when each stratum contained at least 25 athletes and logistic models retained at least 10 classification events per estimated predictor. Sensitivity analyses tested whether the direction and magnitude of the GLS, GWE, GWW, and MPI associations remained stable when performance classification was repeated using tertile, quartile, and decile thresholds. Multiple testing across related echocardiographic and performance outcomes was controlled using the Benjamini-Hochberg false discovery rate procedure.

Results

Baseline characteristics

The full sample included 180 national-level martial artists distributed across the lower-performance internal reference group (n = 60), middle tertile (n = 60), and higher-performance group (n = 60). Age, height, body mass, body mass index, sex distribution, and martial arts discipline were comparable across the lower- and higher-performance groups (Table 1). The higher-performance group had lower body fat percentage, higher skeletal muscle mass, lower resting heart rate, lower diastolic blood pressure, higher RMSSD, longer training age, higher weekly training frequency, and greater weekly training load. These variables were retained as descriptive characteristics and covariates in subsequent models rather than interpreted as causal determinants of cardiac or performance outcomes.

Primary outcomes

The primary performance comparison used 120 athletes from the lower and higher performance tertiles. The higher-performance group had greater Wingate peak power, greater mean power, lower fatigue index, shorter time to peak power, shorter T-test completion time, fewer agility penalties, higher technical execution scores, higher win-loss ratio, and higher competition-index scores (Table 2; Figure 2). These differences were expected because anaerobic power, agility time, and competition index contributed to the composite performance score used for tertile classification; therefore, the results describe the magnitude and statistical consistency of group separation rather than independent causal effects.

Echocardiographic outcomes were compared between the lower-performance internal reference group and the higher-performance group (Table S1). GLS was analysed as a signed negative percentage, with more negative values representing greater longitudinal myocardial shortening; GLS magnitude was also reported to make the direction of interpretation explicit. The higher-performance group showed more negative signed GLS, greater GLS magnitude, higher GWE, lower GWW, and lower LV and RV MPI. This pattern indicates higher resting longitudinal deformation magnitude, greater pressure-adjusted constructive myocardial work relative to total work, less wasted myocardial work during the analysed cardiac cycles, and shorter combined systolic-diastolic timing intervals in the higher-performance group. Since GWE and GWW were derived from cuff-pressure-calibrated pressure-strain loop analysis, these values were interpreted as resting myocardial work indices under standardized loading conditions.

Table 1. Baseline characteristics of participants.

Variable	Full sample (n = 180)	Lower-performance internal reference group (n = 60)	Middle tertile (n = 60)	Higher-performance group (n = 60)	Sig.
Age, years	23.9 ± 4.0	23.8 ± 3.9	23.9 ± 4.0	24.0 ± 4.1	0.787
Male sex, n (%)	112 (62.2)	37 (61.7)	38 (63.3)	37 (61.7)	0.986
Taekwondo, n (%)	64 (35.6)	21 (35.0)	22 (36.7)	21 (35.0)	0.992
Sanda, n (%)	61 (33.9)	20 (33.3)	21 (35.0)	20 (33.3)	0.992
Brazilian jiu-jitsu, n (%)	55 (30.6)	19 (31.7)	17 (28.3)	19 (31.7)	0.992
Height, cm	173.6 ± 7.3	173.2 ± 7.4	173.7 ± 7.4	174.0 ± 7.1	0.548
Body mass, kg	70.8 ± 8.7	70.4 ± 8.8	70.8 ± 8.8	71.2 ± 8.5	0.614
Body mass index, kg/m2	23.5 ± 2.1	23.4 ± 2.2	23.5 ± 2.0	23.6 ± 2.1	0.602
Body fat, %	15.8 ± 3.3	16.8 ± 3.5	15.7 ± 3.2	14.9 ± 2.8	0.001
Skeletal muscle mass, kg	35.8 ± 4.2	34.7 ± 4.4	35.6 ± 4.0	37.1 ± 4.0	0.002
Resting heart rate, bpm	63.4 ± 6.0	65.2 ± 6.2	63.4 ± 5.8	61.7 ± 5.4	0.001
Systolic blood pressure, mmHg	117.1 ± 8.2	118.0 ± 8.5	117.2 ± 8.1	116.2 ± 7.9	0.232
Diastolic blood pressure, mmHg	74.6 ± 6.2	76.4 ± 6.5	74.6 ± 6.0	72.9 ± 5.9	0.003
RMSSD, ms	53.6 ± 12.9	48.2 ± 12.4	54.8 ± 12.3	57.8 ± 12.0	< 0.001
Training age, years	7.9 ± 2.5	6.8 ± 2.3	8.1 ± 2.4	8.9 ± 2.6	< 0.001
Weekly training sessions, n	5.5 ± 1.3	4.8 ± 1.2	5.5 ± 1.1	6.2 ± 1.4	< 0.001
Weekly training load, hours	9.7 ± 3.4	7.9 ± 3.0	9.8 ± 3.1	11.4 ± 3.6	< 0.001

Table 2. Primary performance outcomes by internal performance group.

Outcome	Lower-performance internal reference group (n = 60)	Higher-performance group (n = 60)	Sig.	Cohen's d (95% CI)
Peak power, W/kg	9.3 ± 1.2	11.7 ± 1.3	< 0.001	1.92 (1.49, 2.35)
Mean power, W/kg	7.6 ± 0.9	9.3 ± 1.0	< 0.001	1.79 (1.37, 2.21)
Fatigue index, %	39.8 ± 4.2	34.2 ± 3.7	< 0.001	-1.41 (-1.81, -1.01)
Time to peak power, s	4.6 ± 0.6	3.9 ± 0.5	< 0.001	-1.27 (-1.66, -0.88)
T-test completion time, s	10.6 ± 0.9	9.0 ± 0.7	< 0.001	-1.98 (-2.42, -1.54)
Cone contact penalties, n	1.2 ± 0.6	0.5 ± 0.4	< 0.001	-1.37 (-1.77, -0.97)
Rerun trials, n	0.7 ± 0.5	0.3 ± 0.3	< 0.001	-0.97 (-1.35, -0.59)
Technical execution score, 0 - 10	5.6 ± 1.4	8.4 ± 1.0	< 0.001	2.30 (1.84, 2.76)
Win-loss ratio, %	56.4 ± 14.2	82.7 ± 10.8	< 0.001	2.08 (1.63, 2.53)
Competition index, 0 - 10	5.1 ± 1.1	8.2 ± 0.9	< 0.001	3.08 (2.55, 3.61)

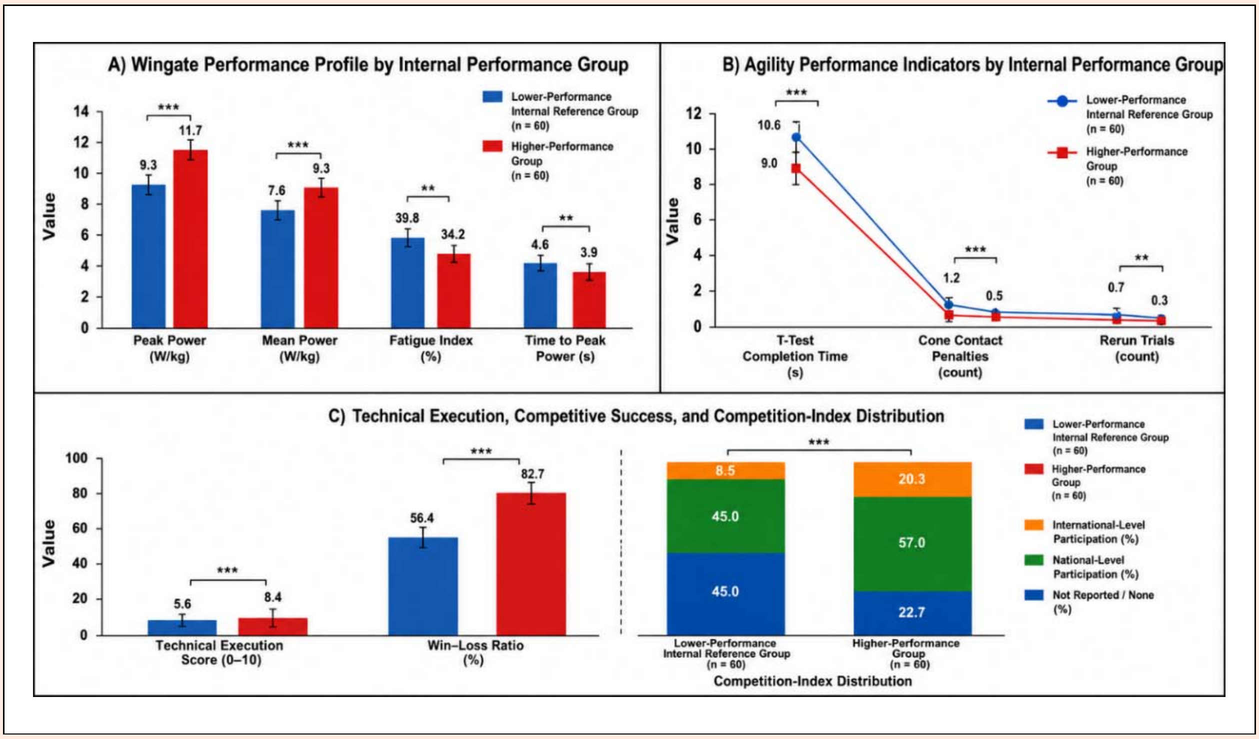


Figure 2. A) Wingate peak power, mean power, fatigue index, and time to peak power by internal performance group; B) T-test completion time, cone contact penalties, and rerun trials by internal performance group; C) technical execution score, win-loss ratio, and competition-index distribution across the lower-performance internal reference group and higher-performance group.

Segmental GLS analysis showed more negative strain values in the higher-performance group across all 17 LV segments (Table S2; Figure 3). The largest standardized differences were observed in the mid anteroseptal, apical anterior, apical septal, and mid anterior segments. The direction of the effect sizes is negative because GLS was entered as a signed percentage; therefore, negative values indicate more negative GLS in the higher-performance group.

Secondary outcomes

Secondary neuromotor outcomes were also compared between the lower- and higher-performance tertiles (Table 3). The higher-performance group had shorter reaction time, lower reaction-time variability, fewer total BESS errors, fewer condition-specific balance errors, more FTNAT repetitions, and higher pacing adherence. For BESS outcomes, lower values indicate fewer balance errors and therefore better balance performance.

Correlation analyses were conducted in the full sample of 180 athletes (Table S3; Figure 4). GLS magnitude was used for correlation interpretation, while signed GLS was retained in regression models. Higher GLS magnitude and higher GWE were associated with greater peak power, shorter T-test time, higher competition index, and fewer BESS errors. MPI was positively correlated with T-test time and BESS errors, indicating that higher MPI was associated with longer agility completion time and more balance errors, while lower MPI was associated with better agility and balance scores.

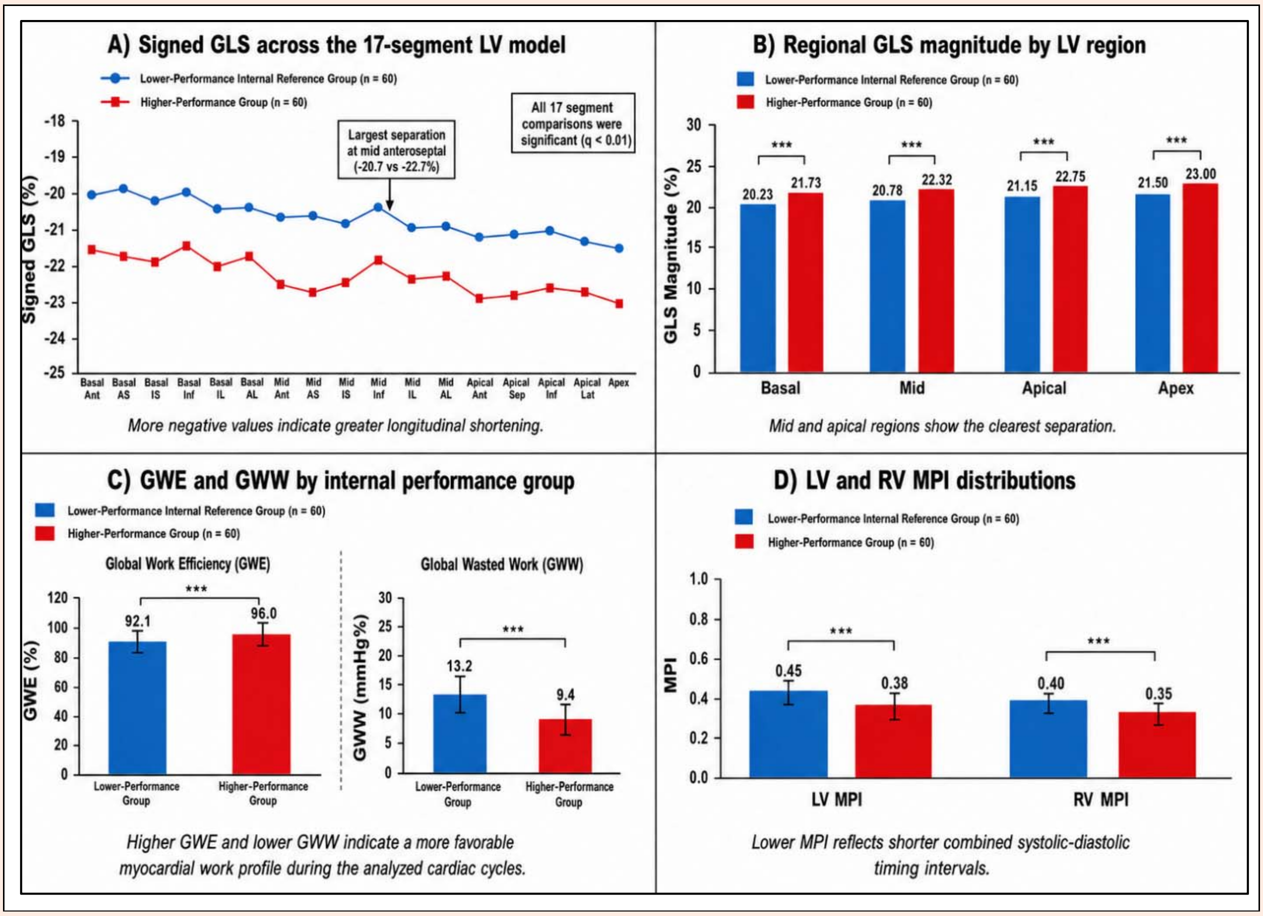
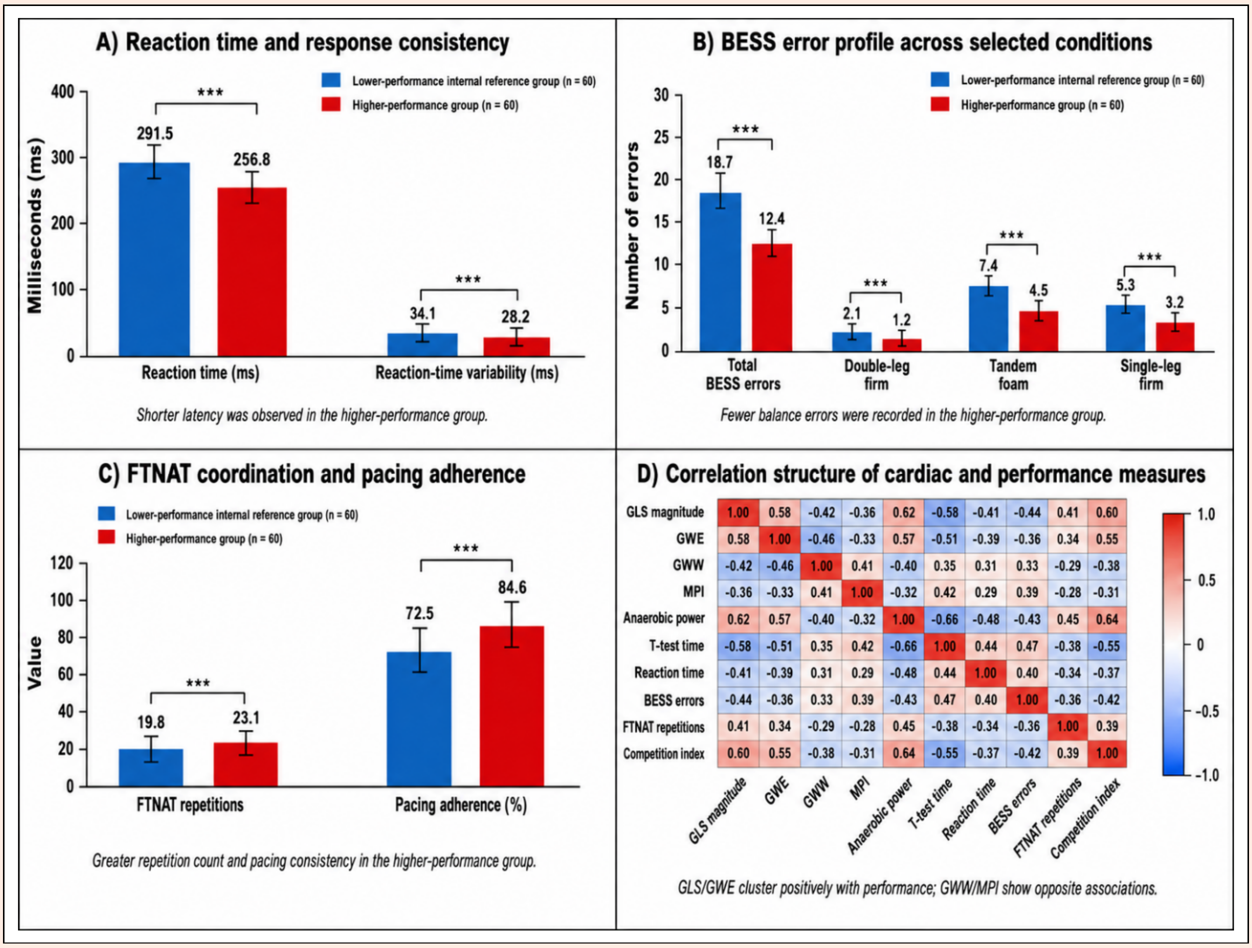


Figure 3. A) Signed GLS values across the 17-segment LV model in the lower-performance internal reference group and higher-performance group; B) GLS magnitude by LV region; C) GWE and GWW distributions by internal performance group; D) LV MPI and RV MPI distributions by internal performance group.

Table 3: Secondary neuromotor outcomes by internal performance group

Secondary outcome	Lower-performance internal reference group (n = 60)	Higher-performance group (n = 60)	Sig.	Cohen's d (95% CI)
Reaction time, ms	291.5 ± 27.3	256.8 ± 24.9	< 0.001	-1.33 (-1.73, -0.93)
Reaction-time variability, ms	34.1 ± 5.9	28.2 ± 6.1	< 0.001	-0.98 (-1.36, -0.60)
Total BESS errors, n	18.7 ± 4.5	12.4 ± 3.8	< 0.001	-1.51 (-1.92, -1.10)
Double-leg firm-surface errors, n	2.1 ± 0.7	1.2 ± 0.5	< 0.001	-1.48 (-1.89, -1.07)
Tandem foam-surface errors, n	7.4 ± 1.9	4.5 ± 1.6	< 0.001	-1.65 (-2.07, -1.23)
Single-leg firm-surface errors, n	5.3 ± 1.6	3.2 ± 1.2	< 0.001	-1.49 (-1.90, -1.08)
FTNAT repetitions, n	19.8 ± 2.3	23.1 ± 2.6	< 0.001	1.34 (0.94, 1.74)
FTNAT pacing adherence, %	72.5 ± 6.8	84.6 ± 7.3	< 0.001	1.71 (1.29, 2.13)



	GLS magnitude	GWE	GWW	MPI	Anaerobic power	T-test time	Reaction time	BESS errors	FTNAT repetitions	Competition index
GLS magnitude	1.00	0.58	-0.42	-0.36	0.62	-0.58	-0.41	-0.44	0.41	0.60
GWE	0.58	1.00	-0.46	-0.33	0.57	-0.51	-0.39	-0.36	0.34	0.55
GWW	-0.42	-0.46	1.00	0.41	-0.40	0.35	0.31	0.33	-0.29	-0.38
MPI	-0.36	-0.33	0.41	1.00	-0.32	0.42	0.29	0.39	-0.28	-0.31
Anaerobic power	0.62	0.57	-0.40	-0.32	1.00	-0.66	-0.48	-0.43	0.45	0.64
T-test time	-0.58	-0.51	0.35	0.42	-0.66	1.00	0.44	0.47	-0.38	-0.55
Reaction time	-0.41	-0.39	0.31	0.29	-0.48	0.44	1.00	0.40	-0.34	-0.37
BESS errors	-0.44	-0.36	0.33	0.39	-0.43	0.47	0.40	1.00	-0.36	-0.42
FTNAT repetitions	0.41	0.34	-0.29	-0.28	0.45	-0.38	-0.34	-0.36	1.00	0.39
Competition index	0.60	0.55	-0.38	-0.31	0.64	-0.55	-0.37	-0.42	0.39	1.00

Figure 4. A) Reaction time and reaction-time variability by internal performance group; B) total and condition-specific BESS errors by internal performance group; C) FTNAT repetitions and pacing adherence by internal performance group; D) correlation matrix linking GLS magnitude, GWE, GWW, MPI, anaerobic power, T-test time, reaction time, BESS errors, FTNAT repetitions, and competition index.

Robustness and subgroup analyses

Multivariable regression models used the full sample of 180 athletes. The base covariate model included age, sex, discipline, training age, weekly training load, body fat percentage, and skeletal muscle mass (Table S4). Adding GLS and GWE increased explained variance beyond the base model. The combined GLS plus GWE model showed higher explanatory performance than either index alone. MPI and GWW added smaller incremental variance after GLS and GWE were included. Variance inflation factors remained below the prespecified threshold of 5.0 in all models. The hierarchical regression structure, coefficient stability, and classification performance of the models are summarised in Figure 5.

Logistic classification models used the lower-performance internal reference group and higher-performance group only (n = 120). The combined GLS plus GWE model had higher discrimination than the base covariate model and the single-index models (Table S5). The full myocardial model provided the highest AUC, although the increase beyond the GLS plus GWE model was small.

Sex and discipline moderation were evaluated in full-sample regression models using interaction terms. Subgroup sample sizes were reported before interpretation. Sex interactions were exploratory because the female subgroup was smaller than the male subgroup, although both strata exceeded the minimum sample-size threshold (Table S6). The exploratory moderation results, sensitivity of AUC values across different classification thresholds, and multicollinearity diagnostics are presented in Figure 6. Discipline analyses were also exploratory and were interpreted as evidence of possible variation in association strength rather than separate confirmatory subgroup findings.

Sensitivity analyses examined whether the GLS and GWE associations remained stable when classification thresholds were changed. The combined GLS plus GWE model retained similar direction and magnitude across tertile, quartile, and decile definitions, although the decile model had wider confidence intervals because it used only the most extreme 10% of the distribution (Table S7). Residual diagnostics supported model adequacy, and multicollinearity remained below the prespecified threshold.

Discussion

The main findings indicate that higher-performance martial artists had higher GWE, lower GWW, greater GLS magnitude, lower LV and RV MPI, higher anaerobic output, faster agility performance, fewer BESS errors, and stronger internal classification performance when GLS and GWE were entered into adjusted models. These findings support RQ1 and H1 by showing that myocardial deformation, myocardial work, and timing indices were associated with anaerobic, agility, neuromotor, and competition-related outcomes. RQ2 and H2 were supported most clearly for GLS and GWE because these indices added explanatory information beyond age, sex, discipline, training age, weekly training load, body fat percentage, and skeletal muscle mass. RQ3 and H3 were supported within the internal tertile-based classification framework because the combined GLS plus GWE model showed stronger discrimination than the covariate-only and single-index models. This evidence should be interpreted as cross-sectional association and internal classification, not as longitudinal prediction of competitive success or validation for athlete selection. The higher GWE and lower GWW values indicate a larger proportion of constructive myocardial work relative to total myocardial work and less wasted work during the analysed resting cardiac cycles. This interpretation is consistent with the pressure-strain loop framework, in which GWE and GWW are derived from speckle-tracking deformation data calibrated against brachial blood pressure rather than direct metabolic measurement (Wang and Yin, 2024). Erevik et al. (2024) similarly reported that GWE was associated with VO_2max and treadmill exercise duration in trained male athletes, supporting the relevance of myocardial work indices to athletic capacity. The present findings extend that logic to martial arts, where performance depends on short explosive exchanges, rapid recovery intervals, agility control, and neuromotor coordination.

High-performance athletes demonstrated significantly greater GLS magnitude than the lower-performance internal reference group, indicating greater longitudinal myocardial shortening at rest. Abibillaev et al. (2025) similarly reported that GLS differentiated training adaptations, with endurance athletes showing more negative GLS values than resistance-trained peers despite stable LVEF, emphasizing the added sensitivity of deformation indices over volumetric measures alone. Randazzo et al. (2024) proposed a composite Myocardial Performance Score integrating GWE and LV power, which was associated with endurance outcomes and prognostic utility in clinical cohorts. The greater GLS magnitude in the higher-performance group may indicate a resting longitudinal deformation profile associated with training exposure and internal performance classification in this cohort. This interpretation aligns with Abibillaev et al. (2025), who reported

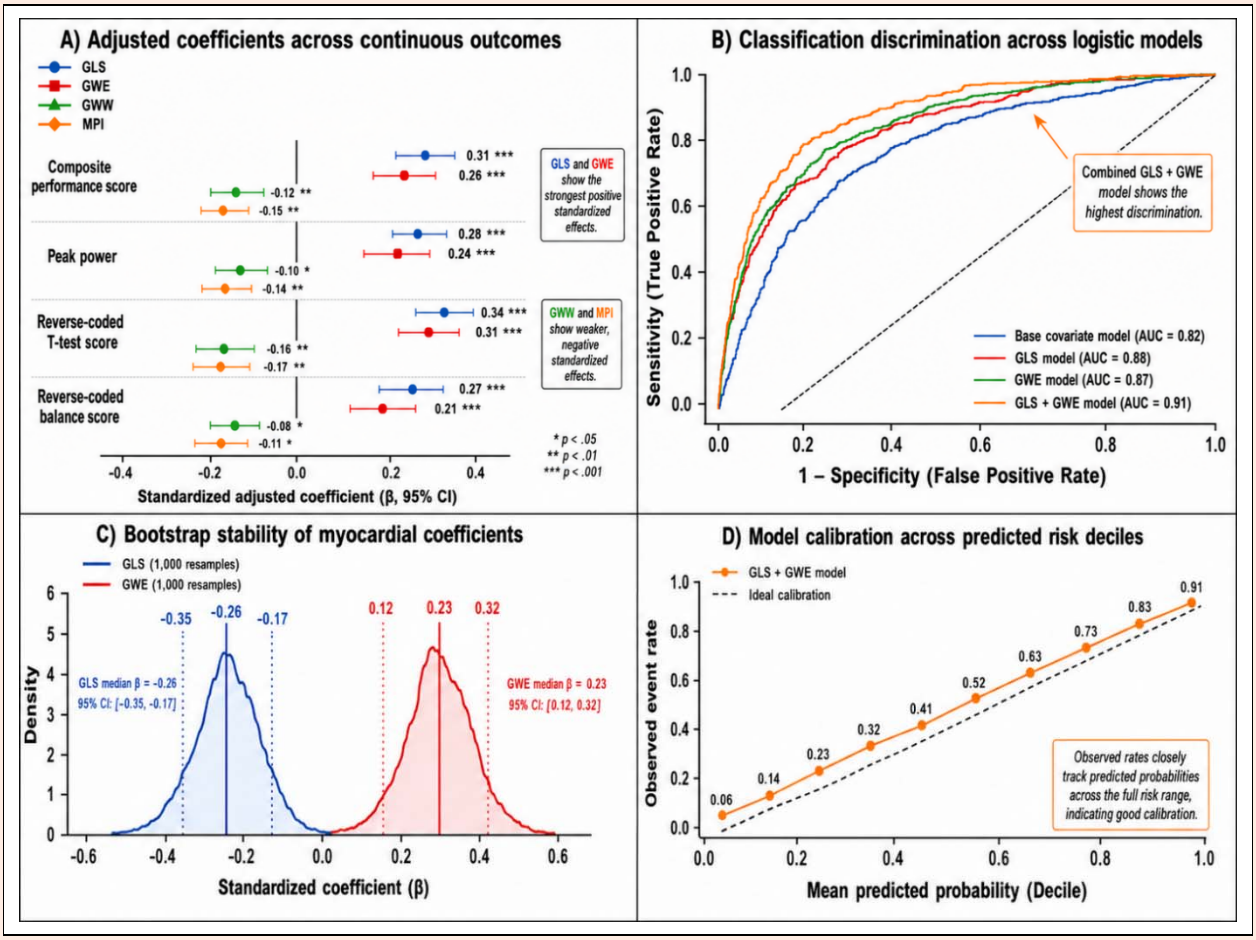


Figure 5. **A) Adjusted linear regression coefficients for GLS, GWE, GWW, and MPI across continuous performance outcomes; B) ROC curves for the base model, GLS model, GWE model, and combined GLS plus GWE model; C) bootstrap distribution of standardized GLS and GWE coefficients across 1,000 resamples; D) model calibration plot for higher-performance versus lower-performance classification.**

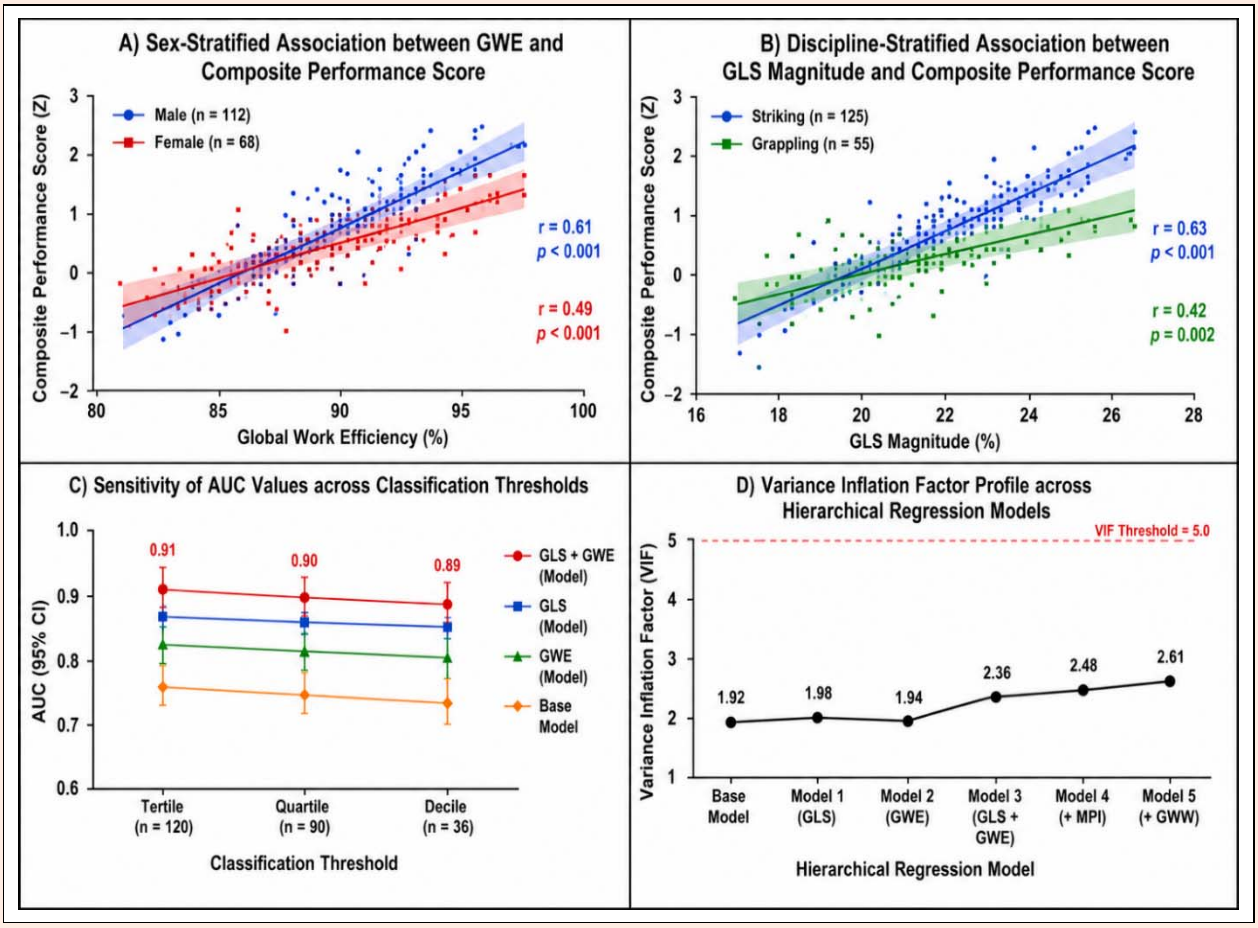


Figure 6. **A) Sex-stratified association between GWE and composite performance score; B) discipline-stratified association between GLS magnitude and composite performance score; C) sensitivity of AUC values across tertile, quartile, and decile classification thresholds; D) variance inflation factor profile across hierarchical regression models.**

sport-related differences in GLS despite preserved LVEF, and with Randazzo et al. (2024), who emphasized the value of integrating deformation and myocardial efficiency indices when evaluating cardiac performance profiles. GLS should therefore be interpreted as one component of echocardiographic athlete profiling, particularly when considered alongside GWE, GWW, MPI, and sport-specific performance outcomes.

Anaerobic and agility outcomes aligned with the cardiac timing and myocardial work indices. The higher-performance group showed greater peak power, lower fatigue index, and shorter time to peak output, while lower MPI was associated with shorter T-test time and fewer BESS errors. MPI provides a timing-based complement to GLS, GWE, and GWW because it expresses combined isovolumic contraction and relaxation time relative to ejection time. Lower MPI values in this cohort therefore indicate more compact systolic-diastolic timing at rest, which may accompany the physiological profile of athletes with faster change-of-direction performance and fewer balance errors. This interpretation remains cohort-specific because Alsafi et al. (2017) reported no clear MPI difference between elite and sedentary female athletes, indicating that MPI associations may vary by sport exposure, sex distribution, Doppler method, sample structure, and selected performance endpoint. Martial arts performance also depends on neuromotor execution, perceptual speed, balance recovery, and technical decision-making, so MPI is best interpreted as an associated cardiac timing marker within the wider performance profile.

Model-based analyses indicated that GLS and GWE contributed to internal performance classification after adjustment for anthropometric and training covariates. The combined GLS plus GWE model showed stronger discrimination than either index alone, suggesting that longitudinal deformation magnitude and pressure-adjusted myocardial work provided complementary information within the tertile-based performance framework. Kandels et al. (2023) similarly reported that exercise-related changes in Global Work Index correlated with VO_2max in football and handball players, while GLS showed limited dynamic change, supporting the value of myocardial work indices when evaluating functional reserve in trained athletes. In the present resting-data design, GLS and GWE are best interpreted as associated echocardiographic markers within an internal classification model. Longitudinal follow-up and stress echocardiography are needed to determine whether these indices track training response, performance change, or competitive outcomes across time.

GLS, GWE, GWW, and MPI aligned with anaerobic output, agility, balance, coordination, and competition-index measures in the same cohort. This pattern indicates that the echocardiographic indices contributed physiological information that paralleled the multidomain performance profile rather than functioning as isolated cardiac markers. Martial arts performance requires repeated acceleration, deceleration, visual-motor response, postural correction, coordination, and technical execution during short high-intensity exchanges. Resting GLS, GWE, GWW, and MPI add information on myocardial deformation, pressure-adjusted work, and systolic-diastolic timing under standardized conditions. Spanakis et al. (2024) similarly proposed multidomain athlete assessment using cardiovascular, neuromotor, and performance markers, supporting the combined interpretation of echocardiographic indices with Wingate outputs, reaction time, balance, and competition measures. Zholshybek et al. (2023) also emphasized cardiac imaging as part of athlete monitoring for distinguishing physiological adaptation patterns from maladaptive remodeling. In this study, the cardiac indices functioned as adjunctive physiological markers within a broader performance-assessment battery.

Theoretical and Practical Implications

The findings support a cardiomechanical interpretation of performance stratification in martial arts, where GLS, GWE, GWW, and MPI align with anaerobic output, agility, balance control, coordination, and competition-index measures. The theoretical contribution is the integration of resting myocardial deformation, pressure-adjusted myocardial work, and systolic-diastolic timing into a multidomain athlete-profile framework. This framework is relevant to martial arts because performance requires repeated high-intensity exchanges, rapid recovery intervals, postural correction, and neuromotor precision. In practical terms, echocardiographic indices may be used as adjunctive monitoring markers alongside Wingate output, agility testing, BESS, FTNAT, training-load history, and competition records. Their value is strongest when interpreted as part of a broader performance and cardiac-screening battery, especially for identifying athletes who may need closer monitoring of cardiac adaptation, recovery status, or training-load tolerance. Application to athlete selection, talent identification, or development policy requires longitudinal validation, external replication, stress-imaging evidence, and proof of added value beyond established performance tests.

Limitations and Future Research

The cross-sectional design limits inference to association and internal classification. The study cannot determine whether GLS, GWE, GWW, or MPI preceded performance status, resulted from long-term training exposure, or changed in response to recent training load. Group allocation was based on post hoc tertiles of a composite performance score, which strengthened separation between internal comparison groups but may overestimate classification performance when applied to independent athlete populations. Recruitment through federation lists, coaches, and national training centers may have favored athletes already retained in structured competitive systems. The use of resting echocardiography also means that myocardial responses during combat-like exertion, fatigue, and recovery were not captured. GWE and GWW were derived from cuff-pressure-calibrated pressure-strain loop analysis, so loading conditions, blood pressure measurement, and speckle-tracking quality remain important sources of measurement variation. Multiple related echocardiographic and performance outcomes were examined, although false-discovery correction, bootstrap stability testing, and sensitivity analyses were applied. Sex and discipline moderation analyses were exploratory interaction tests in the full sample, with subgroup sizes reported, and should be interpreted as preliminary. Future studies should use longitudinal designs, external validation cohorts, balanced sex-stratified sampling, stress echocardiography, repeated measures across training phases, and prospective competition follow-up to determine whether these indices track training response, recovery status, or future performance change.

Conclusion

Higher-performance martial artists showed more favorable resting cardiac strain, myocardial work, and timing indices than the lower-performance internal reference group in this cross-sectional cohort. GLS magnitude and GWE were consistently associated with anaerobic power, agility, neuromotor outcomes, and internal performance classification, while lower MPI aligned with shorter agility time and fewer balance errors. Echocardiographic indices therefore appear useful as adjunctive markers for performance-related monitoring in trained martial artists. The results should be interpreted as cohort-based associations within an internal classification framework. Longitudinal validation, external replication, stress-imaging protocols, and cost-effectiveness evaluation are required before myocardial efficiency screening can be recommended for athlete-development policy, selection systems, or injury-prevention programs.

Acknowledgements

The datasets generated during the current study are not publicly available but are available from the corresponding author upon reasonable request. The authors declare that they have no conflict of interest. All experimental procedures were conducted in compliance with the relevant legal and ethical standards of the country where the study was carried out. The authors declare that no Generative AI or AI-assisted technologies were used in the writing of this manuscript.

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Key points

- This study provides direct evidence that myocardial efficiency markers (GLS and Global Work Efficiency) are robust, non-invasive predictors of anaerobic power, agility, and technical performance in elite martial artists.
- It establishes quantitative relationships, showing that superior cardiac strain and efficiency independently predict group classification with over 80% accuracy and correlate significantly with key neuromotor outcomes.
- These findings advocate for the integration of echocardiographic screening into athlete talent identification and development programs, moving beyond traditional metrics to optimize training periodization and potentially prevent maladaptation.

AUTHOR BIOGRAPHY

Honghong SONG
Employment
Shandong Sport University
Degree
Master's degree
Research interests
cardiovascular function in elite athletes, exercise physiology, and the biomechanics of martial arts
E-mail: songhh1976131@163.com

🖂 **Honghong Song**
Martial Arts Academy, Shandong Sport University, Jinan, Shandong, 250000, China

Supplementary Materials

Table S1. Echocardiographic myocardial indices by internal performance group.

Echocardiographic index	Lower-performance internal reference group (n = 60)	Higher-performance group (n = 60)	Sig.	Cohen's d (95% CI)
Signed GLS, %	-20.4 ± 1.9	-22.6 ± 1.6	< 0.001	-1.25 (-1.64, -0.86)
GLS magnitude, %	20.4 ± 1.9	22.6 ± 1.6	< 0.001	1.25 (0.86, 1.64)
GWE, %	92.1 ± 3.6	96.0 ± 2.8	< 0.001	1.21 (0.82, 1.60)
GWW, mmHg%	13.2 ± 4.8	9.4 ± 3.6	< 0.001	-0.90 (-1.28, -0.52)
LV MPI	0.45 ± 0.08	0.38 ± 0.07	< 0.001	-0.93 (-1.31, -0.55)
RV MPI	0.40 ± 0.07	0.35 ± 0.06	< 0.001	-0.77 (-1.14, -0.40)
Segment tracking success, %	88.6 ± 7.2	92.8 ± 5.6	0.001	0.65 (0.28, 1.02)
Full-loop retention, %	86.4 ± 8.1	91.2 ± 6.2	< 0.001	0.67 (0.30, 1.04)

Table S2. Segmental GLS values across the 17-segment LV model.

LV segment	Lower-performance internal reference group (n = 60), %	Higher-performance group (n = 60), %	q value	Cohen's d
Basal anterior	-20.1 ± 2.1	-21.6 ± 1.8	< 0.001	-0.77
Basal anteroseptal	-19.9 ± 2.0	-21.8 ± 1.7	< 0.001	-1.02
Basal inferoseptal	-20.3 ± 1.9	-21.9 ± 1.6	< 0.001	-0.91
Basal inferior	-20.0 ± 2.0	-21.4 ± 1.8	0.001	-0.74
Basal inferolateral	-20.6 ± 2.1	-22.0 ± 1.9	0.001	-0.70
Basal anterolateral	-20.5 ± 2.0	-21.7 ± 1.8	0.003	-0.63
Mid anterior	-20.8 ± 1.8	-22.5 ± 1.6	< 0.001	-1.00
Mid anteroseptal	-20.7 ± 1.7	-22.7 ± 1.5	< 0.001	-1.25
Mid inferoseptal	-20.9 ± 1.8	-22.4 ± 1.5	< 0.001	-0.90
Mid inferior	-20.4 ± 1.9	-21.8 ± 1.7	< 0.001	-0.78
Mid inferolateral	-21.0 ± 2.0	-22.3 ± 1.7	0.001	-0.70
Mid anterolateral	-20.9 ± 1.9	-22.2 ± 1.6	< 0.001	-0.74
Apical anterior	-21.2 ± 1.7	-22.9 ± 1.4	< 0.001	-1.09
Apical septal	-21.1 ± 1.8	-22.8 ± 1.5	< 0.001	-1.03
Apical inferior	-21.0 ± 1.7	-22.6 ± 1.5	< 0.001	-1.00
Apical lateral	-21.3 ± 1.9	-22.7 ± 1.4	< 0.001	-0.84
Apex	-21.5 ± 1.8	-23.0 ± 1.5	< 0.001	-0.90

Table S3. Correlations between myocardial indices and performance outcomes in the full sample

Myocardial index	Peak power, W/kg	T-test time, s	Competition index	Reaction time, ms	BESS errors	FTNAT repetitions
GLS magnitude	r = 0.62, q < 0.001	r = -0.58, q < 0.001	r = 0.60, q < 0.001	r = -0.41, q < 0.001	r = -0.44, q < 0.001	r = 0.41, q < 0.001
GWE	r = 0.57, q < 0.001	r = -0.51, q < 0.001	r = 0.55, q < 0.001	r = -0.39, q < 0.001	r = -0.36, q < 0.001	r = 0.34, q = 0.002
GWW	r = -0.40, q < 0.001	r = 0.35, q = 0.001	r = -0.38, q < 0.001	r = 0.31, q = 0.004	r = 0.33, q = 0.002	r = -0.29, q = 0.006
MPI	r = -0.32, q = 0.003	r = 0.42, q < 0.001	r = -0.31, q = 0.004	r = 0.29, q = 0.006	r = 0.39, q < 0.001	r = -0.28, q = 0.008

Table S4. Hierarchical linear regression models for composite performance score in the full sample

Model	Predictors added beyond base covariates	Adjusted R2	ΔR2	Standardized β for myocardial index	p value	Maximum VIF
Base model	Age, sex, discipline, training age, weekly load, body fat, skeletal muscle mass	0.286	-	-	< 0.001	1.92
Model 1	GLS	0.407	0.121	βGLS = -0.34	< 0.001	1.98
Model 2	GWE	0.389	0.103	βGWE = 0.31	< 0.001	1.94
Model 3	GLS + GWE	0.462	0.176	βGLS = -0.27; βGWE = 0.24	< 0.001; 0.002	2.36
Model 4	GLS + GWE + MPI	0.474	0.012	βMPI = -0.13	0.041	2.48
Model 5	GLS + GWE + MPI + GWW	0.481	0.007	βGWW = -0.10	0.083	2.61

Table S5. Logistic classification models for lower- versus higher-performance status

Model	Sample used	AUC (95% CI)	Sensitivity	Specificity	Classification accuracy	Maximum VIF
Base covariate model	n = 120	0.82 (0.74, 0.89)	0.78	0.77	77.5%	1.94
Base + GLS	n = 120	0.88 (0.81, 0.94)	0.82	0.83	82.5%	2.02
Base + GWE	n = 120	0.87 (0.80, 0.93)	0.80	0.82	81.7%	1.98
Base + GLS + GWE	n = 120	0.91 (0.85, 0.96)	0.85	0.87	85.8%	2.39
Base + GLS + GWE + MPI + GWW	n = 120	0.92 (0.86, 0.97)	0.87	0.88	87.5%	2.63

Table S6. Exploratory moderation analyses by sex and discipline

Moderator model	Stratum sample sizes	Interaction term	βinteraction	P value	Q value	Interpretation
GLS magnitude × sex	Male n = 112; female n = 68	GLS × female sex	0.11	0.041	0.082	Exploratory; not retained after FDR correction
GWE × sex	Male n = 112; female n = 68	GWE × female sex	0.14	0.028	0.074	Exploratory; not retained after FDR correction
GLS magnitude × discipline type	Striking n = 125; grappling n = 55	GLS × striking discipline	0.16	0.018	0.054	Directionally stronger in striking athletes
GWE × discipline type	Striking n = 125; grappling n = 55	GWE × grappling discipline	0.18	0.012	0.048	Retained after FDR correction
MPI × discipline type	Striking n = 125; grappling n = 55	MPI × grappling discipline	-0.09	0.096	0.132	Not retained
GWW × sex	Male n = 112; female n = 68	GWW × female sex	-0.07	0.144	0.176	Not retained

Table S7. Sensitivity and diagnostic analyses.

Analysis	Sample used	Main estimate	95% CI	Diagnostic value
Continuous full-sample model	n = 180	Adjusted R2 = 0.462 for GLS + GWE model	0.371, 0.541	Maximum VIF = 2.36
Tertile classification	n = 120	AUC = 0.91 for GLS + GWE model	0.85, 0.96	Accuracy = 85.8%
Quartile classification	n = 90	AUC = 0.90 for GLS + GWE model	0.82, 0.96	Accuracy = 84.4%
Decile classification	n = 36	AUC = 0.89 for GLS + GWE model	0.76, 0.98	Accuracy = 83.3%
Bootstrap stability	1, 000 resamples	Median βGLS = -0.26; median βGWE = 0.23	βGLS: -0.35, -0.17; βGWE: 0.12, 0.32	Direction retained in 94.7% of resamples
Normality of model residuals	n = 180	Shapiro-Wilk W = 0.982	p = 0.116	Assumption retained
Variance equality for primary group models	n = 120	Levene's test range = 0.084 - 0.612	-	Welch correction used where p < 0.05
Multiple-testing correction	n = 180	Benjamini-Hochberg procedure	q threshold = 0.05	Primary GLS and GWE findings retained

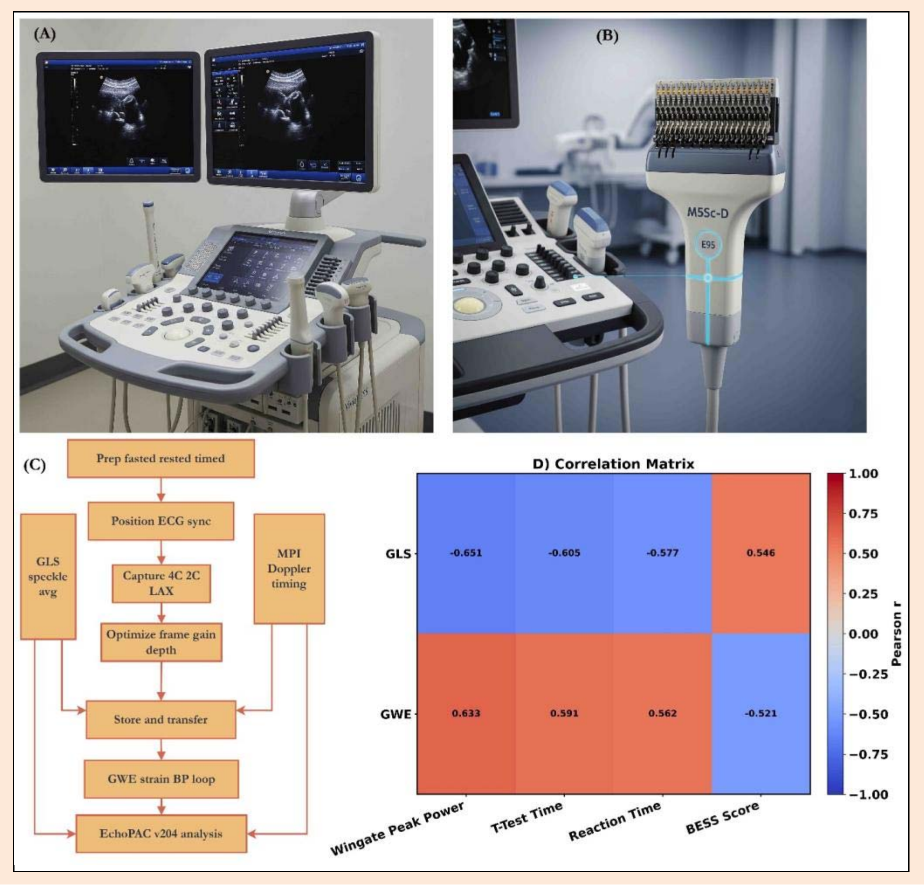

Figure S1. (A) Echocardiography console, (B) probe interface, (C) acquisition workflow, (D) correlation matrix.