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Computing, Electronics, and Health for Everybody: A Multi-Country Workshop on Low-Cost ECG Acquisition

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Abstract

A persistent interdisciplinary gap continues to hinder the development of Health 4.0 educational initiatives. Biomedical Engineering programs typically emphasize physiology and instrumentation while providing limited exposure to modern software ecosystems, whereas Informatics curricula often overlook the physical and physiological foundations of bio-instrumentation. To address this dual deficiency, this paper presents a low-cost and modular educational intervention aligned with the “Computing, Electronics, and Health for Everybody” philosophy. The proposed approach is a hands-on technical workshop that translates core biomedical signal-processing concepts into an accessible learning experience using the Arduino platform and the AD8232 ECG sensor. The intervention was implemented simultaneously across universities in Chile, Peru, and Ecuador, involving a total of $n = 92$ undergraduate engineering students. Learning outcomes were evaluated using a pre-post assessment design. The results demonstrate a statistically significant improvement in participants’ conceptual understanding of ECG signal components ($p < 0.001$), with mean scores increasing across all evaluated dimensions. In addition, students reported higher confidence in interpreting physiological signals and applying interdisciplinary reasoning. These findings indicate that the proposed intervention effectively supports interdisciplinary learning for software-oriented engineering students by introducing core biomedical acquisition and signal-processing concepts through an accessible and scalable educational framework.



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Keywords: computing education; electronics for all; Health 4.0; ECG; Arduino; low-cost sensors

1. Introduction

The convergence of disciplines is the hallmark of the 21st century [1]. The concept of “Computing, Electronics, and Health for Everybody” represents a paradigm shift where technology is no longer a siloed domain but a transversal tool for well-being. As AlAssaf et al. [2] detail, the rise of Health 4.0 requires professionals who are fluent in languages such as (i) computing: algorithms, cloud architecture, and data visualization; (ii) electronics:

sensors, analog filtering, and data acquisition; and (iii) health: biological physiology, noise interpretation, and patient safety. Traditionally, teaching the intersection of these fields has been restricted by high costs and rigid curricula, particularly due to the dependence on specialized biomedical acquisition hardware, proprietary clinical-grade devices, and licensed signal analysis software that are rarely available within standard engineering teaching laboratories [3]. This research proposes a democratizing educational intervention implemented in Chile, Peru, and Ecuador to bring this triad of knowledge to Informatics students.

This research addresses a structural limitation in contemporary engineering curricula that constrains the advancement of Health 4.0 systems. We identify a dual-competency deficiency that constitutes a critical barrier to interdisciplinary innovation. On the one hand, the Biomedical Gap emerges when Biomedical Engineering students, despite having solid foundations in human physiology, biosignal acquisition, and instrumentation, often lack sufficient competencies in modern software engineering practices, data processing pipelines, and applied data science [4,5]. On the other hand, the Informatics Gap characterizes students in Informatics and Systems Engineering programs who demonstrate strong proficiency in algorithmic reasoning and computational abstraction but often lack a basic understanding of biomedical signal characteristics, including physiological variability, noise sources, and safety-critical constraints inherent to biological systems [6,7]. The coexistence of these gaps limits the development of integrated Health 4.0 solutions, where reliable digital systems must simultaneously respect biomedical constraints and leverage advanced computational architectures.

The fragmentation between physical signal acquisition and computational processing has led to the formation of professional silos in Health 4.0 development [8]. As Veiga et al. [9] remark, a human bio-signal acquisition system follows a well-defined architectural pipeline composed of four tightly coupled stages: (1) the *Transducer*, which converts ionic currents generated by physiological activity into electronic signals; (2) the *Analog Front-End* (AFE), responsible for amplification and filtering; (3) the *Analog-to-Digital Converter* (ADC), which discretizes the conditioned signal; and (4) the *Digital Signal Processing* (DSP) stage, where computational algorithms extract, analyze, and interpret the data. Hence, in practice, Informatics and Systems Engineering students typically interact only with the DSP stage, while the preceding physical layers are treated as an opaque black box [4,10]. However, the development of effective and safe medical devices requires a coherent integration of the entire acquisition and processing chain. Accordingly, the proposed workshop bridges the physical signal path (Stages 1–3) with logical and algorithmic processing (Stage 4) through the use of low-cost, end-to-end hardware platforms.

To bridge this gap effectively, the educational content draws on established expertise in the rigorous development of biomedical instrumentation. This includes prior work on digital electrocardiographic system design and safety-oriented instrumentation considerations [11], as well as algorithmic work on robust QRS detection, which served as a conceptual reference in the workshop [12]. By translating this body of engineering knowledge into an accessible curriculum, the proposed workshop creates a learning environment in which complex instrumentation concepts are demystified for computing-oriented students, while preserving their underlying technical rigor.

The present work specifically targets Informatics and Systems Engineering students and therefore addresses the Informatics Gap. The complementary challenge of strengthening computational competencies among biomedical students remains outside the scope of this study. Accordingly, the proposed workshop bridges the physical signal path (Stages 1–3) with logical and algorithmic processing (Stage 4) through the use of low-cost, end-to-end hardware platforms. The conceptual integration of Computing, Electronics, and Health that underpins this intervention is illustrated in Figure 1.

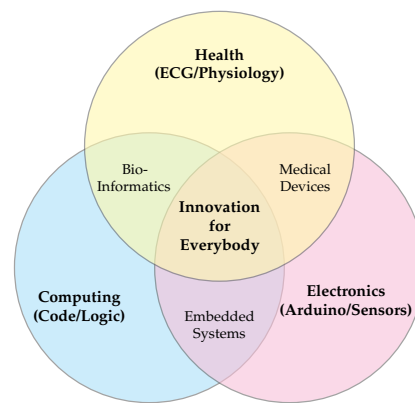


Figure 1. Overview of the interdisciplinary framework. Font size and contrast were adjusted to improve readability.

While low-cost Arduino-based ECG activities have been previously reported in educational contexts [13,14], the novelty of this work does not lie in the hardware itself, but in the pedagogical framing and target population. Specifically, this study focuses on Informatics and Systems Engineering students, a group traditionally excluded from biomedical instrumentation training, and addresses the full acquisition-to-processing pipeline rather than isolated signal visualization tasks. Moreover, the intervention was designed as a scalable, multi-country workshop with a standardized assessment protocol, allowing comparative analysis across diverse institutional contexts.

Accordingly, the pedagogical novelty of this study lies in (i) the explicit targeting of Informatics students rather than biomedical cohorts, (ii) the integration of the full acquisition-to-processing pipeline within a single workshop, and (iii) the use of a standardized assessment protocol across multiple countries.

To mitigate this interdisciplinary disconnect, this paper proposes a hands-on workshop based on low-cost hardware platforms. The primary objective of this study is to empirically validate the efficacy of the proposed workshop. To guide this investigation, we formulated the following Research Questions (RQ) and Hypotheses (H):

- **RQ1:** To what extent does a hands-on, low-cost hardware intervention enhance the bio-instrumentation competencies of Informatics students?
- **H1:** Students will demonstrate a statistically significant improvement ($p < 0.05$) in ECG acquisition and processing concepts between pre-test and post-test assessments.
- **RQ2:** How does direct exposure to physical hardware influence students' perception regarding the feasibility of Health 4.0 solutions?
- **H2:** Participants will report high levels of satisfaction ($>4.0/5.0$) and express increased confidence in bridging the gap between electronics and computing.

The remainder of this paper is organized as follows: Section 2 presents the theoretical framework regarding ECG signals and processing challenges. Section 3 details the methodology, including the materials and experimental procedure. Section 4 reports the learning gains, student satisfaction, and the corresponding educational implications, including the analysis of the cost–safety trade-off in health systems. Finally, Section 5 concludes the study.

2. Theoretical Framework

To effectively program a health solution, Informatics students must first understand the physical and biological nature of the data source. This section outlines the fundamental concepts taught in the workshop, drawing a parallel between classical biomedical engineering and the simplified “Health 4.0” approach.

2.1. The Electrocardiographic Signal

The electrocardiogram (ECG) is the graphical representation of the electrical potentials generated by the heart during the cardiac cycle [7,15]. As described in prior literature [7,15] and in the technical lineage of the workshop materials [11], the signal is captured via surface electrodes forming a specific configuration known as Einthoven's Triangle. For this workshop, the students focused on the electrocardiographic configuration of Lead I (left arm-right arm), selected for its simplicity and relevance in heart rate estimation tasks. Within this configuration, the most critical feature for automated cardiac monitoring is the QRS complex, which represents ventricular depolarization and concentrates the most prominent spectral and temporal characteristics of the ECG signal.

Figure 2 illustrates the morphology of a standard ECG heartbeat, explicitly highlighting the QRS complex as a high-energy short-duration event embedded within lower-frequency components such as the P and T waves, which correspond to atrial depolarization (electrical activation of the atria) and ventricular repolarization (recovery phase of the ventricles following contraction), respectively. As shown in established studies on QRS detection algorithms [12], this waveform constitutes the most distinctive and robust feature for reliable temporal localization under noisy conditions. Consequently, accurate QRS detection is widely regarded as the cornerstone of automated ECG analysis, allowing heart rate estimation and serving as a synchronization trigger for higher-level clinical and computational processes [16,17].

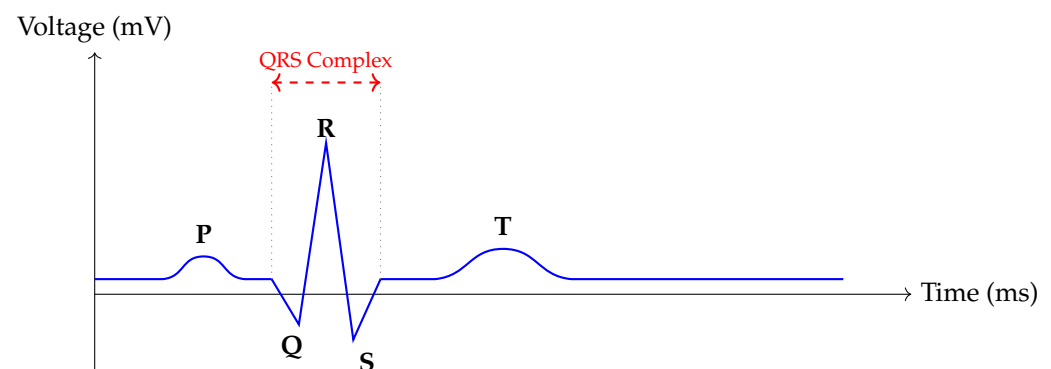


Figure 2. Morphology of a standard ECG heartbeat. Students learn to identify the QRS complex (duration indicated in red) as the primary trigger for Heart Rate variability algorithms.

To complement the visual representation, Table 1 summarizes the principal signal characteristics of the QRS complex that are relevant for computational processing. These parameters explicitly illustrate why ECG analysis cannot be treated as a binary event-detection problem. Instead, the QRS complex must be interpreted as a broadband, high-frequency phenomenon superimposed on low-frequency baseline drift and physiological noise, which directly impacts filter design, sampling strategies, and detection algorithms implemented at the digital signal processing stage.

Table 1. Key signal characteristics of the QRS complex relevant for digital processing and automated detection.

Parameter	Typical Value	Computational Relevance
Amplitude	~1 mV	Determines ADC resolution and dynamic range requirements
Bandwidth	0.05–100 Hz	Defines analog and digital filtering constraints
Center Frequency	10–40 Hz	Guides band-pass filter design for QRS isolation
Duration	80–120 ms	Establishes temporal resolution for peak detection
Noise Sensitivity	High	Requires robust preprocessing and artifact suppression

2.2. Signal Processing Challenges: Noise and Artifacts

A major learning outcome for software-oriented students is realizing that biological data is inherently noisy [6]. Based on the noise sensitivity analysis performed in [12], we categorized the interference sources students encounter in the lab (Table 2).

Table 2. Common noise sources in ECG acquisition and their mitigation strategies.

Noise Type	Frequency	Origin/Cause	Educational Solution
Power Line Interference	50 Hz (Chile/Peru) 60 Hz (Ecuador)	Electromagnetic coupling from the electrical grid	Analog Notch Filter (in AD8232)
Baseline Wander	≤ 1 Hz	Respiration and patient movement	Digital High-Pass Filter (in Code)
Muscle Artifact (EMG)	Broad spectrum	Patient muscle contraction	algorithmic thresholding

2.3. Hardware Abstraction: From Discrete to Integrated

This research leverages the authors' transition from complex analog design to educational abstraction.

- **Professional Approach:** In previous works [11,12], the authors implemented ECG systems using discrete instrumentation amplifiers (INA131) and multiple operational amplifiers (TL074) to build active filters. This provides high control but is complex for beginners.
- **Educational Approach:** For this workshop, we abstract that complexity using the AD8232 (<https://www.analog.com/en/products/ad8232.html>, accessed on 30 January 2026), integrated front-end. This single chip contains the instrumentation amplifier, gain stage, and filters in a simplified package.

This pedagogical shift allows Informatics students to focus on the *logic* of data acquisition (sampling rate, ADC resolution, visualization) without becoming overwhelmed by circuit theory, while still addressing real-world analog constraints.

3. Methodology

This study employs a quantitative, quasi-experimental design (pre-test/post-test) to measure the impact of the workshop. The intervention was designed to be replicable and scalable, adhering to the "Computing, Electronics, and Health for Everybody" philosophy.

3.1. Participants and Settings

The workshop was conducted simultaneously across three South American universities, fostering an international learning environment. The sample consisted of 92 undergraduate students enrolled in the 2nd year of Informatics/Systems Engineering programs:

- **Group A:** Universidad Viña del Mar (<https://ingresa.uvm.cl/>, accessed on 31 January 2026), Chile ($n = 30$).
- **Group B:** Universidad Continental (<https://ucontinental.edu.pe/campus-huancayo/>, accessed on 31 January 2026), Peru ($n = 32$).
- **Group C:** Universidad Estatal de Milagro (UNEMI) (<https://www.unemi.edu.ec/>, accessed on 31 January 2026), Ecuador ($n = 30$).

Participants were undergraduate students enrolled in engineering-related programs, primarily Informatics, Systems Engineering, and closely related disciplines. While most participants had prior experience in programming and basic mathematics, formal training in physiology or biomedical signal processing was limited or absent, reflecting the software-oriented student audience for whom the workshop was designed.

3.2. Materials: The Low-Cost Kit

As indicate Albert et al. [10], a critical barrier to entry in biomedical education is cost. Based on the authors' experience in optimizing hardware components [11,12], we curated a kit that balances signal fidelity with affordability. Table 3 details the Bill of Materials (BoM), totaling approximately USD 16 per station—a fraction of the cost of a standard educational bio-amplifier (approx. USD 400).

Table 3. Bill of materials (BoM) for the student kit.

Component	Role in Health 4.0	Technical Spec	Cost (USD)
Arduino Uno R3	Edge Computing Unit	ATmega328P, 10-bit ADC	\$8.00
AD8232 Module	Analog Front-End	CMRR > 80 dB, Gain 100	\$5.00
ECG Electrodes	Patient Interface	Ag/AgCl Gel	\$1.00
Cabling	Connectivity	Dupont Wires	\$2.00
Total			\$16.00

3.3. Hardware Implementation

Students were tasked with assembling the acquisition system. To ensure safety and simplicity, the complex analog circuitry described in [11] was abstracted into the AD8232 module.

Figure 3 and Table 4 summarize the real circuit implemented in the workshop. A three-electrode Lead I configuration (LA–RA differential with RL reference) was connected to an AD8232 analog front-end module, which provides amplification and analog conditioning. The module output (OUT) was sampled through the Arduino Uno 10-bit ADC (A0) and streamed over USB serial for real-time visualization. Optional lead-off pins (LO+ / LO−) were available to detect electrode disconnection events using digital inputs, improving robustness during hands-on sessions.

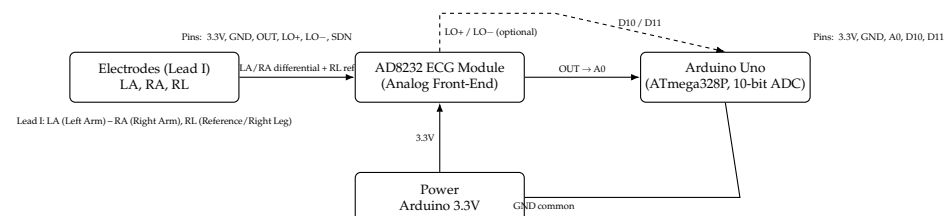


Figure 3. Real wiring setup used in the workshop for ECG acquisition (Lead I) with an AD8232 analog front-end and an Arduino Uno. The conditioned analog output (OUT) is sampled by the Arduino ADC (A0). Optional lead-off pins (LO+ / LO−) can be connected to digital inputs (e.g., D10 / D11) to detect electrode disconnection events.

Table 4. Pin-level wiring list for replicating the ECG acquisition circuit (Arduino Uno + AD8232).

AD8232 Pin	Arduino Uno Pin	Notes
3.3 V	3.3 V	Recommended supply for stable output range
GND	GND	Common ground reference
OUT	A0	Analog ECG signal to ADC input
LO+	D10 (optional)	Digital read for lead-off detection
LO−	D11 (optional)	Digital read for lead-off detection
SDN	3.3 V (or NC)	Keep module enabled (avoid shutdown)

3.4. Experimental Procedure

The workshop was structured into four stages over a 4-h intensive session. To ensure rigorous assessment, we employed specific evaluation instruments, which are cited and described below.

1. **Pre-Test (15 min):** Students completed a 10-question diagnostic instrument designed to assess prior knowledge on sampling rates, noise types, and bio-potentials. The complete set of questions, classified by dimension and technical concept, is detailed in Table 5.
2. **Assembly & Safety (60 min):** Guided by the “Electronics for All” principle, students assembled the kit. Special emphasis was placed on electrical isolation concepts, referencing safety standards discussed in [11,18].
3. **Computing & Visualization (135 min):** Students wrote C++ firmware to sample the signal at 100 Hz. They then visualized the serial data stream and identified the QRS complex in real time.
4. **Post-Test & Feedback (15 min):** The same technical instrument was administered to measure learning gain (H1). Additionally, a perception analysis was conducted using the satisfaction survey presented in Table 6, which evaluates the students’ confidence and their views on the feasibility of low-cost health solutions.

Table 5. Cognitive assessment instrument (pre-test and post-test questions).

ID	Dimension	Question (Correct Answer)	Concept
Q1	Fundamentals	According to Nyquist, if ECG bandwidth is 100 Hz, what is the minimum sampling rate? (Answer: >200 Hz)	Sampling Theorem
Q2	Fundamentals	What is the effect of an insufficient sampling rate in bio-signals? (Answer: Aliasing)	Signal Integrity
Q3	Physiology	What does the QRS complex represent? (Answer: Ventricular Depolarization)	Heart Physiology
Q4	Physiology	What is the typical amplitude of surface ECG? (Answer: 1–5 mV)	Bio-potentials
Q5	Physiology	Identify standard ECG morphology in Lead I. (Answer: P-QRS-T)	Waveform Analysis
Q6	Instrumentation	Main source of 50/60Hz interference? (Answer: Power Line Grid)	Noise Sources
Q7	Instrumentation	Best filter for Baseline Wander removal? (Answer: High-Pass Filter)	Digital Filtering
Q8	Instrumentation	Parameter defining common noise rejection? (Answer: CMRR)	Amplifiers
Q9	Safety	Why is a USB-prototype not a medical device? (Answer: Lack of Galvanic Isolation)	Patient Safety
Q10	Processing	Feature distinguishing QRS from T-wave? (Answer: Higher slope/frequency)	Algorithms

3.4.1. Assessment Instrument Development

The 10-item pre–post instrument was explicitly designed to be curriculum-aligned with the workshop learning objectives, covering key dimensions including sampling, physiology, instrumentation, safety, and basic signal processing. Given its short length and the dichotomous nature of the items (correct/incorrect), the instrument was conceived as an instructional diagnostic tool rather than a fully validated psychometric scale.

Accordingly, the instrument aims to capture short-term conceptual change associated with the intervention, rather than provide a comprehensive measure of latent constructs. Formal validation procedures, such as expert panel review, item discrimination analysis, and reliability estimation (e.g., KR-20 or Cronbach’s alpha), were therefore considered beyond the scope of the present exploratory study. Future work will incorporate these validation steps and examine potential ceiling effects through item-level response distributions.

3.4.2. Student Satisfaction Survey

Student perceptions were collected using a brief post-intervention satisfaction survey composed of five items (S1–S5), presented in Table 6. The survey was designed to capture students' perceived confidence, interdisciplinary understanding, and perceived feasibility of low-cost health technologies following the workshop.

All items were rated on a five-point Likert scale (1 = strongly disagree, 5 = strongly agree). Given the exploratory and formative nature of the study, the survey was intended to provide descriptive insights into student perceptions rather than to function as a validated attitudinal scale. For this reason, responses were analyzed using descriptive statistics (mean and standard deviation) and were interpreted as complementary evidence to the learning gains observed in the pre–post assessment. Future work will consider expanding this instrument and evaluating its internal consistency and construct validity using established psychometric procedures.

Table 6. Student satisfaction survey items (Likert scale: 1–5).

Item	Statement
S1	The workshop helped me understand that ECG is a physical signal, not just a graph.
S2	I feel confident replicating this circuit to capture other signals (e.g., EMG).
S3	I believe it is feasible to develop low-cost health solutions in my country.
S4	I better understand the language of biomedical engineers after this experience.
S5	Medical electronics seem less “magical” and more accessible now.

4. Results

The results are categorized into two dimensions: academic performance (learning gain) and student perception (satisfaction and confidence). Data analysis was performed using paired *t*-tests to determine statistical significance.

4.1. Academic Performance: The “Health 4.0” Gap

The pre-test scores revealed the structural deficiency mentioned in the Introduction. Informatics students initially scored low (Mean = 3.27/10.0), particularly in questions related to “Analog Filtering” and “QRS Morphology”.

However, after the workshop, the post-test scores showed a dramatic improvement. Figure 4 illustrates the comparative performance across the three participating universities.

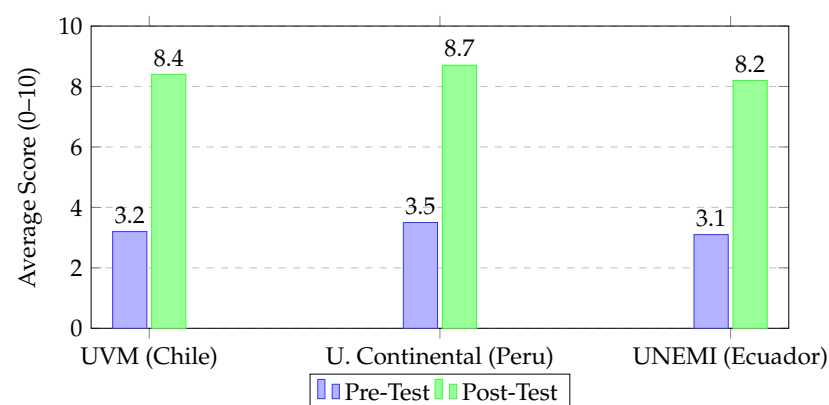


Figure 4. Comparison of academic performance before (Pre-Test) and after (Post-Test) the workshop. Consistent growth across diverse geographies supports the methodology's feasibility at the participating institutions.

Table 7 presents the detailed statistical breakdown. The global learning gain was approximately 158%, with a p -value < 0.001 , confirming that the intervention effectively bridged the knowledge gap.

Table 7. Detailed pre-test and post-test statistics by university (max score: 10.0).

Institution	Pre-Test Mean	Post-Test Mean	Growth	p -Value
UVM (Chile)	3.2 ± 1.1	8.4 ± 0.9	+162%	<0.001
U. Continental (Peru)	3.5 ± 1.2	8.7 ± 0.8	+148%	<0.001
UNEMI (Ecuador)	3.1 ± 1.0	8.2 ± 1.1	+164%	<0.001

Interinstitutional comparisons were not a primary objective of this study, and the sample size per site was not designed to support well-powered between-cohort inference. For transparency, we report site-level descriptive statistics (Table 7) and observe that the pre–post improvements follow a consistent pattern across institutions. To examine inter-university variability, we compared gain scores (Post–Pre) across institutions using a one-way ANOVA (or Kruskal–Wallis when normality was not met). No statistically significant differences were observed ($p = 0.41$), suggesting comparable learning gains across sites under the shared protocol.

4.2. Practical Achievement: Validating Author’s Experience & Student Perception

Beyond academic scores, the practical success rate is a robust indicator of the workshop’s effectiveness. Ninety-five percent (95%) of the student teams successfully visualized a clean, stable ECG signal on their computer screens. This high success rate validates the authors’ pedagogical decision to utilize the AD8232 module as a hardware abstraction layer. By encapsulating the complex analog filtering stages, which typically require rigorous discrete design as detailed in previous research [11], students were able to bypass the frustration of circuit instability and focus on the logic of data acquisition.

Furthermore, the practical component bridged the gap between abstract code and physical reality. Students successfully implemented a simplified thresholding algorithm in C++ to detect the QRS complex [12] in real-time. This achievement confirms that when the “hardware barrier” is lowered, Informatics students can effectively apply their algorithmic skills to biological signals, achieving functional Health 4.0 prototypes in a matter of hours.

Regarding student perception, the satisfaction survey (Table 8) reveals a highly positive reception of this multidisciplinary approach, with a clear shift in student mindset.

Table 8. Student satisfaction survey results (Likert scale: 1 = strongly disagree, 5 = strongly agree).

Survey Question	Mean $\pm$ SD
Q1. The workshop helped me understand the link between Computing and Health.	4.8 ± 0.4
Q2. I feel confident acquiring biological signals with hardware.	4.5 ± 0.6
Q3. I believe low-cost technology can reduce healthcare costs.	4.7 ± 0.5
Q4. The difficulty level was appropriate for my background.	4.2 ± 0.7

The high mean score for understanding the link between Computing and Health (Q1 4.8 ± 0.4) indicates that the workshop effectively bridged disciplinary boundaries and supported interdisciplinary comprehension, with a high level of consensus among participants. Similarly, the strong confidence reported in acquiring biological signals using hardware (Q2, 4.5 ± 0.6) suggests that the hands-on approach successfully reduced perceived barriers related to electronics and instrumentation, albeit with slightly higher variability reflecting differences in prior technical experience. The positive perception regarding the use of low-cost technologies in healthcare contexts (Q3, 4.7 ± 0.5) further

supports the relevance of accessible computational tools within Health 4.0 education. Finally, the perceived appropriateness of the difficulty level (Q4, 4.2 ± 0.7) indicates that the workshop achieved a balance between challenge and accessibility, while also revealing greater heterogeneity in students' self-assessment of task difficulty.

The results obtained in this study indicate that the proposed workshop effectively supports the development of interdisciplinary competencies among software-oriented engineering students. The observed learning gains suggest that translating biomedical signal processing concepts into a computationally accessible framework facilitates conceptual understanding without requiring extensive prior training in physiology or instrumentation. These findings are consistent with prior research emphasizing the value of hands-on and interdisciplinary learning approaches in engineering education, particularly in contexts where students must integrate domain-specific knowledge with computational reasoning. Previous studies have shown that experiential and project-based interventions can reduce conceptual barriers between traditionally separated disciplines and enhance student engagement and learning outcomes [19,20].

From a computational perspective, the proposed approach contributes to ongoing efforts to democratize access to Health 4.0 education by lowering technical and infrastructural barriers. By relying on low-cost hardware and open platforms, the workshop model supports scalability and reuse across diverse institutional contexts, aligning with broader trends in accessible computing education and technology-enabled learning.

4.3. Democratizing Complex Engineering via Abstraction

The significant learning gain ($p < 0.001$) across three different educational contexts (Chile, Peru, Ecuador) suggests that the barrier to entry for biomedical engineering is not intellectual capacity but access to understandable hardware. By replacing the complex discrete instrumentation amplifiers used in the authors' professional designs [11,12,18] with the integrated AD8232 module, we reduced the cognitive load. This allowed Informatics students to focus on the signal logic rather than circuit stability, effectively converting a "Hardware Problem" into a "Computing Problem" they could solve.

4.4. Bridging the Gap: Understanding the Limits of Low-Cost Hardware in Medical Contexts

A central finding of this study is the students' realization of the trade-off between cost and clinical validity. While we demonstrated that an ECG can be acquired for USD 16, the discussion highlighted why professional systems cost upwards of USD 2000.

Drawing from the safety constraints detailed in [11] and the noise sensitivity analysis in [12], we emphasized that our low-cost prototype differs from a medical device in three critical aspects:

- **Patient Safety (Isolation):** Our USB-powered prototype relies on the PC's isolation. A clinical device requires dedicated galvanic isolation (4 kV) to protect the patient from defibrillation shocks [11].
- **CMRR (Common Mode Rejection Ratio):** While the AD8232 is sufficient for education, it lacks the high CMRR (>100 dB) required to reject artifacts in a moving patient [11,12].
- **Diagnostic Bandwidth:** The educational kit filters heavily to produce a "pretty" signal, whereas diagnostic devices must preserve raw frequency content (0.05 Hz–150 Hz) for detecting pathologies like ischemia [12].

In clinical contexts, these safety requirements are formalized in international standards such as IEC 60601, which mandate galvanic isolation levels and leakage current limits that are not achievable in USB-powered educational prototypes. Previous critical analysis is what transforms the workshop from a hobbyist tutorial into a university-level engineering

experience. Students learned that “Low Cost” is excellent for *monitoring* and *education* (Health 4.0), but strict engineering rigor is non-negotiable for *diagnosis*.

The high satisfaction reported (Table 8) indicates a shift in student identity. Informatics students no longer see themselves as passive consumers of medical data but as active creators of health solutions. This mindset is essential for modern healthcare, where the boundary between the “doctor’s tool” and the “patient’s gadget” is blurring. By understanding the physical origin of the data [12,21], these future engineers will write more robust, noise-tolerant code for real-world telemedicine applications.

Although the intervention was designed for engineering students, the modular structure and low-cost hardware suggest that the approach could be adapted for non-engineering learners or resource-limited educational settings, provided that additional scaffolding is incorporated to address differences in technical background.

4.5. Limitations

This study presents several limitations that should be considered when interpreting the results. First, the intervention was evaluated in a single workshop, which may limit the generalizability of the findings to other institutional or curricular settings. In addition, the assessment focused on short-term learning outcomes measured immediately after the intervention, without evaluating long-term retention or knowledge transfer effects. The workshop was intentionally limited to a four-hour session and focused exclusively on single-lead (Lead I) ECG acquisition, which constrains both the physiological scope and the instrumentation complexity addressed in this study.

Although the workshop was implemented across multiple countries, the participant sample was restricted to undergraduate students enrolled in Informatics and Systems Engineering programs. Consequently, the results may not directly extend to other educational levels or professional contexts. Moreover, the intervention specifically addressed the Informatics Gap; the complementary biomedical gap was not examined from the perspective of biomedical students. As such, reciprocal workshop designs involving biomedical cohorts that engage with the computational and algorithmic aspects of biosignal processing remain an important direction for future research.

From a methodological standpoint, the absence of a control or comparison group constitutes an important limitation. While the pre–post quasi-experimental design employed in this study is widely accepted in educational research, it does not support strong causal inferences. The observed results should therefore be interpreted as learning gains associated with the intervention rather than definitive causal effects. Overall, this study should be regarded as an exploratory step that motivates future investigations employing longitudinal designs, broader participant cohorts, and controlled or comparative experimental frameworks. Additionally, the workshop was intentionally limited in duration (four hours) and focused exclusively on single-lead (Lead I) ECG acquisition, which constrains the scope of physiological interpretation and instrumentation complexity.

5. Conclusions

This study provides empirical evidence of learning gains associated with an interdisciplinary workshop aimed at reducing the structural disconnect between computing and biomedical domains in Health 4.0 education.

The statistically significant learning gains observed (+158%, $p < 0.001$) suggest that the proposed workshop supports the development of introductory bio-instrumentation competencies among Informatics students in the studied context. Participants transitioned from abstract coding concepts toward an initial understanding of physical bio-instrumentation, acquiring a foundational bio-engineering baseline relevant to Health 4.0 contexts. Import-

tantly, the results suggest that improved accessibility does not necessarily require sacrificing technical rigor. By translating established expertise in professional ECG design and QRS algorithm development into a scaffolded educational experience, the study demonstrates the feasibility of teaching complex biomedical concepts using low-cost hardware (USD 16) while preserving essential physical principles.

Beyond technical skills, a key outcome of the workshop was the students' increased awareness of ethical and safety considerations in health technologies. Participants recognized that while "Electronics for All" facilitates rapid prototyping, professional healthcare applications require strict adherence to safety standards and signal fidelity requirements. This distinction helped clarify that the difference between an educational prototype and a clinical device lies not only in cost but fundamentally in patient safety. To support reproducibility and scalability, the wiring diagrams, firmware examples, and assessment instruments used in this study are available from the corresponding authors upon reasonable request. Future work will include the public release of these materials in an open educational repository.

Finally, the multi-country implementation suggests that the proposed approach is scalable and adaptable across diverse educational contexts. Future work will explore the integration of edge computing capabilities using platforms such as the Arduino Nano 33 BLE. From a pedagogical perspective, this extension would allow students to experience the full pipeline from signal acquisition to real-time inference at the edge, reinforcing concepts such as latency, energy efficiency, and algorithmic optimization under hardware constraints.

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References

1. Sánchez-Hernández, M.I.; Rabazo-Martín, A.; Rodríguez-Rivero, E.; Guerrero-Cáceres, J.M. The Convergence of the Fourth Sector and Generation Z's Biospheric Values: A Regional Empirical Case Study in Spain. *World* **2025**, *6*, 83. [\[CrossRef\]](#)
2. Al-Assaf, K.; Bahroun, Z.; Ahmed, V. Transforming Service Quality in Healthcare: A Comprehensive Review of Healthcare 4.0 and Its Impact on Healthcare Service Quality. *Informatics* **2024**, *11*, 96. [\[CrossRef\]](#)
3. Jayousi, S.; Barchielli, C.; Guarducci, S.; Alaimo, M.; Caputo, S.; Zoppi, P.; Mucchi, L. From Innovation to Integration: Bridging the Gap Between IoMT Technologies and Real-World Health Management Systems. *Sensors* **2025**, *25*, 6660. [\[CrossRef\]](#) [\[PubMed\]](#)
4. Pollak, M.; Ebner, M. The Missing Link to Computational Thinking. *Future Internet* **2019**, *11*, 263. [\[CrossRef\]](#)

5. Kernytsky, I.; Hlinenko, L.; Yakovenko, Y.; Horbay, O.; Koda, E.; Rusakov, K.; Yankiv, V.; Humenuyk, R.; Polyansky, P.; Berezovetskyi, S. Problem-Oriented Modelling for Biomedical Engineering Systems. *Appl. Sci.* **2022**, *12*, 7466. [\[CrossRef\]](#)
6. Nowroozilarki, Z.; Mortazavi, B.J.; Jafari, R. Variational Autoencoders for Biomedical Signal Morphology Clustering and Noise Detection. *IEEE J. Biomed. Health Inform.* **2024**, *28*, 169–180. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Georgieva-Tsaneva, G.; Gospodinova, E.; Cheshmedzhiev, K. Examination of Cardiac Activity with ECG Monitoring Using Heart Rate Variability Methods. *Diagnostics* **2024**, *14*, 926. [\[CrossRef\]](#) [\[PubMed\]](#)
8. Kotzias, K.; Bukhsh, F.A.; Arachchige, J.J.; Daneva, M.; Abhishta, A. Industry 4.0 and healthcare: Context, applications, benefits and challenges. *IET Softw.* **2023**, *17*, 195–248. [\[CrossRef\]](#)
9. Veiga, R.; Morais, R.; Bastos, L.; Rosário, D.; Guidoni, D.L.; Cerqueira, E. Bio-Signal Multistream Architecture Classification for Federated Learning. In *2025 21st International Conference on Distributed Computing in Smart Systems and the Internet of Things (DCOSS-IoT)*; IEEE: New York, NY, USA, 2025; pp. 625–632. [\[CrossRef\]](#)
10. Albert, M.; Rowland, P.; Friesen, F.; Laberge, S. Barriers to Cross-Disciplinary Knowledge Flow: The Case of Medical Education Research. *Perspect. Med. Educ.* **2022**, *11*, 149–155. [\[CrossRef\]](#) [\[PubMed\]](#)
11. Vidal Silva, C.; Pavesi Farriol, L. Desarrollo de un sistema de adquisición y tratamiento de señales electrocardiográficas. *Rev. Fac. Ing.-Univ. Tarapacá* **2005**, *13*, 39–46. [\[CrossRef\]](#)
12. Vidal Silva, C.; Gatica Rojas, V.; Alegría León, D.; Arce Lillo, P. Mejoramiento de algoritmo clásico de detección de complejos QRS en señal electrocardiográfica. *Ingeniare. Rev. Chil. Ing.* **2010**, *18*, 176–182. [\[CrossRef\]](#)
13. Rahman, M.M.; Rimón, M.A.H.; Hoque, M.A.; Sammir, M.R. Affordable Smart ECG Monitoring Using Arduino & Bluetooth Module. In *Proceedings of the 2019 1st International Conference on Advances in Science, Engineering and Robotics Technology (ICASERT)*; IEEE: New York, NY, USA, 2019; pp. 1–4. [\[CrossRef\]](#)
14. Lai, Y.H.; Su, K.; You, Y.Q.; Liang, Y.X.; Lan, L.; Lee, M.H.; Huang, F.; Chen, D.Q. Development of Arduino Based ECG Device for STEM Education and HRV Applications. In *Proceedings of the 2022 8th International Conference on Control, Automation and Robotics (ICCAR)*; IEEE: New York, NY, USA, 2022; pp. 329–333. [\[CrossRef\]](#)
15. Joukar, S. A comparative review on heart ion channels, action potentials and electrocardiogram in rodents and human: Extrapolation of experimental insights to clinic. *Lab. Anim. Res.* **2021**, *37*, 25. [\[CrossRef\]](#) [\[PubMed\]](#)
16. Möller, T.J.; Wunderwald, M.; Tünnte, M. Real-Time ECG Analysis with the ArdMob-ECG: A Comparative Assessment. In *Machine Learning Applications in Medicine and Biology*; Ahmed, A., Picone, J., Eds.; Springer: Cham, Switzerland, 2024. [\[CrossRef\]](#)
17. Borgquist, R.; Marinko, S.; Platonov, P.G.; Wang, L.; Chaudhry, U.; Brandt, J.; Mörtzell, D. Maximizing QRS Duration Reduction in Contemporary Cardiac Resynchronization Therapy Is Feasible and Shorter QRS Duration Is Associated with Better Clinical Outcome. *J. Interv. Card. Electrophysiol.* **2023**, *66*, 1799–1806. [\[CrossRef\]](#) [\[PubMed\]](#)
18. Vidal-Silva, C.; Lineros, M.I.; Uribe, G.E.; Olmos, C.J. Electrónica para Todos con el Uso de Arduino: Experiencias Positivas en la Implementación de Soluciones Hardware-Software. *Inf. Tecnológica* **2019**, *30*, 377–386. [\[CrossRef\]](#)
19. Chang, H.T.; Wu, H.H.; Chang, Y.T. Evaluating Learning Outcomes by Applying Interdisciplinary Hands-On Learning to Advanced Technology Courses. *Innov. High. Educ.* **2023**, *48*, 619–636. [\[CrossRef\]](#)
20. May, D.; Terkowsky, C.; Varney, V.; Boehringer, D. Between hands-on experiments and Cross Reality learning environments – contemporary educational approaches in instructional laboratories. *Eur. J. Eng. Educ.* **2023**, *48*, 783–801. [\[CrossRef\]](#)
21. Vidal Silva, C.; Gatica Rojas, V. Diseño e implementación de un sistema electrocardiográfico digital. *Rev. Fac. Ing.* **2010**, *53*, 99–107. [\[CrossRef\]](#)

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