

CardioTattoo: Unlocking Continuous ECG from Commercial Smartwatches with Ultrathin Graphene Tattoos

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This paper introduces CardioTattoo, a system that enables continuous ECG monitoring from commercial smartwatches using ultrathin graphene electronic tattoos. While smartwatches like the Apple Watch bring medical-grade ECG hardware to over 100 million wrists, they require users to stop, touch the crown, and wait 30 seconds for each reading—making continuous monitoring impossible. CardioTattoo overcomes this limitation through the *CardioTattoo principle*: rather than fighting the instability of textile-skin electrode interfaces, we relocate it to a motion-robust metal-metal junction. An imperceptible graphene tattoo (300nm thick) conforms to the skin and connects via a thin gold interconnect to a textile electrode on a garment's elastic cuff, routing the signal to the opposite wrist where the smartwatch completes the circuit. In head-to-head comparison on unmodified Apple Watches, CardioTattoo achieves 93% measurement success during walking versus 82% for manual crown touch, with around 2× tighter agreement to ground truth. Across nine daily activities with 15 participants, timing-based ECG metrics remain within clinical thresholds (20ms), and longitudinal deployment over 6–8 hours demonstrates sustained performance: >96% R-peak detection, >80% ECG availability, and 1.42ms HRV error. A formative survey (N=99) confirms user acceptance, with 84% willing to adopt an imperceptible tattoo compared to just 6% for gel electrodes or chest straps, and study participants rated the system above 8/10 across all usability dimensions, including comfort, unobtrusiveness, and willingness to wear.

CCS Concepts: • **Hardware** → **Emerging interfaces**; • **Computer systems organization** → **Sensors and actuators**; • **Human-centered computing** → **Ubiquitous and mobile computing**; • **Applied computing** → **Consumer health**.

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1 INTRODUCTION

Today's ECG monitoring landscape is divided into two categories of devices. On one side are episodic devices designed for convenience: smartwatches like the Apple Watch bring medical-grade ECG hardware to over 100

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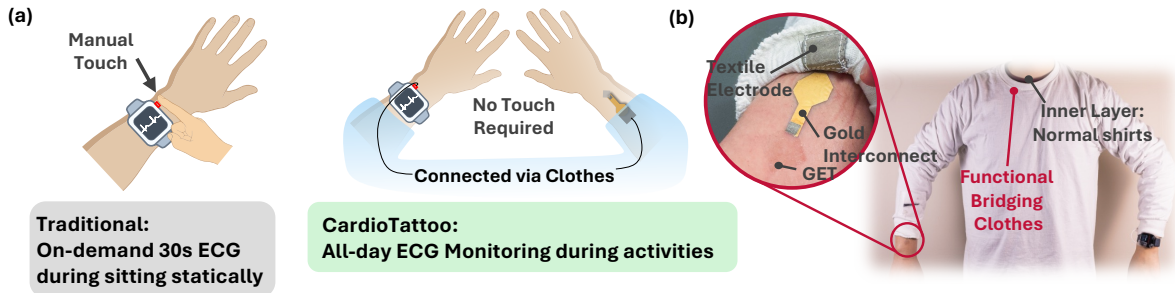


Fig. 1. Overview of CardioTattoo. (a) Compared to the traditional ECG monitoring via on-demand manual touch on a smartwatch, CardioTattoo re-purposes the ECG function in a commercial smartwatch for high-quality automatic monitoring. (b) Demonstration of CardioTattoo's system, including a smartwatch (commercial or research-purpose), a bridging shirt housing the connects, a textile electrode contacts with a gold tape, and a graphene tattoo covering both the skin and the gold tape. This system is compatible with commercial watches and enables automatic ECG monitoring without modifying their internal hardware and software. It is also compatible with other normal daily clothes, e.g., a shirt underneath.

million wrists worldwide, but require users to sit still, touch the crown, and wait 30 seconds for a single reading. On the other side are continuous devices designed for clinical observation: Holter monitors, adhesive chest patches, and ECG-enabled chestbands can record for days or weeks, but require dedicated hardware that users must obtain, wear, and maintain separately from devices they already own [7, 21]. While the clinical value of continuous monitoring is well established — it can catch transient arrhythmias that spot-checks miss, including atrial fibrillation that significantly increases stroke risk [3, 74] — patients today face a binary choice: convenient but episodic, or continuous but cumbersome.

This raises a natural question: *can we achieve continuous ECG monitoring using the same smartwatch hardware that hundreds of millions of people already wear?* The advantage of this model is that we can leverage the existing user base for smartwatches whose ECG circuit is already fully capable of continuous operation. The back electrode maintains contact with the left wrist throughout the day; what the crown-touch interaction provides is simply a second electrode contact point on the right side of the body to complete the measurement circuit. So, instead of designing a different hardware platform for continuous monitoring, we need only establish a persistent second contact point and route the signal back to the watch.

This raises a follow-on question — where should we place the second electrode? If we place it on the chest or other locations on the torso, we lose the convenience advantage of consumer wearables that we would like to preserve. Instead, if we can just use the other wrist for this second electrode, then we utilize a location where people already wear things without a second thought.

Why the wrist is hard. But the wrist is hostile territory for electrodes. Arm movements during daily activities are far more dramatic than chest movements, producing frequent and large mechanical disturbances at the electrode-skin interface. The ECG signal amplitude at the wrist is inherently smaller than at the chest due to the distance from the heart, so the signal-to-noise ratio is lower. In addition, unlike chest-mounted devices that are hidden under a shirt, a wrist electrode is exposed during social interaction, making it essential that the electrode is as unobtrusive as possible. This precludes the use of clinical-grade gel electrodes that offer excellent signal quality but are unacceptable for something completely unobtrusive. What we need is an electrode so unobtrusive that users forget it exists: lightweight enough to be imperceptible, transparent enough to be invisible, and comfortable across the full range of daily activities.

Previous attempts at wrist-based continuous ECG have struggled because of these constraints. Textile electrodes integrated into clothing offer comfort but create electrically unstable interfaces with the skin. Arm movements

cause the fabric to rub against the skin surface, producing dramatic swings in contact impedance that manifest as motion artifacts that drown out the cardiac signal. This is why commercial ECG shirts require tight compression garments and still struggle with motion, and why textile-based wrist electrodes have shown poor signal quality in prior work [65]. The standard response has been to engineer better skin-contact electrodes through improved materials, tighter fits, and conductive gels. But this compromises convenience.

The CardioTattoo principle. Our work takes a different approach: rather than fighting the instability of the skin-electrode interface, we relocate it. The core insight is that not all interfaces are equally fragile. A textile-skin interface is capacitive and motion-sensitive because charges cannot pass freely between the conductor and the electrolyte; any mechanical disturbance produces large transient voltages that overwhelm the microvolt-scale ECG signal. A metal-metal interface, by contrast, is predominantly resistive—actual charge transfer occurs between the two conductors. This makes metal-metal contacts far more tolerant of motion; changes in contact area or pressure produce proportionally smaller impedance variations.

We exploit this asymmetry through a simple architectural choice. We place an ultrathin graphene electronic tattoo (GET, 300nm thick—approximately 1/300th the thickness of a human hair) directly on the skin, connected to a thin gold interconnect that extends to the edge of the wrist. On the garment’s elastic cuff, a conductive textile pad makes contact with this gold interconnect. The tattoo conforms intimately to skin topology and remains mechanically coupled to the skin during movement, maintaining a stable interface. The potentially unstable interface between gold interconnect and textile is now metal-to-metal, which makes it resistive, tolerant of motion, and far less demanding on contact conditions.

In effect, we have *relocated* the instability from a fragile, motion-sensitive skin-electrode contact to a robust metal-metal interface that can absorb mechanical variation without corrupting the signal. This trick now makes the wrist tractable as an ECG sensing location.

Our approach. We present CardioTattoo, a system that unlocks continuous ECG from commercial smartwatches through the CardioTattoo principle. As Figure 1 illustrates, our system uses a full-sleeve garment with conductive thread sewn through the fabric, connecting the watch crown on one wrist to a small textile electrode at the opposite cuff. The user applies the graphene tattoo to their right wrist (similar to applying a temporary tattoo), then puts on the shirt and watch as usual. The natural pressure of the elastic cuff maintains contact between the textile electrode and the tattoo, completing the circuit. From that point on, continuous ECG monitoring proceeds automatically without requiring any manual touch or active user involvement.

Removal is equally straightforward. The tattoo leaves only an imperceptible film on the skin, which means no adhesive residue to clean and no electrodes to peel off. Also, the electrical connection relies solely on the natural pressure between cuff and wrist, so ending a monitoring session requires nothing more than taking off the shirt.

Formative survey. A formative online survey (N=99 valid respondents), approved by the Institute Review Board (IRB), confirmed strong user demand for this approach. When asked to compare different continuous heart monitoring methods, 84% of participants expressed willingness to use an imperceptible daily tattoo, compared to just 6% for gel electrodes or tight-fit chest straps which are the current standards for ambulatory ECG (Table 1). Participants rated comfort (83% “very important”) and function during all activities (82%) as their top priorities, with invisibility and low daily maintenance also ranking highly. Notably, willingness increased sharply with perceived health risk: 96% expressed willingness if a doctor recommended monitoring after detecting an irregular ECG. These findings guided our design toward a system that prioritizes imperceptibility and seamless integration with everyday wearables. More details are in Appendix A.

Results. We validate CardioTattoo through extensive evaluation spanning controlled benchmarks, user studies, and longitudinal deployment. In head-to-head comparisons with textile-only electrodes under controlled motion, our CardioTattoo approach reduces ECG metric errors by more than 10× across PR interval, QTc, and heart rate variability measurements. When integrated with unmodified Apple Watches, CardioTattoo achieves higher

Table 1. User preference for continuous heart monitoring methods (N=99). Participants strongly favored imperceptible approaches over clinical alternatives, despite the latter's superior signal quality.

Monitoring Method	Likely to Adopt	Neutral	Unlikely to Adopt
Ultrathin invisible tattoo (this work)	83.8%	10.1%	6.1%
Manual crown touch 5×/day	70.8%	15.1%	14.1%
Tight-fit chest strap	6.1%	13.1%	80.8%
Sticky gel electrodes (daily replacement)	6.1%	7.0%	86.9%

Note: "Likely" combines "very likely" and "somewhat likely" responses; "Unlikely" combines "somewhat unlikely" and "very unlikely" responses; "Neutral" includes "neither likely nor unlikely".

measurement success rates during walking than manual crown touch (93% vs. 82%), with better signal quality and tighter agreement with ground-truth chest-based ECG. CardioTattoo therefore eliminates the need for manual crown contact, enabling hands-free operation while matching or exceeding the performance of conventional smartwatch-based sensing.

In studies simulating daily activities such as typing, eating, household tasks, leisure, and sleep postures, CardioTattoo maintains mean absolute errors well below clinical thresholds (20ms for ECG timing metrics, 2ms for HRV) across most conditions. A longitudinal deployment over 6–8 hours of natural, unscripted activity demonstrates sustained performance: greater than 96% R-peak detection accuracy, greater than 80% ECG segment availability, and HRV measurements within 1.42ms mean absolute error of chest-band ground truth across activities including desk work, phone use, eating, and light exercise.

Our main contributions are:

- We introduce the CardioTattoo paradigm for wearable bio-potential sensing, demonstrating that interface instability can be strategically relocated from fragile skin-electrode contacts to robust metal-metal interfaces. This design yields substantial improvements in motion tolerance, achieving up to 33 dB lower impedance variation and 10× lower error in ECG metrics under motion compared to a textile electrode.
- We present the first system enabling continuous, automatic ECG monitoring from commercial smartwatches without hardware or software modification, using an imperceptible graphene tattoo and clothing-integrated conductive pathway. Participants wearing our system in the study rated the system highly, reporting 9.3/10 comfort, 9.1/10 willingness to wear, and 9.6/10 preference over traditional gel electrodes.
- We provide comprehensive evaluation across controlled benchmarks, structured user studies (N=15), and longitudinal in-the-wild deployment, demonstrating that CardioTattoo maintains clinical-grade accuracy across diverse daily activities, with overall errors below 20 ms for ECG metrics and below 2 ms for HRV metrics.
- We characterize the design space through large-scale user preference studies (N=99), identifying acceptance thresholds and practical deployment considerations for tattoo-based wearable sensing. Notably, 84% of the respondents were likely to adopt CardioTattoo daily, compared to only 6% for chestbands or gel electrodes.

2 RELATED WORK

CardioTattoo repurposes existing smartwatch ECG hardware for continuous monitoring by introducing a novel electrode architecture that relocates interface instability from the skin to a motion-robust metal-metal contact. Table 2 summarizes how this approach compares to prior work in cardiac monitoring systems and electrode technologies; the remainder of this section details the gaps in each domain that motivate our design.

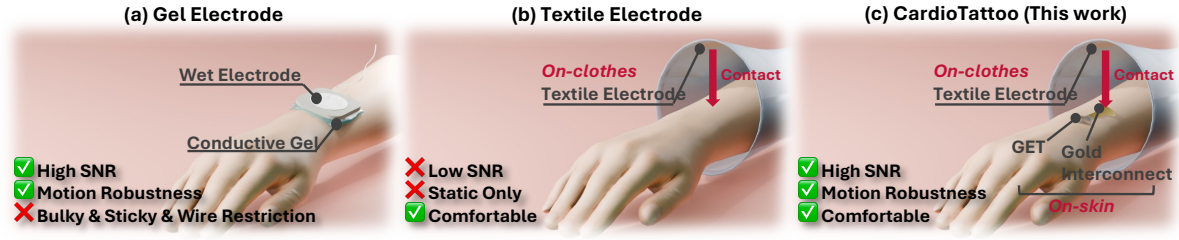


Fig. 2. Demonstration and Comparison between possible electrode solutions for on-wrist ECG monitoring: (a) gel electrodes, (b) textile electrodes, and (c) CardioTattoo. CardioTattoo combines the advantages of the other two electrode types, providing a sensitive, comfortable ECG with motion robustness.

Table 2. Comparison of related work vs CardioTattoo.

		System					Evaluation		
		Area	Signal Source	Cont.	Wearable Compatibility	Electrode Comfort	Granularity	In-Activity ECG Evaluation	Longitudinal Study
Commercial	Smartwatch	Wrist	Bio-potential	No	Yes (itself)	Dry	Wave Detail	None	Yes [3]
	ECG Patch	Chest	Bio-potential	Yes	No (standalone device)	Wet	Wave Detail	During Activity [9]	Yes [7, 21, 52]
	ECG Chestband	Chest	Bio-potential	Yes	No (special chestband)	Dry	Wave Detail	During Activity [51]	Yes [83]
	ECG Shirt	Chest	Bio-potential	Yes	No (special shirt)	Dry	Wave Detail	During Activity [68]	Yes [20]
Research	ECG Necklace [89]	Chest	Bio-potential	Yes	No (special necklace)	Dry	Wave Peak	None	Yes (8-hour in-the-wild study)
	Kim et al [41]	Gluteal	Capacitance	Yes	No (not wearable)	Isolated (very close to skin)	R-peak	None	No
	Heartquake [71]	Whole Body	Mechanical (estimated ECG from geophone)	Yes	No (not wearable)	No Electrode Required	Wave Detail	During Activity (mild only)	Yes (5-hour sleep study)
	Wang et al [86]	Chest	Mechanical (estimated ECG from UWB)	Yes	No (not wearable)	No Electrode Required	Wave Detail	None	No
	Cao et al [10]	Wrist	Mechanical (estimated ECG from IMU)	Yes	Yes (smartwatch)	No Electrode Required	Correlation w/ Ground Truth	During Activity but w/ high error	Yes (24-hour in-the-wild study)
	This work	Wrist	Bio-potential (Direct ECG)	Yes	Yes (smartwatch and other daily clothes)	Ultrathin Dry (skin-conformal)	Wave Detail	During Activity	Yes (Fine-grained 7-hour in-the-wild study)

2.1 Continuous Ambulatory ECG Monitoring

As noted earlier, ECG monitoring devices fall into two broad classes: continuous systems designed for clinical observation, and episodic systems designed for convenience.

Continuous chest-based systems. Holter monitors [13, 27, 62] have long served clinical needs through gel electrodes wired to a chest-mounted unit, capturing 24–48 hours of ambulatory ECG for detecting transient arrhythmias. More recently, adhesive chest patches [33, 34] and dry-electrode chestbands [17, 23] have reduced form factor while preserving continuous measurement capability [5, 21, 38]. ECG-sensing shirts [31, 63] and smart necklaces [73, 89] further integrate monitoring into wearable garments. These systems prioritize chest placement for its signal advantages such as stronger amplitude and better motion-artifact rejection, but at the cost of dedicated hardware that users must obtain, wear, and maintain separately. Discomfort is also common: chestbands require a tight fit, patches are sticky and leave residue, ECG shirts preclude undergarments, and necklaces require low-necked clothing [15].

Episodic wrist-based systems. Commercial smartwatches, including the Apple Watch [30] and Google Pixel Watch [32], have brought single-lead ECG to the wrist with validated atrial fibrillation detection [3]. However, these devices require manual crown touch and a stationary posture for each 30-second reading, so they only provide an episodic spot-check.

Infrastructure-based alternatives. A separate line of work explores ambient sensing for user-unaware monitoring, embedding ECG or cardiac-correlated sensing into beds [71], toilet seats [41], chairs [50], and

room-scale systems using mmWave radar [90] or ultra-wideband signals [86]. While these eliminate wearable burden, they can only monitor in specific locations and often only in controlled postures, so they do not provide a reliable continuous ECG for clinical use.

What has not been studied is whether the smartwatch hardware that hundreds of millions of people already wear daily can be transformed from a spot-check device into a continuous monitor.

2.2 The Electrode Challenge at the Wrist

Transforming smartwatches into continuous monitors requires solving an electrode problem that is particularly acute at the wrist. The second electrode must maintain stable electrical contact with the skin throughout daily activities, deal with high motion amplitude, while also being aesthetically appealing and imperceptible.

Textile and polymer electrodes. These electrodes offer natural integration with clothing and are flexible enough to conform to curved body surfaces [1, 65]. However, they are thick and, as a result, create air gaps between fabric and skin that produce high and variable contact impedance. Achieving acceptable signal quality requires tight compression against the skin and extended wetting time to stabilize the interface [88]. Under motion, the fabric-skin contact shifts constantly, producing impedance fluctuations that manifest as severe baseline wander and motion artifacts. Existing textile-electrode ECG systems on the chest [31, 63] mitigate this through tight garment fit, chest placement, and large electrode sizes, where signals are stronger and arm motion has less effect. These methods do not apply at the wrist: the arm moves far more than the torso, tight compression around the wrist is uncomfortable for extended wear, and the wrist area is limited.

Rigid dry electrodes. Metal plate electrodes of the type used in commercial EMG wristbands and the smartwatch crown itself [30, 61, 70] are easy to manufacture and integrate but have high, unstable skin-electrode impedance due to poor conformability to the skin surface [53, 88]. Micro-needle electrodes [77, 85, 92] can reduce impedance by penetrating the stratum corneum, but are invasive and risk inflammation. Capacitive electrodes [4, 64] avoid direct skin contact but are low in signal-to-noise ratio and highly susceptible to motion artifacts, making them less appropriate for high-motion wrist movement.

The fundamental issue is that dry electrodes behave as polarizable interfaces where charge transfer occurs capacitively rather than through direct current flow [88]. Any mechanical disturbance, including skin stretching, electrode sliding, and contact pressure variation, changes the charge distribution at the interface, producing large transient voltages that overwhelm the microvolt-scale ECG signal. Wet gel electrodes (Ag/AgCl) approach non-polarizable behavior and are the clinical gold standard for this reason [26, 82], but their adhesive gels cause discomfort, skin irritation, and residue that make them unsuitable for daily wearable use [19, 54]. In addition, they are noticeable and unacceptable for unobtrusive wrist wear.

The gap and GET as solution. Across all of these approaches, a common pattern persists: each treats interface instability as an obstacle to be minimized at the point of skin contact through improved materials, tighter fits, or conductive gels. Graphene electronic tattoos (GETs) offer a partial solution—their ultrathin profile (approximately 300nm, more than 1000× thinner than typical dry electrodes) enables conformal contact with skin microstructure, providing stable impedance that thicker electrodes cannot match [35, 45, 57]. Among e-tattoo materials, graphene has attracted particular attention for biopotential sensing due to its sub-micron thickness [66], high electrical conductivity [8], mechanical flexibility [22], and biocompatibility [75]. Yet prior GET work has required rigid wires secured with conductive paste, tethering users to laboratory equipment and negating the unobtrusiveness that makes GETs attractive in the first place. The open problem is how to leverage GET conformability for a practical, untethered wrist ECG.

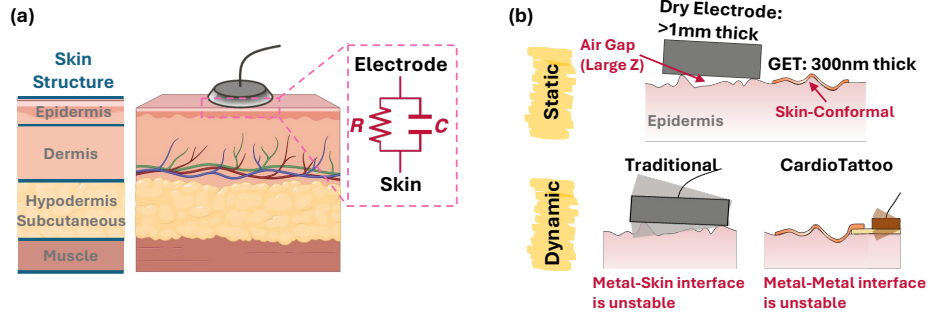


Fig. 3. Fundamentals and principles of CardioTattoo. (a) Skin structure and modeling of electrode-skin interface in circuit perspective¹. (b) Comparison between CardioTattoo and traditional dry, rigid electrodes in both static and dynamic scenarios, showing the mechanism that enables CardioTattoo with improved performance.

3 THE CARDIOTATTOO PRINCIPLE

The previous section identified a gap: graphene tattoos provide the skin-conformal interface that wrist-based ECG requires, but connecting them to external circuitry without wires and paste remains unsolved. This section presents the architectural insight that resolves this challenge.

3.1 Electrochemical Basis

Let us start by looking at the function of an electrode. It serves as a transducer, converting ionic current in the body's electrolyte into electronic current in a circuit. This electrode-electrolyte interaction behaves like a half-cell battery system. When current flows, polarization occurs at the interface, altering the equilibrium potential by an amount known as the overpotential:

$$V_p = E^0 + V_{over}$$

where V_p is the observed potential, E^0 is the zero-current half-cell potential, and V_{over} reflects the collective effect of ohmic, concentration, and activation overpotentials. The concentration and activation components exhibit capacitive characteristics—charges accumulate at the interface rather than passing freely through it.

This electrochemistry divides electrodes into two categories. *Nonpolarizable* electrodes (closer to ideal resistors) allow charges to pass via redox reactions, producing minimal overpotential and thus minimal motion artifacts. Wet electrodes like Ag/AgCl approximate this behavior, which is why they remain the clinical gold standard. *Polarizable* electrodes (closer to ideal capacitors) accumulate charge at the interface; any disturbance in contact conditions causes dramatic impedance changes that contaminate the signal. Dry electrodes—including the metal plates in smartwatches and the textile electrodes used in wearable garments—fall into this category.

Figure 3(a) depicts the equivalent circuit model of the skin-electrode interface: a resistor and capacitor in parallel, with frequency- and current-dependent behavior that matches real-world observations [60, 88]. The capacitive component is the source of motion artifacts. When the electrode shifts against the skin, the contact area changes, the pressure distribution changes, and the charge distribution at the interface is disturbed. The result is a spike in impedance, often orders of magnitude, that drowns the ECG signal in noise.

3.2 The CardioTattoo Insight

CardioTattoo takes a different approach: rather than fighting the instability of the skin-electrode interface, we *relocate* it. The core insight is that not all interfaces are equally fragile. A metal-skin interface is capacitive

¹Figure(s) partially created in BioRender. Lei, Z. (2026) [<https://BioRender.com/udaexye>]

and motion-sensitive because charges cannot pass freely between the conductor and the electrolyte. A metal-metal interface, by contrast, is predominantly resistive, i.e. actual charges transfer between the two conductors. This makes metal-metal contacts far more tolerant of motion; changes in contact area or pressure produce proportionally smaller impedance variations, and the variations that do occur are less capacitive.

CardioTattoo exploits this asymmetry through a simple architectural choice. As Figure 3(b) illustrates, we place an ultrathin graphene electronic tattoo (GET) directly on the skin of the right wrist. At 300nm thick, the GET is more than 1000× thinner than conventional dry electrodes (>1mm). This extreme thinness, combined with the substrate's mechanical flexibility, allows the tattoo to conform intimately to the skin surface according to Euler-Bernoulli beam theory [47, 55], thereby eliminating the air gaps that present problems with rigid electrodes and ensuring that the tattoo moves *with* the skin rather than sliding against it.

The tattoo connects to a thin, flexible gold interconnect that extends to the edge of the skin. On the garment's elastic cuff, a conductive textile pad makes contact with this gold interconnect. The natural pressure between an elastic cuff and the arm secures this connection without requiring wires, adhesives, or mechanical fasteners. A conductive thread, together with an ultrathin micro coax cable, sewn through the garment, then routes the signal to the smartwatch electrode on the opposite wrist, completing the circuit.

Figure 3(b) also contrasts the two approaches in static and dynamic scenarios. In static conditions, the GET's conformality eliminates air gaps and reduces contact impedance compared to rigid electrodes. In dynamic conditions, traditional electrodes experience dramatic capacitance variations as the metal-skin interface shifts; CardioTattoo's metal-metal interface experiences primarily resistive variations of much smaller magnitude. Section 4.5 validates this principle quantitatively, demonstrating up to 33dB improvement in capacitive stability under controlled motion.

3.3 Architectural Distinction from Conventional Electrodes

These gains come from geometry, not from a new sensing principle. Electrochemically, the GET is a standard polarizable dry electrode of the same family as the metal plates in smartwatches and the textile electrodes in instrumented garments; the transduction mechanism is identical to the one in §3.1. But at 300nm, the tattoo is thin enough to track skin microtopography rather than sit on top of it, eliminating the air gaps and contact-pressure dependence that drive motion artifacts in rigid dry electrodes.

However, the skin-side interface is only half the problem. A wire connecting the tattoo to readout electronics would re-introduce the mechanical loading that any tethered skin electrode imposes, undoing the comfort gain. CardioTattoo's contribution is therefore the connection architecture. An on-skin gold interconnect plus a textile pad on the garment cuff replaces the wire, leaving metal-to-metal as the only motion-sensitive contact. Section 4.5 validates that this contact is far more tolerant of motion than the skin-electrode interface that it replaces.

A useful property of the split architecture is that it extends beyond graphene. Any sufficiently thin and flexible conductor would serve the same role; we chose graphene because its atomic thickness meets the conformality requirement easily. CardioTattoo's novelty, relative to prior electrode designs (Figure 2), lies in the split rather than the material.

4 SYSTEM DESIGN

4.1 System Challenges

Translating the CardioTattoo principle into a practical system raises three challenges:

- (1) *Tattoo Design*: The graphene tattoo and gold interconnect must be highly conductive and mechanically robust against real-world interference such as tearing and stretching, while remaining thin enough to be flexible and skin-conformal. Transferring such a delicate structure onto the skin must also be simple and reliable enough for daily consumer use, comparable to applying a contact lens.

- (2) *Signal Routing*: The electrical signal at the tattoo must travel to the watch on the opposite arm, routing through the garment across the body. This requires stable contact at the gold-textile interface with uniform pressure across activities, as well as low-loss signal propagation, all while retaining the softness and flexibility of normal clothing.
- (3) *Signal Processing*: Existing ECG delineation algorithms are optimized for static, chest-based signals and degrade substantially on wrist-based ECG under motion, particularly for QRS onset detection. Extracting reliable cardiac metrics from CardioTattoo requires a processing pipeline adapted to these conditions.

4.2 Tattoo Design

For practical daily use, graphene tattoos must be easy to apply and skin-conformal, while remaining robust against common mechanical interference. We designed our tattoo structure and fabrication procedure to meet these requirements.

4.2.1 Sensor Structure and Working Principle. Graphene electronic tattoo (GET) is an ultrathin, skin-conformal bioelectronic interface that leverages the atomic thickness and high conductivity of graphene to achieve stable electric contact. It conforms to the microscale roughness of human skin, enabling conformal adhesion and minimizing motion artifacts. A single layer of graphene tends to have flaws, so we combined two layers to improve integrity and conductivity, as suggested by [44]. Therefore, even if flaws exist (i.e. holes or cracks that are not conductive) in one layer, the current can still propagate through the other, improving the robustness against localized failure.

Graphene has a Young's modulus of 10^{12} Pa [91], making it too rigid to deform comfortably with the skin. To improve robustness and flexibility while retaining an ultrathin profile, we integrated a flexible poly(methyl methacrylate) (PMMA) membrane as a support layer to absorb strain and stress. As shown in Figure 4, the overall thickness is approximately 300nm, enabling good skin conformability. We also patterned small holes into the GET to improve breathability and prevent sweat accumulation. Figure 5 shows the layout: $50 \times 100 \mu\text{m}$ triangular holes on a 1 mm pitch, following the design of [44]. The reported water-vapor evaporation rate of this pattern is comparable to uncovered skin and substantially higher than a holeless GET. The holes manage a tradeoff in sweat: excess sweat compromises the tattoo's mechanical adhesion, while a small amount actually improves skin-tattoo conductivity through ionic conduction.

A temporary tattoo paper was used as the transfer substrate due to its multilayer polymer structure and reversible adhesive behavior for transferring to the skin. This tattoo paper consists of a cellulose backing coated with a water-soluble polyvinyl alcohol (PVA) layer and an intermediate resin layer composed of polyamide, polyallyl, and polyurethane polymers. Initially, the PVA layer was removed by brief immersion in the water. The underlying resin layer exhibits adhesive behavior when it is dry, and becomes lubricious when wet, enabling controlled release of the tattoo on top of it.

When transferring to the skin, a GET with the tattoo paper was first immersed in water for at least 10 minutes to activate release. It was then removed from the water using a tweezer and placed on a water-absorbing non-woven tissue to remove extra water. Later, it was put on the skin with the graphene side down. A finger pressed the back of the tattoo paper and slowly slid on top of the skin. The lubricious property of the wet tattoo paper helped release the GET membrane without much hindrance and left it conformally on the skin. A GET can usually dry within 30–60 seconds. This procedure is easy to execute even for non-experts, as only a water tank, a tweezer, and a tissue are required. We expect that as technology evolves, the process will become as simple as a commercial temporary tattoo. The removal procedure of the tattoo is even easier in our design: simply rubbing against the skin with water. This avoids the use of organic solvent that may be stimulating and harmful to human's skin. There is also no involvement of sticky glues that can be annoying to remove. In our experiments, we observed no skin irritation, damage, allergic reaction, or redness directly from the tattoo. This is consistent with prior reports

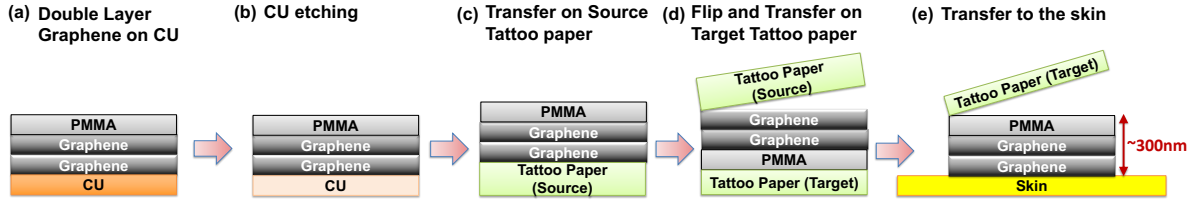


Fig. 4. Fabrication and transfer procedure of GET.

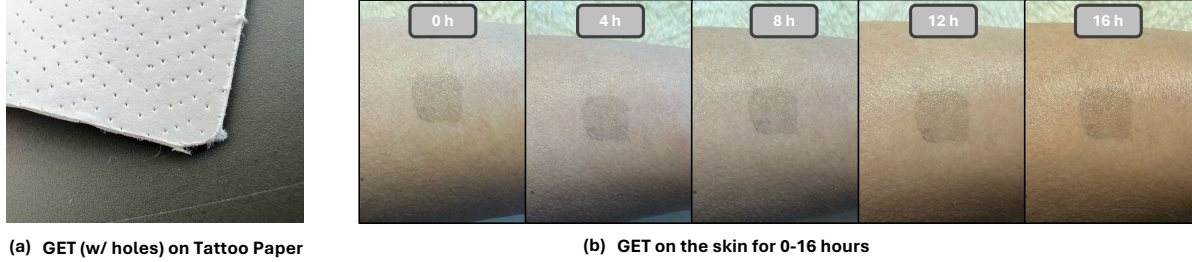


Fig. 5. (a) GET with holes on a tattoo paper. The tattoo (in light gray) is ultrathin and almost invisible on the paper. These holes were designed for breathability and sweat draining. (b) GET on skin for 16-hour long-form biocompatibility test, showing no observable skin redness.

on GET [43, 45]. As an additional check, Figure 5(b) shows a 16-hour wear test with hourly skin inspection, again with no redness observed.

For electrical interfacing, a soft gold interconnect (tape) was placed on top of the skin, with its rectangular end covered by a double-sided conductive tape to secure the graphene under external mechanical interference. The GET is then transferred to cover both the skin and this conductive tape, connecting these two parts electrically through the conductive graphene layer. Notably, only a small corner of the GET covered the tape to provide connectivity while alleviating too much stretching from the gold.

4.2.2 Fabrication. To make the GETs, we used the high-quality monolayer graphene synthesized on copper foil using chemical vapor deposition (CVD). To support graphene during copper removal, the graphene/copper foil was encapsulated with poly(methyl methacrylate) (PMMA) by spin coating around 200 nm PMMA layer (950 A4) at 2,500 rpm for 60 seconds, which was then cured at 200 °C for 15–20 min (see Figure 4(a)). Following this, as in Figure 4(b), the PMMA+Graphene+Copper was placed on a solution of 0.1 mol/L ammonium persulfate ($(\text{NH}_4)_2\text{S}_2\text{O}_8$) for 8–12 hours to etch the copper. A temporary tattoo paper (Silhouette Cameo), working as "Source", was then cut and employed to transfer the PMMA/Graphene stack on top of it (Figure 4(c)). A separate tattoo paper, working as "Target", was then prepared, where the PMMA/Graphene stack on the Source tattoo paper was transferred again (Figure 4(d)). This makes the graphene side exposed, ready for applying to the skin when in use. The original prepared tattoo had a dimension of around 40mm by 40mm. Patterning using a mechanical cutter plotter (Silhouette Cameo) was performed to cut it to smaller sizes (15mm by 15mm in our case) and create holes. The devices were finally stored under ambient, dust-free conditions. We mainly followed the procedure in [43].

We built our own gold interconnects instead of purchasing directly from the market, as an ultrathin version is required to retain the skin conformability feature. Specifically, we evaporated a 100nm layer of gold on top of an adhesive polymer film (Iwatani, ISR-BSMK10G). The result was a gold tape with an overall thickness of only 10um, maintaining conformal on the skin. Similar to GET, it was first synthesized in a large form factor, and then



Fig. 6. Design and fabrication of CardioTattoo's customized bridging shirt, achieving appropriate contact with tattoos and smartwatches and low-loss signal propagation, without reducing the softness and flexibility of the garment.

cut into smaller, designed shapes. A small square of conductive tape (3M, 5113DFT) was finally placed on the end of the gold interconnect.

4.3 Connecting Tattoo to the SmartWatch

The ECG signal must travel from the tattoo on one wrist to the watch on the other; maintaining signal fidelity across the entire width of the body requires attention to three critical components: (1) Interface with the tattoo (gold). (2) Routing through the clothes. (3) Interface with the watch.

Cuff Design. The interface between the textile electrode and the gold interconnect requires consistent pressure — loose contact produces unstable impedance, while excessive pressure is uncomfortable and risks stretching the tattoo. We addressed this by modifying a standard long-sleeve shirt cuff as shown in Figure 6. We folded back the original cuff and attached a commercial silver-coated conductive textile pad (around 20 mm by 20 mm) (Adafruit) on the inner surface of the sleeve. This pad, serving as the textile electrode, was secured by ironing an iron-fusible fabric (LUTER, fusible interfacing fabric) in the middle, which melted under heat and steam and thus hooked the textile pad and the sleeve together firmly while preserving washability. The textile electrode was then connected with a high-conductivity, high-strength thread [84] (40 filament count; 4.5 Threads Per Inch (TPI)) sewn with straight stitch (stitch length=2.5mm, both sides secured by reverse stitching) by a commercial sewing machine (Brother, CS7000X). This exposed a usable electrode area in the middle of around 15 mm by 15 mm, same as the GET size we used. The same procedure was then applied to fix the folded cuff (straight stitch: stitch length=4.0mm, both sides secured by reverse stitching), 35 mm away from the end of the cuff.

We now have a good contact point with the tattoo; however, we also need appropriate pressure to secure the cuff on the wrist so it can contact the tattoo. For pressure regulation, we inserted a 25mm elastic band into the cuff's double-layer chamber, with velcro (Velcro Brand, Slek&Thin Stick-On Hem Tape) at both ends for adjustability. This allows per-participant tuning while maintaining uniform pressure around the wrist during wear. Figure 6 illustrates the construction.

Clothes Routing. The second challenge is that we have a long signal path spanning roughly 2 meters from wrist to wrist, which requires low-loss transmission without sacrificing the feel of the garment. Our solution uses the garment's existing seams to house the cables, since they are thick enough to hold the cables without deformation, can tolerate strong stretching across the clothes, and are unobtrusive. We used a micro coax cable (Alpha Wire, AWG 34; outer diameter=0.81mm) to transmit the signal through the clothes. This provides good

signal quality and moderate EMI isolation, while being thin enough to bend in small radius. As Figure 6 shows, we first punctured holes (diameter=1mm) on these seams with a fabric hole puncher for every 50 mm along the seam. Then, the micro coax were inserted into these holes in a running stitch style, which helps the fabric seams hold the cables while enabling moving back and forth freely—this is important in tuning and routing the cable through the entire clothes easily. Seams located near the neck and shoulder area are covered by an extra cloth for comfort. Instead of puncturing, we used the seam ripper to open the ends of this cloth to create a tunnel to route our cable. After routing across the shirt, the micro coax penetrated the fabric to reach the shirt’s outer surface, and was then anchored with loops. With these measures, it was secured on the shirt tightly while retaining flexibility and softness to avoid stretching.

Watch Interface. A key design goal is compatibility with commercial smartwatches without hardware modification. The interface must be conductive and robust for repeated use, yet removable so users can disable continuous monitoring when desired.

We achieve this through conductive tape rather than soldering or pasting, which would be difficult to remove cleanly. The approach exploits the fact that we need not modify watch software or hardware — we simply need the watch’s ECG circuit to register electrical contact as if a finger were touching the crown. A copper tape carries the signal from the garment’s conductive thread, with a flexible double-sided conductive tape (3M, 3304BC) on the contact end covering the crown and electrodes. This creates a low-impedance path connecting the watch electrodes to the tattoo on the opposite arm. The result is high conductivity without much signal distortion, and users can disable continuous monitoring simply by peeling off the tape.

4.4 Signal Collection and Processing

4.4.1 QRS Onset/Offset Detection. Standard ECG delineation algorithms such as Neurokit [58] and ECG-Kit [14, 59] were developed for chest-based signals collected under static conditions with clinical equipment. Wrist-based ECG during daily activities presents a harder problem: lower signal amplitude, less distinct Q waves due to electrode placement, and greater motion artifacts from arm movement. QRS onset (start of Q wave) detection is particularly affected because it lacks the sharp rising edge that makes R-peak detection robust; however, it is critical for the calculation of PR interval, QRS duration, and QTc.

We address this with a simple yet effective strategy: a narrow, zero-phase bandpass filter (7–35 Hz) emphasizes Q, R, and S peaks while suppressing P/T waves and motion artifacts, followed by zero-crossing detection on the third derivative within a 120 ms window from Q/S peaks. We first benchmarked this method on standard, clinician-annotated datasets (LUDB and QTDB) on chest-based ECG without motion. Various diseases were involved, such as abnormal heart rate, conduction abnormalities, extrasystolies, hypertrophies, abnormal cardiac pacing, and ischemia. Only Lead I records were considered as we focus on the wrist-based ECG. The results in Table 3 show that our method achieves top performance for QRS onset/offset detection, in comparison with representative methods from classical to state-of-the-art, with a standard deviation under the strict clinical standard from CSE [72]. The error is higher in QTDB due to inaccuracy and inconsistency in the manual annotations, as mentioned in [18, 25].

We then integrated our method into CardioTattoo’s ECG detection pipeline (details in the following subsection), and compared our method with other baselines on our dataset. Unlike the standard dataset, ours contained much more motion and were collected from the wrist. Instead of calculating the timing error between computer algorithm and clinician annotations as in the standard ones, in our dataset, we ran our algorithm on both the ground truth (ECG chestband) and data from CardioTattoo’s device, and calculate the timing error. This result reflects detection consistency and CardioTattoo’s agreement with ground truth, rather than absolute timing accuracy, and thus is not comparable to that on standard datasets.

Table 3. QRS onset/offset detection performance benchmarked on standard clean datasets with clinician-annotated fiducial points (LUDB [24, 37] and QTDB [24, 46], Lead I only), involving various cardiac diseases. A strict tolerance ($2\sigma_{CSE}$) is also provided as a reference for the standard deviation. Sensitivity (Se) and temporal error as mean $\pm$ standard deviation ($m \pm \sigma$) are reported. The result shows our QRS onset/offset detection method achieves top performance on ECG records without motion and from patients.

Method	Metric	QRS Boundary Detection on Lead I			
		LUDB [24, 37]		QTDB [24, 46]	
		QRS Onset	QRS Offset	QRS Onset	QRS Offset
This work	Se (%)	99.29	99.29	100.00	100.00
	$m \pm \sigma$ (ms)	2.82 ± 6.26	-1.08 ± 7.65	4.28 ± 9.45	-5.09 ± 9.09
ECG-Kit [14, 59]	Se (%)	99.73	99.23	99.06	98.74
	$m \pm \sigma$ (ms)	2.04 ± 8.13	-1.41 ± 8.54	8.62 ± 10.32	5.60 ± 10.09
NK (DWT) [58]	Se (%)	94.37	90.81	83.07	80.97
	$m \pm \sigma$ (ms)	-37.46 ± 19.52	15.82 ± 13.92	-57.25 ± 20.47	4.19 ± 15.12
Emrich et al [18]	Se (%)	99.40	99.23	99.48	98.79
	$m \pm \sigma$ (ms)	5.66 ± 6.93	-8.92 ± 8.28	4.81 ± 10.19	-26.53 ± 11.07
$2\sigma_{CSE}$ (ms) [72]		6.5	11.6	6.5	11.6

A full result of this is provided in Table 9 in Section 5.1.3, after our user study and dataset are introduced. The baselines now present more errors than in previous standard datasets. For hand- and finger-related activities, for example, Neurokit achieves QRS duration ($QRS_{\text{offset}} - QRS_{\text{onset}}$) error of 77.07 ± 30.33 ms and ECG-Kit achieves 21.38 ± 8.71 ms, both above the 20 ms threshold recommended for reliable ECG delineation [12, 80]. At this level of error, algorithm inaccuracy can wipe out any benefit from the other parts of CardioTattoo. Our method, by contrast, achieves QRS duration error of 3.24 ± 1.59 ms, lower than both traditional methods (NK, ECG-Kit) and recent algorithms such as Emrich et al. [18] (7.00 ± 1.89 ms).

4.4.2 Data Collection and Synchronization. After preparing the tattoos and the bridging shirt for routing, we connected them to the smartwatches (Apple Watch or ADI Study Watch). For the Apple Watch, we used its native ECG application and retrieved the raw ECG data via Apple Health. For the ADI Study Watch, we implemented a custom Python wrapper based on its API to continuously stream ECG data to a laptop in real time over Bluetooth Low Energy (BLE), with live visualization. The ECG signals were sampled at 512 samples per second (SPS) on the Apple Watch and 500 SPS on the ADI Study Watch.

During the study, we developed a graphical user interface (GUI) to prompt participants on the upcoming activities. As described in Section 5.1.3, we employed a counterbalanced design to randomize activity order across participants and mitigate carryover effects, resulting in four distinct activity sequences. At the start of each session, the GUI randomly selected one sequence and displayed a timer indicating the elapsed time in the current activity.

An ECG chestband designed for athletes (MoviSens ECG Move 4 [23]) was employed as the ground truth, since it provided a clean, robust recording under moderate motion. Because the chestband does not support real-time streaming or external triggering, its timestamps can drift dramatically from other devices. To address this, we asked the participants to jump five times quickly and aligned the corresponding peaks according to the acceleration channels in both the watch and the chestband, obtaining a mapping between the samples and the correct timestamps. We did such synchronization three times: once at the beginning, once in the middle, and once at the end. We then realigned the timestamps of the chestband samples to compensate for both absolute timestamp offsets and relative clock drift accumulated during the study.

4.4.3 ECG/HRV Calculation. We upsampled the raw ECG signals to 1024 samples per second (SPS) and applied a zero-phase 4th-order band-pass filter (BPF, 0.5–40 Hz), followed by a zero-phase 2nd-order notch filter centered at 60 Hz with a 2 Hz stopband. These preprocessed data were further split into different window sizes and saved together with time-synchronized chestband data (ground truth) for evaluation.

In ECG metric calculation, the preprocessed data were smoothed using a 4th-order Savitzky-Golay filter with a 50 ms window. For ECG R peak and QRS onset/offset detection, we further filtered the signal via a zero-phased 4th-order Butterworth BPF with a 7–35 Hz passband. The DWT algorithm in the Neurokit 2 library was employed to detect the R peaks, with detections near window boundaries and those producing impossible short R–R intervals (<200 ms) removed. To detect QRS onset, we began with searching for the first Q peak on the left of the R peak in a 120 ms window, adapted from [18]. If the Q peak was detected successfully, we looked for the first zero-crossing (negative-to-positive only) of the third derivative of the signal on the left of the Q peak in the same window length. QRS offset was detected symmetrically using the S peak. For other fiducial points essential for ECG metrics, including P onset, P offset, and T offset, the default ECG delineating algorithm in Neurokit 2 was employed. These detection algorithms were then integrated into our framework to generate per-beat fiducial point timing, which handled duplicate and missing events. All ECG metrics were finally computed as medians over 10 s windows.

For HRV analysis, we focused on RMSSD, which is suitable for short-term HRV assessment [81]. RMSSD was computed over the full activity duration (2 min, as mentioned in Section 5.1.3). R peak detection followed the same pipeline as in ECG, with additional outlier removal for healthy subjects: only R–R intervals between 500 ms and 1500 ms (40–120 bpm) were retained, and abrupt instantaneous HRV changes exceeding 100 ms were excluded. The ectopic beats were further removed using the Karlsson method [39], adapted from hrv-analysis python package [78]. Finally, HRV metrics were calculated with Neurokit 2 from these preprocessed signals.

For the longitudinal study, we added a signal-quality screening step to address in-the-wild noise. An aggregated signal quality index (SQI), combining signal standard deviation, kSQI, and the proportion of normal RRs, was computed for each 1 min window, and windows below an empirically chosen threshold were discarded. As a result, approximately 80% data met the quality criteria and were used to calculate the RMSSD across several hours.

4.5 System Benchmarks

The preceding sections argued that CardioTattoo relocates interface instability from a capacitive skin-electrode contact to a resistive metal-metal contact. Here we validate this principle through controlled experiments that isolate CardioTattoo’s advantages over textile-only electrodes — first under static conditions where garment fit varies, then under controlled motion where the resistive-versus-capacitive distinction matters most.

Static: Does CardioTattoo relax fit requirements? The first question we look at is whether CardioTattoo’s metal-metal interface tolerates looser fits that would degrade textile-only ECG performance.

To test this, we secured both electrode types at identical positions on the right forearm using a pressure-regulated armband (0 mmHg for loose fit, 45 mmHg for tight fit), with a standard 3M gel electrode (3M Red Dot 2670) providing a stable reference so that only one interface varied. Impedance was measured 60 times alternating between CardioTattoo and textile-only across both fit conditions at 10 kHz, using a handheld LCR meter (Keysight U1731C). ECG waveforms were recorded using a BioPac MP160 system (widely used gold standard for ECG), with a ground-truth channel (both ends gel electrodes) collected simultaneously; 960 seconds of data (approximately 1.2k ECG segments) were collected across all configurations.

Figure 7(a) shows the results. Under tight fit, CardioTattoo yields substantially lower impedance ($5.1\text{k}\Omega \pm 0.2\text{k}\Omega$) than textile-only ($29.3\text{k}\Omega \pm 4.2\text{k}\Omega$). The gap is even larger in the case of loose-fit: CardioTattoo ($15.9\text{k}\Omega \pm 1.1\text{k}\Omega$) has considerably lower impedance than textile-only ($51.7\text{k}\Omega \pm 15.2\text{k}\Omega$). The fact that *loose-fit CardioTattoo outperforms*

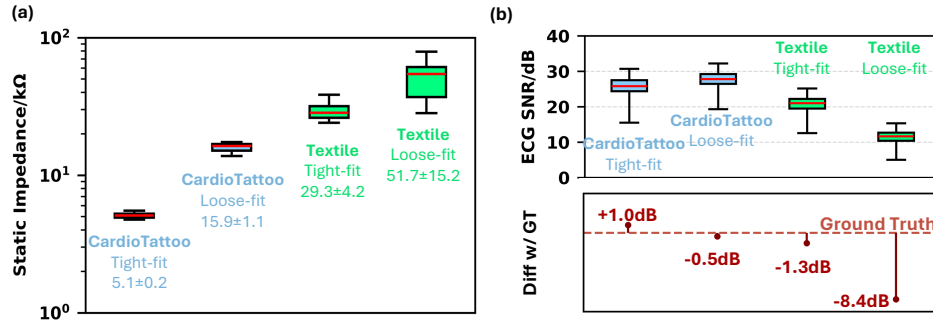


Fig. 7. Comparison between CardioTattoo and textile-only electrode solutions head-to-head under static configurations and different clothes fitness. (a) Impedance measurement, showing CardioTattoo is of much smaller overall contact impedance than textile-only, even for loose-fit setting. (b) ECG waveform SNR, showing a dramatic performance degradation is observed for textile loose-fit compared to other settings. This indicates CardioTattoo relies less on the clothes fitness than textile-only, because the contact property is more resistive than capacitive.

tight-fit textile-only shows that CardioTattoo can provide excellent performance without the discomfort of high compression.

Signal quality tracks these impedance differences. Figure 7(b) compares SNR to the ground-truth gel recording. CardioTattoo tight-fit, CardioTattoo loose-fit, and textile tight-fit all show similarly high SNR and close agreement with ground truth (1.0dB, -0.5dB, and -1.3dB). Textile loose-fit, however, drops sharply to -8.4 dB. This degradation is consistent with the capacitive nature of the textile-skin interface, where reduced contact pressure dramatically increases impedance variability. CardioTattoo’s resistive contact tolerates the same loose fit with minimal penalty.

Dynamic: Does CardioTattoo improve motion robustness? The theoretical advantage of CardioTattoo is that metal-metal interfaces produce primarily resistive impedance variations under motion, whereas textile-skin interfaces produce large capacitive swings that contaminate ECG signals. We tested this directly by measuring impedance change under three controlled motion directions (Figure 8(a)): pressing (Z-axis), sliding along the electrode (X-axis), and sliding across the electrode (Y-axis).

We built a real-time four-wire impedance measurement system (AD5940-based, 10 kHz excitation, 2 MSPS sampling decimated to 100 SPS via 1024-point DFT) to capture impedance dynamics during motion. As before, a gel electrode provided a stable reference. We collected 360 measurements of maximum impedance change across all motion directions, alternating between CardioTattoo and textile-only configurations.

Figure 8(b,c) confirms the theoretical prediction. For resistance (real part), CardioTattoo shows changes of 3%, 16%, and 67% for pressing, sliding along, and sliding across, respectively; textile-only shows 35%, 184%, and 205% i.e. a maximum improvement of 22.6 dB. The difference is even more pronounced for reactance (imaginary part, reflecting capacitance): CardioTattoo changes only 3%, 13%, and 16%, while textile-only changes 36%, 588%, and 699%. This yields up to 33.1 dB improvement i.e. more than 10 dB beyond the resistive component. The disproportionate capacitive improvement directly validates the mechanism: by relocating the motion-sensitive interface to a metal-metal contact, we suppress precisely the capacitive fluctuations that dominate motion artifacts.

From impedance to ECG metrics. With a stable electrical interface, wrist-based ECG can capture the fine-grained waveform detail needed for clinically meaningful metrics (summarized in Table 4) [16]. To verify this end-to-end, we recorded ECG under the same controlled motions using the BioPac MP160 system (3600 seconds of data, approximately 5k ECG segments across all configurations) and computed clinically relevant metrics.

Figure 9 shows the results for both intra-segment metrics (PR interval, QTc—spanning P, R, and T wave fiducial points) and inter-segment metrics (RMSSD for heart rate variability, R-peak false discovery rate). Across

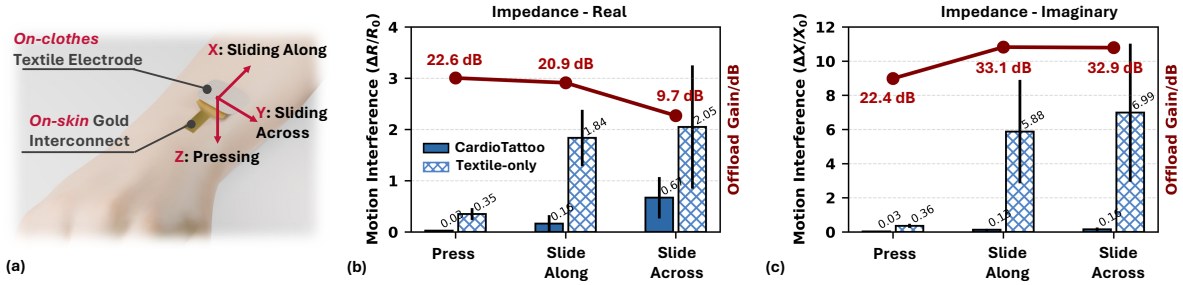


Fig. 8. Impedance change under motion. (a) Demonstration of three representative controlled motion directions. (b) Resistance (the real part of impedance) changes under motion for CardioTattoo and textile-only settings. (c) Reactance (the imaginary part of impedance) changes under motion for CardioTattoo and textile-only settings. These indicate CardioTattoo's robustness against motion, especially for the reactance (capacitance).

Metric	Normal Range	Clinical Relevance
RR interval	600–1200ms	Ventricular rhythm; Atrial Fibrillation
Heart Rate Variability (RMSSD)	19–75ms	Stress; Anxiety; Sleep Apnea
P wave duration	≤120ms	P-mitrale; Atrial abnormalities
PR interval	120–220ms	AV block; Pre-excitation (WPW)
QRS duration	70–100ms	Bundle branch block; PVC
QTc	≤450ms (M) / ≤460ms (F)	Ventricular arrhythmia risk

Table 4. Timing-based ECG metrics available through CardioTattoo, with normal ranges and clinical applications. Unlike systems that provide only R-peak detection (heart rate), CardioTattoo captures full waveform morphology including P and T waves.

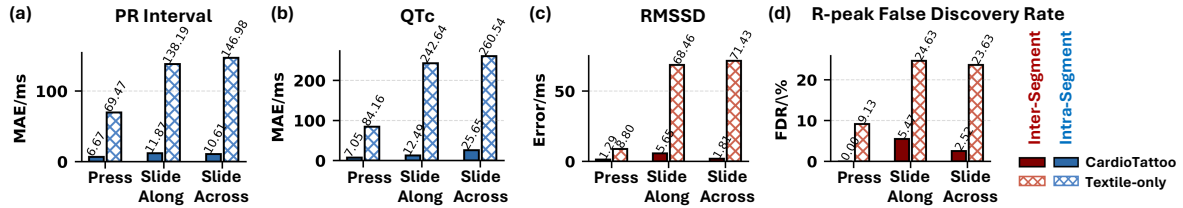


Fig. 9. Comparison of representative metrics under motion, including both intra- (a-b) and inter-segment (c-d) metrics. (a) PR interval. (b) QTc. (c) RMSSD (d) False discovery rate of R peaks. CardioTattoo shows significantly lower errors than the traditional textile-only electrode solutions, pushing wrist-based ECG towards practicability and feasibility.

all metrics and motion directions, CardioTattoo reduces measurement error by more than 10× compared to textile-only. The pattern mirrors the impedance results: pressing causes the smallest errors, sliding across the largest, but CardioTattoo consistently maintains low error while textile-only degrades substantially. These results demonstrate that CardioTattoo's impedance advantages translate directly to the waveform fidelity needed for clinical ECG analysis.

Robustness under External Friction. In the above dynamic experiments, the textile pads on the clothes were manually rubbed against the gold interconnect, to simulate the friction and displacement in the real world during activities. The dynamic results therefore demonstrate both physical resilience and signal quality. The ultrathin, skin-conformal tattoo stays in place under friction, and the PMMA substrate's stretchability absorbs the pulling forces transmitted from the gold-textile interface.

Table 5. Numerical user statistics in the main study.

	Mean	Std	Min	Max		Mean	Std	Min	Max
Age	28.7	5.9	19	45	Skin Tone (L'Oreal metric)	3.9	2.3	2	11
Room Temp (°C)	20.3	0.8	19.0	22.0	Forearm Perimeter (mm)	185.5	21.9	152.4	228.6
Room Humidity	26.7%	9.7%	20.0%	58.0%	BMI	23.8	3.9	18.3	31.4

Table 6. Categorical user statistics in the main study.

Sex	Count	Hair Density	Count	Clothes Size (USA)	Count
Male	11	Nil	8	Men S	1
Female	4	Sparse	4	Men M	6
		Moderate	2	Men L	3
		Dense	1	Men XL	1
				Women XS	1
				Women S	2
				Women M	1

5 EVALUATION

We evaluate CardioTattoo through two complementary studies: a) a user study to demonstrate that an Apple Watch integrated with CardioTattoo can provide high-quality ECG measurement under different static and dynamic scenarios, and under different locations and movements, and b) a longitudinal deployment over 6–8 hours to demonstrate that CardioTattoo supports long-term, continuous measurement in-the-wild.

5.1 Main User Study

The benchmarks in Section 4.5 established that CardioTattoo dramatically reduces impedance fluctuation under controlled motion. We now look at whether these electrochemical advantages translate to practical benefit: does CardioTattoo actually enable continuous, high-quality ECG from commercial smartwatches during real-world use? We structured the evaluation around two research questions:

- **RQ1: Can CardioTattoo eliminate the need for manual crown touch without compromising performance?** Hands-free operation is only useful if CardioTattoo matches or exceeds direct-touch performance on the same task. We test this by comparing CardioTattoo against traditional crown-touch interaction on Apple Watches, head-to-head, under both static and dynamic conditions.
- **RQ2: Does CardioTattoo maintain clinical-grade ECG accuracy continuously across diverse daily activities?** If CardioTattoo stabilizes the electrode interface as predicted, timing-based ECG metrics should remain within clinically acceptable error bounds regardless of body posture or activity type. We test this through continuous monitoring in a residential-simulated environment spanning representative daily routines.

5.1.1 Participants and Data Collection. We recruited 15 healthy participants (N=15) under Institutional Review Board (IRB) approval. Each participant completed both parts of the study i.e. the Apple Watch comparison and the daily activities protocol, followed by a debriefing questionnaire capturing demographics, physiological characteristics, and subjective feedback. The full protocol required approximately 100 minutes per participant; compensation was a \$35 gift card for completion or \$10 for partial participation.

Tables 5 and 6 summarize participant demographics. The sample included 11 males and 4 females, ages 19–45 (mean 28.7, std 5.9), with deliberate diversity across physiological characteristics relevant to electrode performance: skin tone ranged from 2–11 on the L'Oreal scale [56], forearm hair density from nil to dense, BMI from 18.3 (underweight) to 31.4 (obese), and forearm perimeter from 152–229mm. Participants with dense forearm hair were shaved prior to tattoo application. Room humidity varied substantially across sessions (20–58%), providing natural variation in skin conductivity. A single adjustable garment (Men's L with tunable cuff) accommodated all participants.

Two participants were excluded from Part 2 analysis due to equipment issues discovered mid-session: P6 experienced tattoo transfer problems, and P13 had garment fit complications. Their questionnaire responses were retained for qualitative analysis.

The resulting dataset comprises 156 thirty-second sessions from Apple Watch (Part 1) and 117 two-minute sessions from the ADI study watch (Part 2), totaling 18,720 seconds of ECG recording—approximately 25,000 heartbeat segments with fine-grained activity labels.

5.1.2 Part 1: Commercial Smartwatch Integration. To address RQ1, we conducted a head-to-head comparison between CardioTattoo and traditional crown-touch interaction on unmodified Apple Watches. The comparison spans two conditions: static standing (where both methods should perform well) and walking (where CardioTattoo should have an advantage). Standing serves as a baseline confirming that CardioTattoo matches direct-touch under ideal conditions. Walking is the primary test: if CardioTattoo genuinely relocates interface instability from a motion-sensitive skin-electrode contact to a motion-tolerant metal-metal contact, we should observe higher measurement completion rates, better signal quality, and tighter agreement with ground-truth chest-based ECG during motion. Our protocol is inspired by established methodology [6, 68, 74, 76].

Study Procedure. Each participant wore a Movisens ECG Move4 chestband [23] as ground truth throughout the study. After verifying adequate chestband signal quality during a brief walking calibration, we time-synchronized all devices using a jump-based accelerometer alignment protocol (details in Section 4.4.2).

The study followed a within-subjects design with direct-touch tested before CardioTattoo. For each method, participants completed three 30-second measurement trials in each condition (standing, walking at 0.5 mph on a treadmill), yielding 12 trials total per participant. The 30-second duration matches the Apple Watch’s standard ECG measurement window; three trials per condition provide robustness against single-measurement anomalies while keeping total study duration practical.

For direct-touch trials, participants wore an unmodified Apple Watch and initiated ECG measurement by touching the crown with their index finger per standard usage. For CardioTattoo trials, following standard skin preparation, participants donned the bridging shirt with cuff tension adjusted to their wrist circumference. Researchers applied the gold interconnect and transferred the graphene tattoo, allowing five minutes for the tattoo to dry and stabilize. A thin wire connected the shirt’s textile electrode to the watch crown (a production system could integrate this connection into the watchband itself). The same standing and walking protocol was then repeated.

We recorded three outcomes for each trial (typical procedures show in Figure 10): normal completion (full 30-second measurement with normal sinus rhythm), completion with quality warning (full measurement but watch displayed “poor recording” or “inconclusive”), or early termination (watch interrupted the session due to signal quality, with duration logged). This three-tier classification captures both binary success and gradations of signal quality. Total protocol duration was approximately 50 minutes per participant, including preparation and data collection.

Result. The results consistently confirm the prediction from the principle: under static conditions both methods perform well, but under motion, CardioTattoo demonstrates clear advantages across every metric. This observation shows CardioTattoo enables hands-free ECG monitoring without signal degradation, and sometimes even with better performance. Table 7 summarizes the four metrics used to evaluate measurement reliability, signal quality, and clinical agreement with ground truth.

Figure 11 provides an illustrative comparison. During standing, both direct-touch and CardioTattoo produce clean ECG waveforms with clearly identifiable fiducial waves. During walking, the difference is more striking: direct-touch signals exhibit severe baseline wander characteristic of unstable electrode-skin impedance, while CardioTattoo maintains waveform clarity comparable to static conditions.

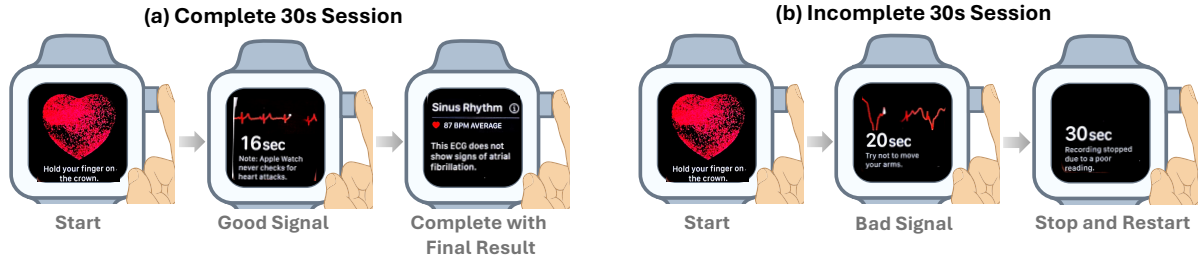


Fig. 10. Procedure of ECG measurement on Apple Watches. (a) Example of a complete ECG session on Apple Watch. (b) Example of an incomplete ECG session on Apple Watch.

Table 7. Metrics for evaluating Apple Watch ECG comparison.

Metric	Definition	Interpretation
Success Rate (SR)	$\frac{\# \text{ complete 30s sessions}}{\# \text{ all sessions}}$	Measurement completion reliability
basSQI	$1 - \frac{P_{0-1\text{Hz}}}{P_{0-40\text{Hz}}}$	Motion artifact contamination (higher = cleaner)
RRI Mean	$\frac{RRI_{\text{test}} + RRI_{\text{GT}}}{2}$	Bland-Altman x-axis
RRI Diff	$RRI_{\text{test}} - RRI_{\text{GT}}$	Bland-Altman y-axis (bias)

P = spectral power in frequency band; RRI = mean R-R interval; GT = ground truth (chestband).

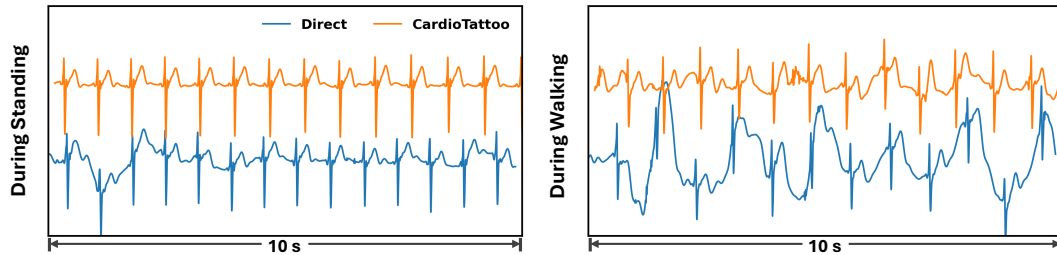


Fig. 11. Example of 10-second raw ECG waveforms under different configurations, directly exported from Apple Watches. CardioTattoo captures ECG with clearly identifiable fiducial waves in static conditions, and achieves higher SNR and reduced motion artifacts than direct-touch during motion.

Measurement completion. Under standing conditions, both methods achieved near-perfect success rates — CardioTattoo at 100% and direct-touch at 98%, indicating that when motion is absent, either approach reliably completes a full 30-second ECG session (Figure 12b). The gap widens when walking: direct-touch success rate dropped 16 percentage points to 82%, while CardioTattoo dropped only 7 points to 93%. A paired t-test confirms this difference is significant for walking ($t(14) = 2.65$, $p = 0.019 < 0.05$, Benjamini-Hochberg corrected) but not for standing ($p = 0.17 > 0.05$). The survival analysis in Figure 12 (a) reinforces this finding: under walking, the Kaplan-Meier curves show clear separation, with CardioTattoo maintaining high survival probability while direct-touch experiences frequent early terminations.

Signal quality. The baseline Signal Quality Index (basSQI), which quantifies motion artifact contamination, tells the same story (Figure 13a). Standing yields high basSQI for both methods (CardioTattoo: 0.99, direct-touch: 0.94). During walking, both degrade but CardioTattoo’s drop is half as large ($0.99 \rightarrow 0.81$, $\Delta=0.18$) compared to

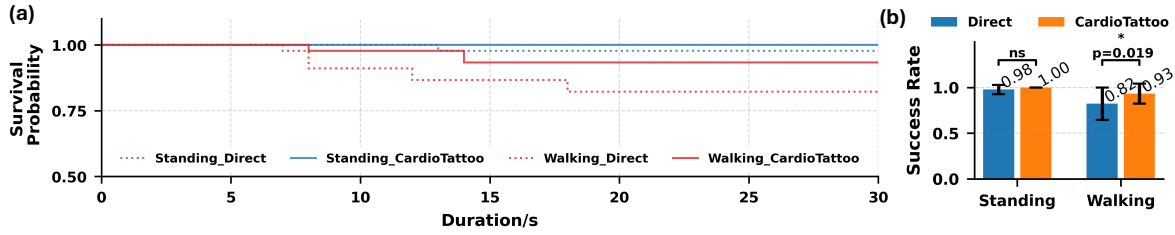


Fig. 12. Survival test of the data acquisition on Apple Watches. (a) Kaplan-Meier Curve. (b) Average success rate (completing full 30s ECG sessions). CardioTattoo provides a higher success rate than direct touch, especially under dynamic settings such as walking.

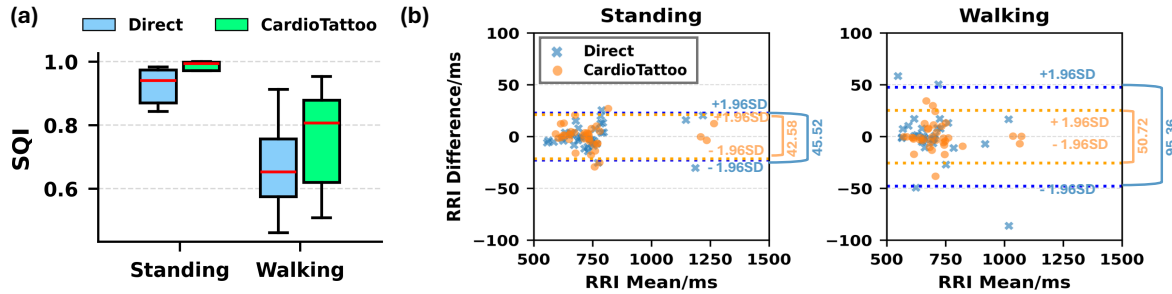


Fig. 13. Signal comparison between CardioTattoo and direct touch on Apple Watch on both standing and walking settings. (a) basSQI distribution, where CardioTattoo presents better signal quality under both settings. (b) Bland-Altman plots on mean R-R peak Intervals (RRI) for each measurement. When RRIs of CardioTattoo and direct touch have similar distribution under the static setting, direct touch has much larger Limits of Agreement (LoA, calculated by $2 \times 1.96\text{std}$), showing CardioTattoo's robustness against motions.

direct-touch (0.95→0.65, $\Delta=0.30$). This pattern directly reflects the impedance stability advantage demonstrated in the benchmarks: CardioTattoo's metal-metal interface absorbs motion that would destabilize a textile-skin contact.

Clinical agreement. Bland-Altman analysis comparing R-R intervals against simultaneous chestband ground truth provides the most clinically relevant validation (Figure 13b). During standing, both methods show tight Limits of Agreement (LoA): 42.58 ms for CardioTattoo, 45.52 ms for direct-touch. The walking condition shows an even greater difference. Direct-touch LoA doubles to 95.36 ms ($\Delta=+49.84$ ms, +109%), indicating substantially degraded agreement with ground truth. CardioTattoo LoA degrades slightly to 50.72 ms ($\Delta=8.14$ ms, +19%), maintaining the same clinical-grade agreement observed during standing. This result directly validates the core claim: by relocating interface instability from the motion-sensitive skin-electrode contact to a motion-tolerant metal-metal junction, CardioTattoo preserves measurement fidelity under conditions where direct-touch fails.

Software-based Motion Artifact Removal. For the Bland-Altman analysis on RRI, we applied a Band Pass Filter (BPF; 7-35Hz; 4th order; zero-phase) to suppress the noises and a Savitzky-Golay Filter (SGF) to smooth the data, equally on both direct-touch and CardioTattoo settings; the filtered signals were then fed into a standard R peak detector as in Neurokit2 [58]. We then compared this against several modern learned denoising methods spanning a range of architectures: Convolutional Neural Network (CNN) [79], Recurrent Neural Network (RNN) [2], Denoising Autoencoder (DAE) [11], Generative Adversarial Network (GAN) [42], Diffusion models [49], and State Space Models (SSM) such as Mamba [29]. We implemented and integrated these methods into our pipeline,

Table 8. Bland-Altman performance comparison between our method and recent software-based denoising models on RRI on the Apple Watch, across all participants. The results show that a simple yet effective combination of a Band Pass Filter (BPF) and a Savitzky–Golay Filter (SGF), used in CardioTattoo, outperforms all other modern software-based methods on our dataset, for both bias and Limits of Agreement (LoA) ($2 \times 1.96\text{std}$, smaller is better). Additionally, under all conditions, CardioTattoo outperforms direct-touch consistently.

Denoising Method	Architecture	LoA (Bias) / ms			
		Direct Touch		CardioTattoo	
		Stand	Walk	Stand	Walk
DRNN [2, 79]	RNN	182.15 (7.77)	266.60 (4.10)	117.54 (-7.07)	168.21 (7.11)
FCN-DAE [11, 79]	DAE	731.95 (101.48)	840.29 (295.14)	450.63 (47.67)	690.08 (178.55)
DeepFilter (Vanilla NL) [79]	CNN	72.47 (4.51)	323.84 (14.86)	42.62 (-1.46)	53.90 (2.24)
DeepFilter (LANLD) [79]	CNN	45.92 (3.75)	225.10 (16.71)	42.67 (-1.43)	55.48 (3.75)
OCGAN (single pass) [42]	GAN	56.50 (2.84)	283.34 (28.04)	42.58 (-1.47)	64.43 (5.21)
OCGAN (dual pass) [42]	GAN	72.23 (4.46)	489.93 (55.15)	44.38 (-1.05)	143.97 (14.14)
TFCDiff [49]	Diffusion	315.79 (21.98)	656.42 (86.23)	78.05 (3.61)	421.28 (45.48)
MECG-E (Complex) [29]	Mamba	54.39 (5.38)	194.27 (20.05)	42.59 (-1.46)	97.02 (8.61)
MECG-E (Phase) [29]	Mamba	52.25 (5.34)	219.02 (23.38)	42.57 (-1.48)	88.09 (7.42)
This Work	BPF+SGF	45.52 (3.49)	95.35 (0.45)	42.59 (-1.46)	50.72 (0.86)

and tested them on our multi-user dataset which none of the models had seen during training. The input was chunked, resampled, unit-converted, and normalized, to match the format of each model’s inference interface.

Table 8 shows that the simple BPF outperforms the other model-based methods on both LoA and bias, and CardioTattoo outperforms direct-touch across all methods and conditions, with the largest gap during walking and the smallest performance drop from standing to walking. Current software methods do not close this gap, and in some configurations they widen it: their training losses reward reconstruction similarity to the clean signal rather than fiducial-point timing, so small localized distortions that shift timing receive little penalty during training. A simple bandpass filter works because restricting the bandwidth is deterministic to reduce out-of-band noises, therefore improving SNR.

5.1.3 Part 2: Daily Activities. To address RQ2, we evaluated whether CardioTattoo maintains clinical-grade ECG accuracy across the diverse postures and movements of everyday life. We selected nine activities spanning major categories of daily time use [67]: three static postures (standing, sitting, lying), two work-related tasks (typing, writing), two leisure activities (watching TV, checking phone), household tasks (wiping tables), and eating (lifting utensils). This selection captures both postural variation affecting electrode contact geometry and arm movements inducing motion artifacts.

The study took place in a residential-simulated apartment lab with activities distributed across bedroom, living room, and kitchen to approximate a natural context, and activities were counterbalanced across four pre-defined sequences. We used the ADI study watch for continuous ECG streaming rather than the Apple Watch. This choice reflects the research question: Part 1 established that CardioTattoo outperforms direct-touch, but continuous monitoring during daily activities cannot be compared against direct-touch because a user cannot type, wipe a table, or eat while holding their finger on the watch crown. The comparison is therefore against clinical ground truth: does CardioTattoo maintain acceptable accuracy across daily activities during which ECG monitoring with crown touch is not possible?

Study Procedure. Participants transitioned directly from Part 1, retaining the bridging shirt and graphene tattoo. After switching to the ADI watch and completing time synchronization, participants performed each activity for two minutes in counterbalanced order across four pre-defined sequences, yielding continuous ECG time-aligned with simultaneous chestband recording.

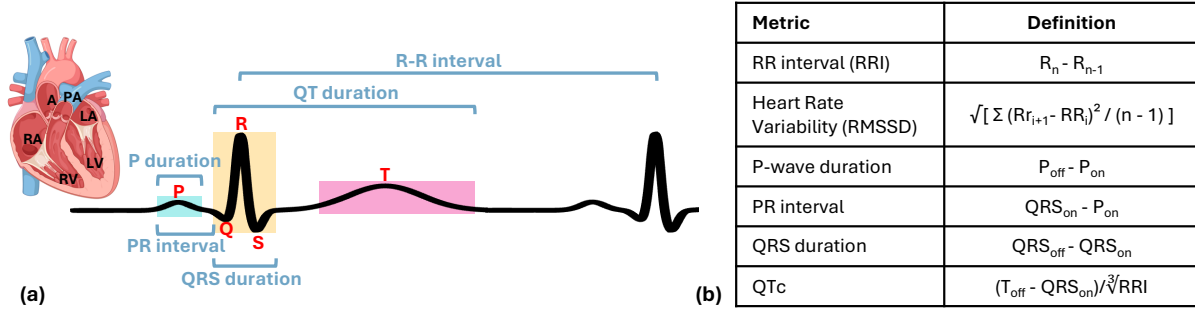
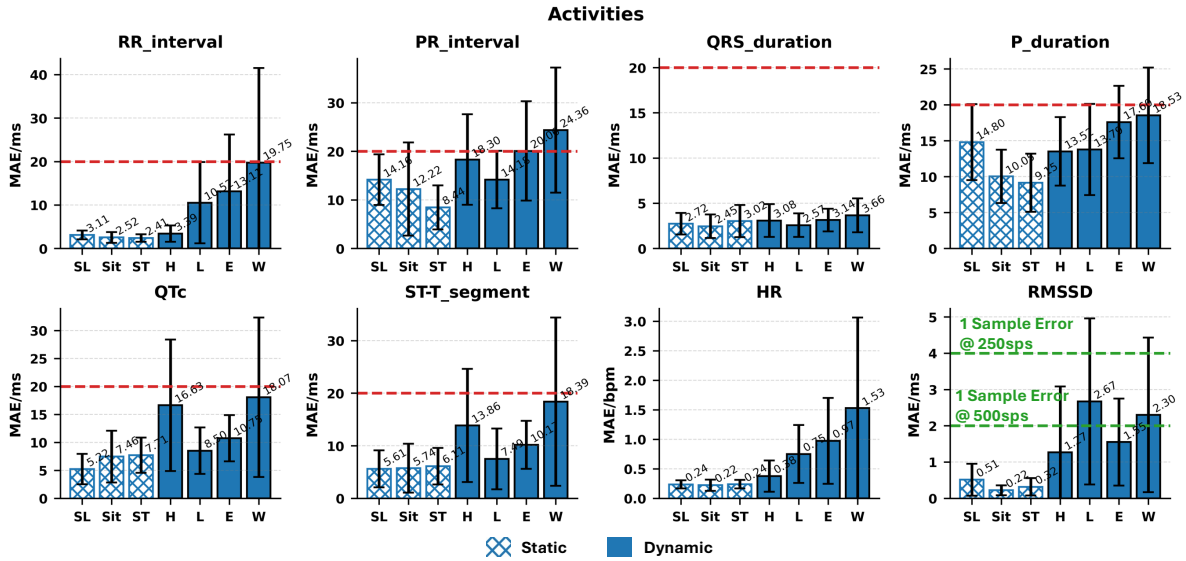


Fig. 14. ECG and HRV Metrics for evaluating CardioTattoo's performance under activities².



SL: Lying/Sleeping; Sit: Sitting; ST: Standing; H: Housework; L: Leisure; E: Eating; W: Working.

Fig. 15. MAE for ECG and HRV metrics across activities for all valid participants. Most of the timing-based results are close to the target error range (2ms for RMSSD and 20ms for others, based on [12, 80]), indicating CardioTattoo can capture these critical fiducial points reliably under both static and dynamic settings.

Success Criteria. Clinical ECG interpretation requires timing accuracy within approximately 20ms corresponding to half a small square on standard ECG paper [12, 80]. For HRV metrics, our 500Hz sampling rate sets a resolution floor of 2ms (one sample interval), below which measurement error cannot be meaningfully distinguished from quantization. We adopt these as our acceptability thresholds: mean absolute error below 20ms for ECG timing metrics (RR interval, P-wave duration, PR interval, QRS duration, QTc) and below 2ms for RMSSD. The definition of these metrics can be found in Figure 14.

Results. Figure 15 shows mean absolute error across activity categories. Static postures (standing, sitting, lying) remain well below clinical thresholds for all metrics, with RMSSD below 2 ms throughout. Dynamic activities show higher but generally acceptable error, with most metrics remaining within bounds.

²Figure(s) partially created in BioRender. Lei, Z. (2026) [https://biorender.com/x5q0aae]

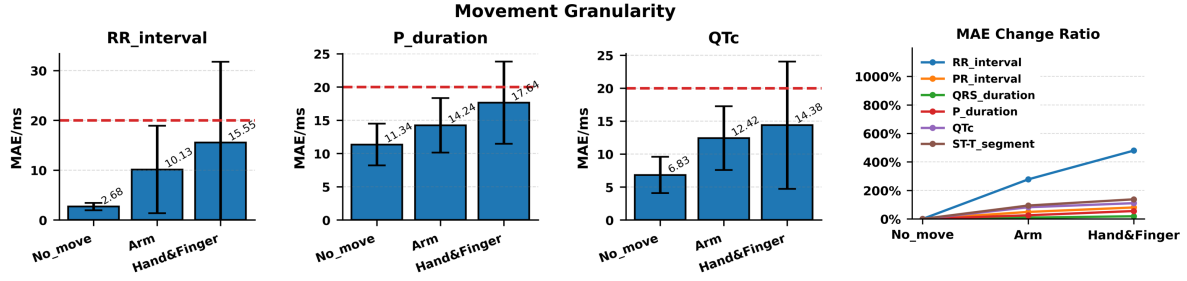


Fig. 16. MAE for ECG and HRV metrics across different movement granularity for all valid participants.

To understand how different movements affect accuracy, we regrouped activities by movement type: no movement (sitting, standing, lying), arm movement (wiping, watching TV, eating), and hand/finger movement (typing, writing, checking phone). As Figure 16 shows, error increases progressively across this gradient—fine motion at the wrist, where the tattoo interfaces with skin, proves more challenging than gross arm motion, which the gold-textile interface handles well.

This pattern directly reflects the CardioTattoo architecture. The gold-textile interface tolerates gross arm motion well—that interface is resistive and mechanically robust. But fine finger and wrist movements create micro-disturbances at the tattoo-skin interface, the one location where CardioTattoo cannot fully relocate instability. The CardioTattoo principle predicts exactly this: we have moved the problem from a difficult regime (textile sliding on skin) to a manageable one (conformal tattoo with residual sensitivity to fine motion).

Table 9 presents a comparison between CardioTattoo and other popular methods in QRS onset/offset detection. DWT method in the Neurokit (NK) library appears to have large errors for all categories, significantly larger than the reference range (20 ms), indicating it is not reliable to delineate the ECG wave details in our dataset. In comparison, our method has the lowest mean error and std. This demonstrates a tighter agreement between our method and the ground truth.

Three different lengths of calculating windows are compared in Table 10: 10 seconds (the smallest window possible), 30 seconds (same as Apple Watch), and 120 seconds (the full duration of the activity we recorded in the study). Within a longer window length (120 seconds), the error is averaged more so that the outliers are further suppressed. However, this also reduces the time resolution and tends to ignore transient, time-sensitive events. On the contrary, a 10s window is less robust against outliers, but provides the highest time resolution and fastest event detection. CardioTattoo employed a 10s window length for ECG metric calculation to prioritize time sensitivity, which is important in daily cardiac event monitoring.

To check how performance varies across the participant population, we regrouped results by BMI, age, forearm perimeter, and skin conductivity (Figure 17). CardioTattoo performs best for participants with healthy BMI (MAE = 8.43 ms) and worst for participants in the obese range (MAE = 16.15 ms), probably reflecting reduced electrical conductivity through more subcutaneous fat. Forearm perimeter (measured 7.5 cm from the wrist) shows a similar trend, with MAE rising from 8.61 ms to 14.62 ms across the range, likely from cuff fit on larger forearms. Skin conductivity, averaged from the ADI study watch at the start and end of each session, has the strongest effect: MAE drops from 12.12 ms at 3–4 μS to 6.22 ms at 5–6 μS , consistent with greater ion mobility through more hydrated skin. Age, by contrast, shows no clear relationship with performance. A larger sample with greater demographic diversity would let future work characterize these effects more precisely.

5.1.4 User Feedback. After completing the study, participants rated CardioTattoo across seven usability dimensions: device fit, skin comfort, unobtrusiveness, freedom of movement, willingness to wear, social acceptance, and preference over gel electrodes. Each dimension was scored 1–10, with optional qualitative comments.

Table 9. MAE of different methods against the ground truth in QRS duration timing, across movement granularity (mean $\pm$ 95%CI, in milliseconds) on the main study data. Lower is better. This demonstrates our QRS on-set/offset detection algorithm outperforms other methods under motion.

Method	No Move	Arm	Hand&Finger
NK (DWT)	66.87 $\pm$ 29.37	68.33 $\pm$ 30.21	77.07 $\pm$ 30.33
Emrich et al	6.54 $\pm$ 2.25	6.30 $\pm$ 1.86	7.00 $\pm$ 1.89
ECG-Kit	11.59 $\pm$ 5.06	15.41 $\pm$ 7.27	21.38 $\pm$ 8.71
Ours	2.73$\pm$1.30	2.98$\pm$1.30	3.24$\pm$1.59

Table 10. MAE of different window sizes against the ground truth, averaged on all ECG metrics, across movement granularity (mean $\pm$ 95%CI, in milliseconds) on the main study data. Lower is better. While the 10s-window has a larger error, it provides the highest time resolution and the fastest event detection.

Window	No Move	Arm	Hand&Finger
10 s	6.85 $\pm$ 2.12	11.42 $\pm$ 3.61	14.29 $\pm$ 7.22
30 s	5.81 $\pm$ 1.80	7.21 $\pm$ 2.12	11.75 $\pm$ 7.12
120 s	5.44 $\pm$ 1.50	6.06 $\pm$ 2.05	10.08 $\pm$ 7.21

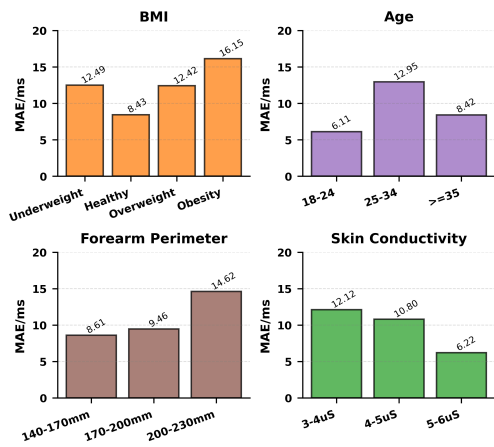


Fig. 17. Aggregated MAE of different user statistics against the ground truth, averaged on all ECG metrics across activities.

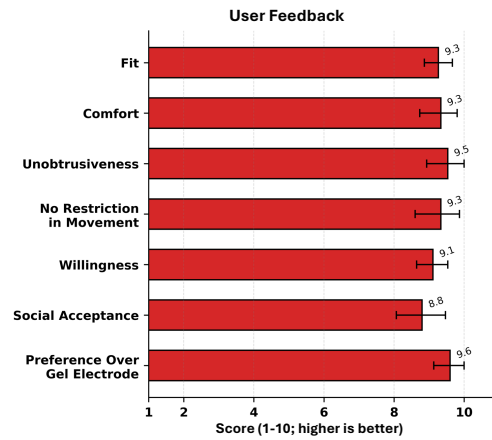


Fig. 18. After-study survey results, providing participants' feedback on CardioTattoo. This shows participants were satisfied with their experience in using CardioTattoo, rating all dimensions over 8/10.

Figure 18 summarizes the results. All dimensions received mean scores above 8.0, with the lower bound of the 95% confidence interval remaining above 8.0 as well—indicating consistent satisfaction rather than high means driven by outliers. Unobtrusiveness scored highest (9.5), with participants noting the system felt similar to a normal shirt. One participant commented that it was “not visible if you don’t pay close attention,” while another noted that “compared to chestbands it is really comfortable—super light and not feeling anything at all.”

Willingness to wear across scenarios (daytime, sleep, outdoors) averaged 9.1, suggesting participants would accept CardioTattoo for extended daily use. Social acceptance scored slightly lower (8.8), reflecting individual variation in preferences—some participants liked that the system looked distinctive, while others preferred it to be indistinguishable from normal clothing. These results align with the formative survey findings that comfort and unobtrusiveness were users’ top priorities.

Skin comfort scored a mean of 9.3 out of 10, showing that the users felt little sensation from the tattoo. Only three participants (P3, P7, P10) mentioned a bit of itchiness from the tattoo. No allergic redness was found related to the tattoo directly. P3 commented “It was a little itchy at the very beginning, but it became completely comfortable after a few minutes.” A likely cause is the cold-water soak required for tattoo transfer: the wet tattoo briefly cools the skin on contact, and the sensation fades as it dries. The same three participants had

moderate-to-dense pre-shaving hair and intermediate-to-low skin conductivity (3.4–4.7 μS), suggesting that drier skin may be more sensitive at the application step. On the garment side, P4 complained that the shirt "leaves a mark on my skin", possibly because the elastic cuff was pressing too tightly; the likely reason is that P4's build (Men's L, BMI 28.2) sat at the upper end of our prototype size range and a larger elastic size would have been more appropriate.

Participant comments also identified areas for improvement: simpler setup procedures, more robust connections for vigorous activity, and aesthetic refinements for fashion-conscious users. These reflect engineering challenges for productization rather than fundamental limitations of the approach.

5.2 Longitudinal Study

The controlled evaluations above demonstrate CardioTattoo's performance under researcher-defined protocols, but real-world use extends over many hours rather than minutes and involves naturalistic activities. To validate that CardioTattoo sustains its performance under naturalistic conditions, we conducted a longitudinal deployment in which participants wore the system throughout their normal daily routines.

Three participants wore CardioTattoo and a Movisens EcgMove 4 chestband (ground truth) for 6–8 hours each in their residential environments. Participants followed their typical routines freely, recording voice memos via Otter AI [69] when switching activities to provide coarse-grained labeling of major tasks lasting more than one minute. Researchers intervened only hourly to prompt a synchronization movement (five jumps with arms crossed) for time alignment between devices. The resulting dataset comprises 430 minutes of continuous ECG per participant on average—77,400 seconds total containing approximately 100,000 heartbeat segments across seven activity categories: checking phone, working, housework, eating, social/calling, watching TV, and light exercise (cycling and slow walking).

We evaluated three metrics that together characterize whether CardioTattoo provides reliable cardiac measurements in daily life: R-peak detection accuracy (false negative and false discovery rates, computed by comparing time-synchronized peaks in 600ms windows), ECG availability (the proportion of windows containing valid P, R, and T peaks with physiologically plausible intervals based on [16, 87]), and HRV accuracy (RMSSD mean absolute error against chestband ground truth).

Results. Figure 19 summarizes performance across activity categories. R-peak detection remains highly reliable, with both 1-FNR and 1-FDR exceeding 90% for nearly all categories. Checking phone achieves the highest accuracy (99.55% and 99.23%), reflecting minimal arm movement, while housework is most challenging (89.49% and 95.52%). Notably, the gap during housework—10.5% missed peaks versus 4.5% false detections—reflects appropriate algorithm behavior: when motion artifacts create ambiguity, the system conservatively avoids reporting uncertain peaks rather than risking false detections.

ECG availability follows a similar pattern. All categories exceed 80% except housework, which drops to 67.37% due to large arm movements involved in lifting, chopping, and washing. For context, the chest-mounted ground truth device—specifically designed for ambulatory recording—achieves 97.2% availability. That CardioTattoo maintains usable ECG for more than two-thirds of even demanding household activities, and more than 80% of typical daily time, demonstrates practical viability for continuous monitoring.

HRV measurement accuracy is similarly strong. Across the full dataset, CardioTattoo achieves RMSSD MAE of 1.42ms with approximately 20% of segments dropped as unusable. For the remaining 80% of the monitoring period, HRV error falls below a single sample interval (2ms at 500 SPS)—effectively the resolution limit of the hardware. Even housework produces MAE of only 2.58ms, just above the one-sample floor.

Consistency over time. Figure 20 shows one-minute windowed performance across a representative participant's full session. The ECG availability remains stable throughout hours of continuous wear, with some activity-dependent variation. Housework intervals show visible dips, but performance recovers immediately when

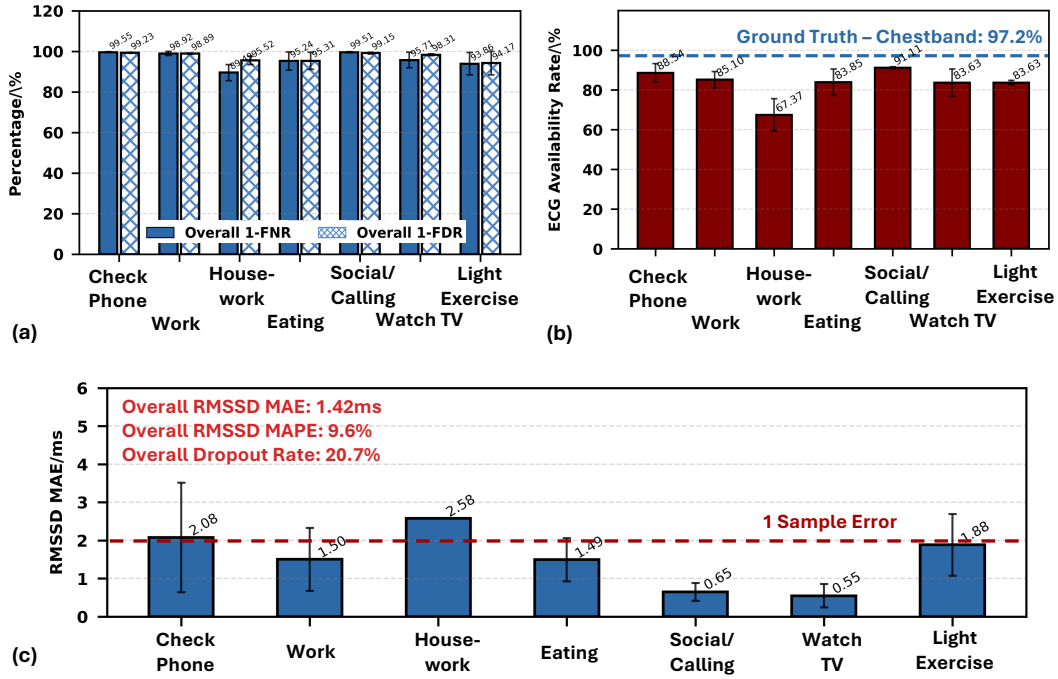


Fig. 19. Longitudinal study (6-8 hours) results across different activities. (a) Overall FNR and FDR (reversed), showing CardioTattoo provides R peak detection reliably. (b) Overall ECG availability, showing CardioTattoo records useful ECG for more than 80% of the time. (c) Overall RMSSD MAE compared with ground truth, showing CardioTattoo measures HRV with high accuracy as low as one sample error (500sps) for various daily activities.

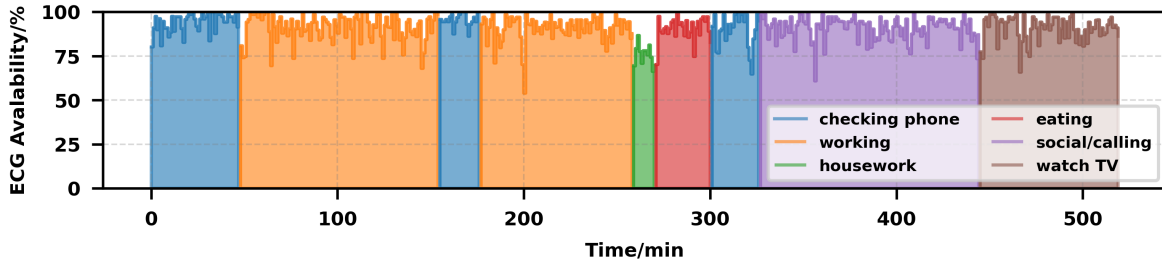


Fig. 20. Representative time series visualization of the longitudinal study with ECG availability over time, showing that useful ECG recordings are available from CardioTattoo over a long period.

activity shifts to less demanding tasks—confirming that reduced accuracy reflects transient motion challenge rather than system drift or electrode degradation.

6 DISCUSSION

CardioTattoo demonstrates that continuous ECG from commercial smartwatches is achievable, but the broader contribution is the *CardioTattoo principle* that makes it possible. Rather than engineering better skin-contact electrodes which is the typical approach in wearable sensing, we relocated interface instability from a fragile

regime (textile on skin) to a robust one (metal on metal). This architectural insight may have implications beyond the specific system we built.

CardioTattoo as a design pattern. The core observation in this work is that in a biopotential sensing system, the skin-electrode interface has been treated as an unavoidable bottleneck that needs to be mitigated through better materials, tighter fits, or conductive gels. But CardioTattoo reframes the problem and allows us to move the instability to an interface whose electrical characteristics (resistive rather than capacitive) make the resulting artifacts manageable.

Concretely, this design pattern of “wearable electronics at one body location, the sensing contact at another, with a metal-metal junction between them” may extend to other wearable sensing modalities. Holter-style continuous ECG monitoring (e.g., [28, 48]) could keep its recorder on a wristwatch while routing chest or torso electrodes through the garment, replacing the bulky gel-based instrumentation that limits long-term adherence. Wrist EMG bands such as the Meta Neuraband [36] could place electronics at the wrist while moving the EMG measurement to the forearm or palm, where muscle signals are stronger. Even EEG (e.g., [40]) could route conformal head-mounted electrodes to a hat- or wristband-mounted recorder. In each of these, the graphene tattoo’s sub-micron thickness, or another conformal alternative, could supply the stable skin anchor, with the routing and metal-metal junction handling the rest.

From tattoo demonstrations to complete systems. Graphene electronic tattoos and epidermal electronics more broadly have shown impressive sensing capabilities in laboratory settings, but prior work has typically relied on rigid wires secured with conductive paste to connect tattoos to measurement equipment. This tethering negates the flexibility and unobtrusiveness that make e-tattoos attractive in the first place, limiting them to controlled demonstrations rather than real-world deployment.

CardioTattoo offers a template for how e-tattoo research can move beyond the lab, treating the tattoo-to-system connection not as a peripheral concern but as a central design problem. By extending the tattoo with a thin gold interconnect and interfacing it with a textile electrode through natural garment pressure, we eliminate rigid wires while maintaining signal integrity, and the connection becomes soft, unobtrusive, and compatible with daily wear. The same architecture (conformal on-skin element, flexible interconnect, pressure-maintained textile interface, garment-integrated routing) can generalize beyond ECG to other e-tattoo applications such as blood pressure monitoring, stress sensing, and continuous glucose monitoring, where the on-skin-to-electronics routing problem is the same.

Characterizing the hardware-software tradeoff. The comparison between hardware reframing and software-based motion artifact removal is itself a research question. Our evaluation in Section 5.1 suggests the hardware fix already outperforms the learned denoisers we tested, but those models were trained on chest-mounted ECG with limited motion variety, and their reconstruction-style losses do not target the fiducial-point timing that downstream metrics depend on. A larger study with wrist-specific motion data would let us answer three open questions: how far the hardware approach itself can be pushed, how much modern transformer-style denoising models can improve when trained on the right data, and whether a combined hardware-plus-software pipeline outperforms either alone. We see this as a productive direction rather than a settled comparison.

Broader Deployment. The longitudinal study that we conducted spans 6–8 hours per participant, and would need to be extended to multi-day deployment typical of clinical Holter monitoring. The constraint comes from our tattoo design: the GET is intentionally easy to remove with water, which keeps replacement painless and chemical-free but in its current form, this trades multi-day continuity for daily reapplication. Our formative survey suggests this is a tradeoff most users would accept (Appendix A); a longer-term evaluation would require either streamlining the daily transfer process, eventually with an automatic transfer device, or developing a waterproof GET with a skin-safe removal solvent for users who cannot self-apply, such as older adults living alone.

A second extension concerns the user population. We benchmarked our algorithm on standard patient datasets containing diverse cardiac abnormalities (Section 4.4, Section 5.1.3), and the user study covered diverse demographics, but we did not deploy the full CardioTattoo system on patients with active cardiac conditions. An in-hospital study with clinician feedback is the natural next step to test generalization beyond healthy participants and to surface deployment issues that healthy-volunteer studies cannot capture.

The garment design space is another avenue for exploration. CardioTattoo's long-sleeve shirt routes from one wrist to the other, but everyday wardrobes include short-sleeve tops where the same routing technique requires adaptation: the tattoo and watch placement would need to migrate higher up the arm, which makes wrist-watch form factor awkward. Possible solutions include using GETs on both arms with the recorder in a chest pocket or on a necklace, or, as some participants in our study chose, wearing a modified long-sleeve shirt on top of the short sleeve, which keeps the existing routing intact.

Long-Term Wear. Heavy sweat and prolonged friction stress the system in ways our short-duration studies cannot fully capture. The perforated GET design (Section 4.2) handles moderate sweat through draining and evaporation, and increasing the hole density and size would extend tolerance to heavier exertion. The other two interfaces in the system, tattoo-to-gold and gold-to-textile, sit away from the skin and are unlikely to encounter sweat directly, so the bottleneck is the GET-skin contact itself.

Friction comes primarily from the elastic cuff sliding against the gold interconnect, and our benchmarks show this is tolerated under moderate pressure. An over-tight cuff is a different matter: it can pull on the gold and fracture the connected tattoo. The mitigation is twofold: personalize the elastic band's tightness for each user's wrist, and add a runtime lead-off check on contact impedance to alert the user if the textile-gold contact is lost or, accidentally, if the cuff slides onto the tattoo itself.

Biocompatibility is the third dimension of long-term wear. Our chemical-free, glue-free transfer process is safe for typical skin, consistent with the post-study survey responses (Section 5.1) and prior reports on GET [43, 45]. Special populations call for additional consideration: users with broken or fragile skin (eczema, wounds, infants, older adults) may benefit from a sterilized variant of the tattoo (with sterilization parameters tuned to avoid degrading the graphene or PMMA) or a thin hydrogel layer to maintain skin humidity, with the hydrogel's thickness traded against the conformality that the tattoo's sub-micron profile depends on.

7 CONCLUSION

In conclusion, we introduced the CardioTattoo principle for wearable biopotential sensing, demonstrating that interface instability can be strategically relocated from fragile skin-electrode contacts to robust metal-metal junctions. We instantiated this principle in CardioTattoo, a system combining ultrathin graphene tattoos with garment-integrated signal routing to enable continuous ECG from unmodified commercial smartwatches. Our evaluation showed that CardioTattoo achieves clinical-grade accuracy across diverse daily activities and sustains performance over multi-hour longitudinal wear. Beyond the specific system, CardioTattoo offers a reusable blueprint for e-tattoo research—showing how conformal epidermal sensors can move from laboratory demonstrations to practical, untethered deployment.

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A USER PREFERENCE INTERVIEW

To understand the demand for CardioTattoo among the consumers, we first conducted an online survey to investigate the user preference and acceptance, with Institute Review Board (IRB) approval. Overall, a total of 107 participants were recruited, among which 99 finished the entire survey, regarded as valid responses ($N=99$). Our subjects included 34 males, 61 females, and 4 of unknown genders. The average age is 22, with a maximum of 44 and a minimum of 18.

Figure 21 demonstrates the user background with a focus on the histories and habits on the technology. As depicted in Figure 21(a), more than half of the participants used health-monitoring devices ($N=99-39=60$, $100\%-39.4\%=60.6\%$), of which a majority wore smartwatches ($N=49$, 49.5%). Considering the family disease history, while most participants did not have this, 32.3% of them answered yes to the question. Although not in the majority, this number is non-trivial and yields a representative sampling of people with family history of cardiac diseases. Finally, while most participants ($N=64$, 64.6%) were "mainstream" for the new technology (adopt once proven), early ($N=20$, 20.2%) and late ($N=14$, 14.1%) adopters and even resisters ($N=1$, 1.0%) were observed in the survey. Overall, our user sample present considerable diversity across device usage, cardiac history, and habits. This enables our result to represent opinions from various kinds of end users.

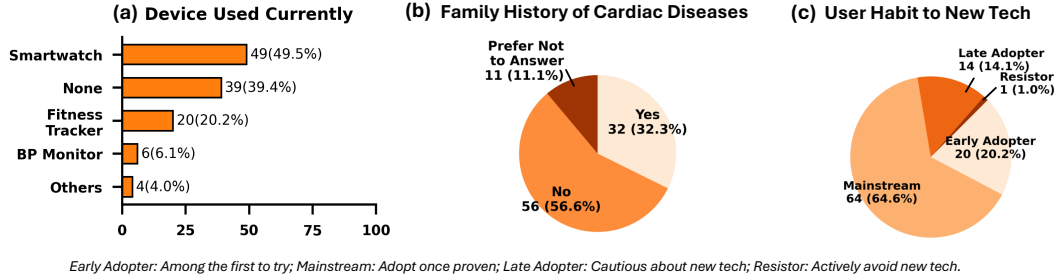
To understand how frequent the participants would prefer to use our system, we investigated their preference for the tattoo itself, tattoo+watch, and likelihood to use for disease prediction. As Figure 22(a) shows, an overwhelming majority of the respondents planned to use the tattoo for no less than 3 days a week, including 7 days ($N=23$, 23.2%), 5-6 days ($N=32$, 32.3%), and 3-4 days ($N=22$, 22.2%). Figure 22(b) demonstrates the result for the entire system, including both the tattoo and the watch, supposing in Year 2030 when this becomes a standard for daily heart monitoring. A similar conclusion retains: most participants would use it frequently (Always on: $N=31$, 31.3% . Weekday: $N=34$, 34.3%). They were also influenced significantly by the doctors, with $N=23$ (23.3%) selected "Only when Doctor Requires". P90 indicated weekend routines were different from weekdays and less stressful, so for healthy people it was less necessary over the weekend. P84 mentioned there can be "Peer Pressure", as everyone is wearing it if it becomes a standard 5 years later and you are not fashionable without them. These comments linked CardioTattoo with human behaviors, providing interesting angles of view beyond the technology.

Figure 22(c) further refined the scenario, supposing CardioTattoo helped the participants prevent a life-threatening stroke. Knowing this, the proportion of respondents accepting this technology daily increased further to 96.0% ($N=58+37=95$) and none of them selected "No, still too much hassle". This shows the health concern can push the users towards using CardioTattoo, reflecting a demand in daily continuous heart monitoring that CardioTattoo provides.

Figure 22(d) shows a comparison of different heart monitoring devices, including this work (Ultra-thin invisible temporary tattoo), tight-fit chest strap (e.g. Polar H10), sticky gel electrodes replaced daily (e.g. 3M gel electrodes), and manually touching the crown 5x daily, as the current way to obtain ECG through a smartwatch. Among these methods, the highest likelihood was observed in CardioTattoo (Op0), where 54.5% ($N=54$) of participants chose "very likely" and 29.3% ($N=29$) chose "somewhat likely". This is much higher than smartwatches (Op3), where only 25.3% ($N=25$) selected "very likely" and 45.5% ($N=45$) selected "somewhat likely", indicating respondents' preference of CardioTattoo over the traditional way of interacting with the smartwatches. Furthermore, almost no participants were likely to use chest straps (Op1) and gel electrodes (Op2) (Op1: $N=0+6=6$, 6.1% . Op2: $0+6=6$, 6.1%), suggesting these methods were not acceptable in the daily life, although they can provide high-quality ECG signals.

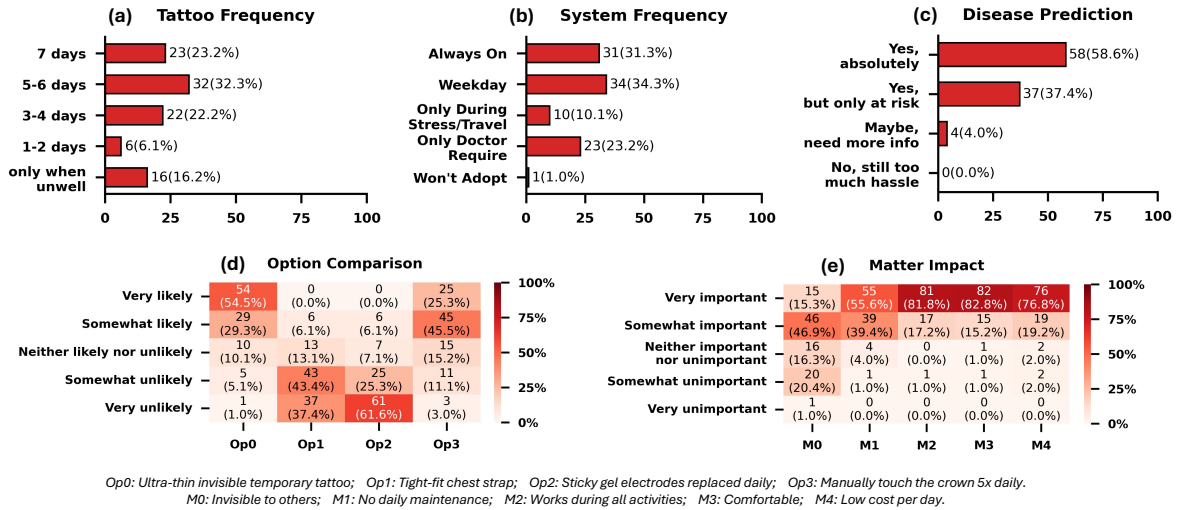
In figure 22(e), most respondents ($>80\%$) rated "Very Important" for the tattoo to be "working during all activities", "comfortable", and "low cost per day", while the ratios are only 55.6% for "No daily maintenance" and

15.3% for "invisible to others". Combined with previous results in Figure 22(a) and (b), it appears that respondents were willing to use the tattoo frequently, but reducing the daily maintenance efforts can be a plus.



Early Adopter: Among the first to try; Mainstream: Adopt once proven; Late Adopter: Cautious about new tech; Resistor: Actively avoid new tech.

Fig. 21. User background for the online survey. (a) Devices being used currently by participants (could pick more than one). (b) Family history of cardiac diseases. (c) User habit, with a focus on how soon participants would adopt new technology after publishing.



Op0: Ultra-thin invisible temporary tattoo; Op1: Tight-fit chest strap; Op2: Sticky gel electrodes replaced daily; Op3: Manually touch the crown 5x daily.
M0: Invisible to others; M1: No daily maintenance; M2: Works during all activities; M3: Comfortable; M4: Low cost per day.

Fig. 22. Result of formative user preference interview. (a) Frequency to use the tattoo similar to daily disposable contact lens. (b) Frequency and condition to use watch and tattoo together, supposing in 5 years this technology becomes a standard for heart health. (c) Frequency to use the entire system, supposing it can catch arrhythmia before symptoms and prevents a life-threatening stroke. (d) Likelihood to adopt different heart-monitoring devices in the daily life continuously. (e) Matter significance for continuous heart monitoring in the daily life as a wearable.

B SUPPLEMENTARY DETAILS IN MAIN USER STUDY

B.1 Part One

At the beginning of the study, the participants wore the ECG chestband (MoviSens ECG Move4 [23]) of appropriate sizes as the ground truth by themselves in a separate clothes-changing room, following the researchers' writing instructions. When completed, they were asked to put on the white data collection unit on the chestband and walk for around 1 minute, and then remove it while leaving the chestband on the body. The researchers then checked the signal quality offline to make sure the electrodes were in appropriate position and good contact to provide decent ECG waveforms under motion. After passing this inspection, the participants put the unit back on their chestbands and the formal data collection started. They were allowed to wear a shirt or hoodie to cover the body on top of the chestbands.

During the study, the participants first did a synchronization to make the timestamps on the chestband and the watches aligned, as the chestband's clock was not calibrated before and it did not support real-time streaming. Then, the researchers helped them wear an unmodified Apple Watch, and collected ECG data with the index finger touching the crown during static standing and slow walking (0.5 mph) on a treadmill. Three trial sessions (30 seconds max) were conducted for each setting, and the results displayed on the watch screen were recorded.

After collecting data for manual touching on a normal Apple Watch, the participants were asked to shave the hair on both arms if too long or dense. Researchers then helped them test the cuff tightness of the clothes and tune its perimeter accordingly, before the participants put on our functional bridging shirt. This was followed by gold interconnect attachment and GET transfer with a 5-min tattoo drying afterwards. The participants were later asked to change to a modified Apple Watch connected to CardioTattoo, and the same data collection repeated.

The preparation and study procedure in this part of study took around 50 minutes.

B.2 Part Two

To show CardioTattoo provides continuous ECG monitoring without interrupting ongoing activities, we designed a study with different daily routines. According to the U.S. Bureau of Labor Statistics [67], the activity time ranking for a person aged 25-34 per day in the USA is (from most to least): personal care including sleep (9.74 hours, 40.6%), working (4.73 hours, 19.7%), leisure and sports (4.25 hours, 17.7%), household (1.71 hours, 7.1%), eating and drinking (1.20 hours, 5.0%), and others (each less than 1 hour, in total 2.37 hours, 9.9%). To representatively simulate a day of adults, we select sleeping for personal care/sleep, typing and writing for working, checking phones and watching TV for leisure, wiping tables for household work, and lifting spoons for eating. While activities with motion can absolutely involve signal turbulence, different body postures, even static, will also result in various arm positions and electrode contact conditions. This diversity, derived from static postures in different daily activities, can influence the ECG measurement significantly and is therefore worth exploring as well. We introduced 2 more static postures (sitting and standing in addition to sleeping) to study this effect. In total, 9 different activities were involved in this study.

To better simulate activities in the real world, this study took place in an apartment-like residential-simulated lab, as shown in Figure 23. We spread the activities across different rooms in the apartment: (1) bedroom bed: sleeping; (2) living room table: sitting, working (typing and writing), and eating; (3) living room sofa: leisure (watching TV and checking phone); and (4) Kitchen countertop: household and standing. To collect data for all activities without a stop, ADI study watch was selected over Apple Watch, as it provides continuous measurement.

At the beginning of this part of study, the participants had already worn the bridging shirt and transferred the tattoo to the skin in Part 1. They first changed the watch from Apple to the ADI study watch for continuous monitoring. The researchers measured the skin conductivity at the start of the study using the ADI watch. The participants were then asked to do a synchronization.

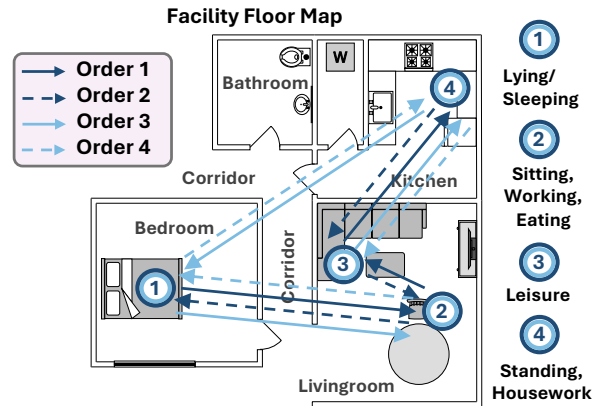


Fig. 23. Floor map and counterbalanced activity orders of our residential-simulated setup.

During the study, the participants did different activities based on the prompt in a counterbalanced treatment as shown in Figure 23: we pre-defined 4 different activity orders that were positionally balanced, and each participant picked one of them randomly. This is a simple yet effective way to alleviate the carryover effects in within-subjects study design, i.e. previous treatments might influence future treatments, such as due to a detached or degraded electrode after the study begins. This method ensures that no specific activity is biased by being placed at the beginning, middle, or end of the event sequence. For each activity, we collected data for 2 minutes, with the participants doing activities continuously.

After the study, the participants did another synchronization, so that we could time-align the ECG samples between the beginning and the end of study from the chestband and the watches. Another skin conductivity measurement was then conducted to record the impedance change across the study. Finally, the participants were asked to fill out a debriefing questionnaire. This part of study took around 45 minutes in total.