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Clarissa Pedrini Schuch, Gabriela Chaves, Bastien Moineau, Sarah Bennett, Meysam Pirbaglou, Edwin Martin Lobo, Milad Alizadeh-Meghrazi

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Clarissa Pedrini Schuch[1, 2] PhD; Gabriela Chaves[1] PhD; Bastien Moineau[1] PhD; Sarah Bennett[1] MSc; Meysam Pirbaglou[1] PhD; Edwin Martin Lobo[3] PGD; Milad Alizadeh-Meghrazi[1] PhD

[1]Research and Development Myant Health Corp. Mississauga CA
[2]Institute of Health Policy, Management and Evaluation Dalla Lana School of Public Health University of Toronto Toronto CA
[3]Software Quality Assurance Myant Health Corp. Mississauga CA

Corresponding Author:
Clarissa Pedrini Schuch PhD
Research and Development
Myant Health Corp.
2660 Speakman Dr
Mississauga
CA

Abstract

Background: Smart textiles offer a promising approach to continuous electrocardiogram (ECG) monitoring, but their real-world clinical application lags behind basic feasibility studies. This review comprehensively examines the characteristics and performance of current textile-based ECG devices, synthesizing existing evidence and identifying key challenges. While textile-based ECG electrodes demonstrate good signal quality and comfort, particularly in static conditions, integrating this technology into clinical practice requires addressing critical issues: clinical validation, data privacy and security, cost-effectiveness, user-friendliness, and data interoperability. Successful integration necessitates a collaborative effort encompassing comprehensive evaluation frameworks, regulatory policies, and robust clinical trials.

Objective: This review aims to map the scientific literature on textile-based ECG monitoring systems integrated into clothing and garments. We will comprehensively synthesize evidence from relevant English-language studies with respect to 3 key areas of research in smart textile-based ECG monitoring, namely, comparative signal quality, static and dynamic performance, and user experience. Subsequently, this review will outline current challenges to clinical adoption, integration, and future research directions.

Methods: A Scoping Review of the Literature

Results: While textile-based ECG electrodes demonstrate good signal quality and comfort, particularly in static conditions, integrating this technology into clinical practice requires addressing critical issues: clinical validation, data privacy and security, cost-effectiveness, user-friendliness, and data interoperability. Successful integration necessitates a collaborative effort encompassing comprehensive evaluation frameworks, regulatory policies, and robust clinical trials.

Conclusions: Smart textiles offer the potential for valuable long-term trends in ECG parameters, improving the detection of transient events and reducing intervention times. However, widespread support and adoption within clinical workflows depend on addressing the identified limitations, incorporating user feedback, and demonstrating the clinical utility and cost-effectiveness of this technology. Only with reliable and meaningful data can textile-based ECG monitoring serve as a valuable diagnostic tool to guide care and improve treatment decisions. Clinical Trial: Not applicable

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Abstract
Smart textiles offer a promising approach to continuous electrocardiogram (ECG) monitoring, but their real-world clinical application lags behind basic feasibility studies. This review comprehensively examines the characteristics and performance of current textile-based ECG devices, synthesizing existing evidence and identifying key challenges. While textile-based ECG electrodes demonstrate good signal quality and comfort, particularly in static conditions, integrating this technology into clinical practice requires addressing critical issues: clinical validation, data privacy and security, cost-effectiveness, user-friendliness, and data interoperability. Successful integration necessitates a collaborative effort encompassing comprehensive evaluation frameworks, regulatory policies, and robust clinical trials.

Keywords: Cardiac monitoring; Smart textiles; ECG, Remote patient monitoring, Wearable

1. Introduction

Cardiovascular disease is a leading cause of morbidity and mortality globally, necessitating the development of improved diagnostic and management tools. In recent years, driven by advances in wearable sensors, wireless connectivity, and cloud computing infrastructure, substantial developments have been seen in large-scale ambulatory collection, transmission, and monitoring of various physiological and clinical outcomes [1-3]. As integrated in telemedicine and remote patient monitoring solutions, these advances offer significant potential to improve healthcare delivery, particularly in cardiology, where continuous monitoring is crucial for early disease detection and timely intervention [1,2]. Among wearable technologies, electronic textile sensors have emerged as a promising solution for unobtrusive, continuous physiological monitoring in free-living environments [3,4]. Indeed, smart textiles have seen widespread application in ambulatory electrocardiogram (ECG) monitoring, a central aspect of cardiovascular disease diagnosis and management [5, 6].

ECG monitoring relies on detecting the electrical activity of the heart with electrodes placed on the skin, transmitting the signal for analysis [7]. Long-term ECG monitoring is vital for early detection of physiological deterioration, enabling prompt treatment to prevent severe complications. Advanced textile-based ECG systems, often termed “smart clothing” or “smart textiles,” integrate sensors and electronics within wearable garments [8-10]. These systems offer the potential for continuous and comfortable ECG monitoring using dry electrodes embedded in conductive fabrics or textiles [12]. This approach avoids the discomfort and limitations of conventional gel (Ag/AgCl) electrodes and conductive gels [12], providing a convenient and unobtrusive method for long-term monitoring [5, 12, 13]. Smart textiles can, therefore, reduce the need for invasive monitoring (e.g. loop and event monitors) modalities, and provide a better diagnostic yield.

Despite enthusiasm, however, the adoption of textile-based ECG monitoring in clinical practice remains limited. While extensive research validates the technology’s feasibility, few clinical studies have assessed and validated its real-world effectiveness [11]. Challenges hindering widespread adoption include the need for rigorous clinical validation, compliance with stringent regulatory requirements regarding data privacy and security, data interoperability with electronic health records (EHRs), and the development of user-friendly technologies.

This review aims to map the scientific literature on textile-based ECG monitoring systems integrated into clothing and garments. We will comprehensively synthesize evidence from relevant English-language studies with respect to 3 key areas of research in smart textile-based ECG monitoring, namely, comparative signal quality, static and dynamic performance, and user experience. Subsequently, this review will outline current challenges to clinical adoption, integration, and future research directions.

2. Developments in Smart Textile Technologies for Electrocardiogram Monitoring

The development of smart textiles to monitor ECG has progressed substantially between 2005-2024, encompassing prototype development [14-33] and observational research studies [34-39, 92, 93, 96]. Smart textile technologies reviewed here employ a range of conductive materials (e.g. silver, copper, stainless steel, and metal inks), as incorporated in different garments (e.g., knitted patches, bands, vests, t-shirts, bras, see Table 1). The diversity and versatility of smart textiles have generated a large body of research examining:

1. **Comparative Signal Quality:** To evaluate the signal quality of smart textile electrodes to traditional gel electrodes in evaluating various ECG indices (i.e. QRS complex, P-wave, T-wave, R-peak).
2. **Performance in Static and Dynamic Conditions:** To evaluate the performance of textile electrodes under static (e.g., resting) and dynamic (e.g. movement) conditions, examining the impact of motion artifacts on signal quality.
3. **User Experience:** To evaluate user comfort, which is a critical factor for long-term adoption and use of smart textile-based ECG monitoring platforms, considering factors such as fabric type, electrode placement, and overall wearability.

Table 1: Summary table for all reviewed textile-based ECG monitoring studies

Author	Study type	Objective	Sample size	Wearable Textile features	Measurement setting	Primary outcome	Findings
Paradiso et al., 2005 [14]	Prototype device	Feasibility of a system based on fabric sensing elements	1 healthy subject	Vest with strain fabric sensors based on piezoresistive yarns and fabric electrodes realized with metal-based yarns.	Dynamic (walking on the spot); Simultaneously using fabric and standard electrodes.	ECG (heart rate and QRS duration)	Metal-based fabric electrodes reliably recorded bioelectric potentials related to cardiac activity.
Rienzo et al., 2005 [15]	Prototype device	Test the application of a textile-based wearable device	1 healthy subject	Sensorized vest and a portable electronic board. Two woven electrodes made by conductive fibers so to obtain an ECG lead.	Dynamic (incremental exercise)	ECG (RR-interval)	Textile provided readable signals during the incremental exercise.
Rienzo et al., 2006 [39]	Observational study	Test textile-based wearable device to monitor vital signs in cardiac inpatients	31 cardiac inpatients	Two ECG electrodes, textile-based piezoresistive transducer (vest)	Static and dynamic (cycloergometer and walking)	ECG quality, artifact rate, and capability to identify rhythm abnormalities	Readable signals for more than 99% and 97% of the time in cardiac inpatients lying and pedalling, respectively. Correct identification of the targeted rhythm aberrances.
Mestrovic et al., 2007 [26]	Prototype device	Assess the use of dry fabric electrodes from existing commercially available conductive yarns and filaments.	1 healthy subject	Silver coated nylon (AgNy), stainless steel yarn (SSt), and silver coated copper (AgCu) with different properties. Square patch surrounding each electrode was cut from the knitted bands and adhered to the model garment structure with VelcroTM.	Static (sitting)	ECG	In general, the SSt, AgNy, and AgCu (m), fabric electrode sets led to good ECG signals. The four fabric electrodes ECG waveforms had different attributes, and all had lower signal-to-noise ratios than the reference ECG.
Pola et al., 2007 [27]	Prototype device	Compare the properties of four structurally different textile electrodes.	4 healthy subjects	Four different textile electrodes (silver) were attached to the thorax using an elastic belt (chest band)	Static (sitting) and dynamic (moving arms, jogging).	ECG (QRS-complex, P-wave, T-wave, Noise, baseline short time and long time, baseline level, R peak amplitude variation)	Measurements on dry skin were noisy in most cases due to the high impedance. Jogging caused the biggest problem in measurements. Very good results were obtained with embroidered electrode.
Pandian et al., 2008 [20]	Prototype device	Test a smart textile system for remote monitoring of physiological parameters.	25 healthy subjects	T-shirt which uses an array of sensors (silicon rubber with pure silver fillings) for continuously monitoring physiological signals.	Static (standing) and dynamic (walking); simultaneously using the Smart Vest and reference ECG.	ECG, heart rate, and other parameters	The RR intervals, QRS duration and QT intervals during resting and walking presented good stability. A few data outside the range represented artifacts during recording.
Coyle et al., 2010 [38]	Prototype device	Feasibility of biosensing textiles for monitoring system	N/A	Chest band/vest with three textile electrodes (piezoresistive	Static and dynamic (indoor cycling)	Sensing modules included sweat rate, ECG,	ECG signals gathered during rest showed high quality and reliability, allowing T

				sensor)		respiration, and blood oximetry	wave and morphology analysis.
Perez de Isla et al., (2011) [95]	Feasibility Study	Assess the feasibility of Nuubo dynamic ECG system during exercise echocardiography; compare results with a conventional treadmill system.	31 cardiology patients	nECG SHIRT: Biomedical shirt with integrated textile electrodes (BlendFix®) for ECG signal acquisition.	Exercise echocardiography; simultaneous monitoring with conventional treadmill system (StressVue) and the Nuubo system.	Heart rate (baseline and peak) ST segment (presence, direction, and magnitude of depression or elevation)	Good inter-method agreement for common ECG parameters. Nuubo shirt allowed pre- and post-test echocardiography. System offers continuous, non-invasive, remote monitoring. Initial device had frequency limitations (0.5-100 Hz), affecting ST-segment analysis.
Kannaian et al., 2012 [29]	Prototype device	Feasibility of a textile electrode for continuous physiological monitoring.	3 healthy subjects	Textile electrodes designed by embroidering the conductive yarn on polyester fabric attached in two chest belts using Velcro.	Static	ECG (QRS-complex, P-wave, and T-wave, QT interval, R wave amplitude, stabilization time)	ECG signal from the textile electrode was similar to the gelled electrode. QRS-complex, P wave, and T-wave appeared clearly. After 2 weeks and 4 weeks, performance ratings of the electrode presented no significant changes, making it suitable for long-term monitoring.
Vojtech et al., 2013 [30]	Proof of concept	Development and measurement of wearable textile electrodes for ECG monitoring.	1 healthy subject	T-shirt with sensing electrodes embroidered with yarn based on a mixture of polyester coated with silver nanoparticles and cotton.	Static (lying)	ECG (P waves, QRS complex and T waves).	The amplitude of the individual waves of ECG signal obtained using the textile electrodes was smaller than the reference signal, which was caused by different electrode placements.
Romagnoli et al., (2014) [93]	Observational study	Compare heart rate (HR) and heart rate variability (HRV) parameters obtained using a smart textile system (GOW) with those from a standard ECG during a continuous cycling test in cardiology patients.	12 male cardiology patients	Smart textile system (GOW) with embedded textile electrodes in shirt, transmitting data to an electronic module.	30-minute continuous cycling test at a stable submaximal intensity.	RR intervals, HRV parameters	Excellent agreement between GOW and ECG for RR intervals (LoAs around ±3 ms). Good agreement for MeanRR, SDNN, SD2. Poor agreement for RMSSD, HF, LF/HF, HFnu, and SD1 (wide limits of agreement). The GOW system showed overall good accuracy for HR but limited accuracy for many HRV parameters.
Olmos et al., (2014) [96]	Observational study	Assess the accuracy of the Nuubo dynamic ECG system in diagnosing patients with reflex syncope; compare results to a conventional tilt table test.	31 patients with clinical suspicion of reflex syncope	nECG SHIRT: Biomedical shirt with integrated textile electrodes (BlendFix®) for ECG signal acquisition.	Tilt table test; simultaneous monitoring with the conventional tilt table test system and the Nuubo system.	The maximum PR interval (the time between the P wave and the QRS complex) was measured.	Excellent correlation between Nuubo system and conventional tilt table test for commonly assessed ECG parameters during tilt testing.
Gonzales et al., 2015 [31]	Prototype device	Describe a textile-based ECG monitoring system	N/A	T-shirt with three dry silver-based electrodes.	Static and dynamic (jogging)	ECG quality	Good efficacy of dry electrodes even in a high motion environment.
Weder et	Prototype	Development of an	12 healthy	Two Ag/Ti-	Static and dynamic	ECG (P waves,	The embroidered

al. 2015 [32]	device	embroidered textile electrode for long-term ECG monitoring	subjects	coated polyethylene terephthalate (PET) electrodes embedded into a chest belt.	conditions, moist and dry situations compared to gelled electrodes	QRS complex and T waves).	electrodes presented signals comparable with Ag/AgCl gel electrodes. Textile electrodes showed low impedance, and when moisturized, they were insensitive to motion artifacts.
Pani et al., 2016 [33]	Prototype device	Evaluate textile electrodes based on woven fabrics treated with conducting polymers PEDOT:PSS	10 healthy subjects	Patch of textile electrodes made by treating conventional fabrics with a highly conductive solution of PEDOT:PSS was attached to the skin with adhesive tape.	Static (sitting) and dynamic (deep breathing while sitting, stairs climbing, and stepping); simultaneously fabric (wet and dry) and standard electrodes (Holter monitor).	ECG quality (QRS complex) and electrode-skin contact impedance	Textile electrodes showed a similar performance or even better in wet conditions (both at rest and in motion) than standard electrodes.
Trindade et al., 2016 [16]	Prototype device	Evaluate the design and development of a textile wearable to capture cardio and respiratory signals.	5 patients (hospital setting)	T-shirts comprised of five skin-contact textile electrodes	Static (standing) and dynamic (walking); simultaneously t-shirt and Holter monitoring device.	Real time ECG signals, signal-to-noise ratio amplitude	T-shirt prototypes provided adequate performance in standing states. Motion artifact interference, mainly caused by friction between the textile electrodes and the skin, considerably limited the performance of the prototypes in mobile contexts.
Dai et al., 2016 [21]	Prototype device	Evaluate textile electrodes and a recording circuit specialized for ECG monitoring	6 healthy subjects	Flexible polypyrrole textile electrodes (FPTEs) embedded into a t-shirt (wet electrodes).	Static (sitting) and simultaneously compared to reference ECG.	ECG signal	Heart rate accuracy of each subject was more than 95%, and the average accuracy of the proposed ECG system was 98%.
Yapici et al., 2017 [17]	Prototype device	Development of a wearable textile for ECG monitoring.	1 healthy subject	Graphene-clad conductive textiles on wristband and neckband.	Static. Textile electrodes compared to conventional gel electrodes	Real time ECG (PQRS complexes)	The performance of the prototype wearable ECG wristband was similar to the conventional Ag/AgCl electrodes.
Yu et al., (2017) [94]	Cohort study	Evaluate the performance of a wearable 12-lead ECG T-shirt with textile electrodes for unobtrusive long-term monitoring, focusing on signal quality and artefact detection.	5 male subjects (part of an ongoing, larger clinical trial)	Wearable 12-lead ECG T-shirt with ten dry textile electrode patches (Shieldex Medtex P180) and active electrodes	Daily live for a total of 422 hours	ECG signal quality (50 Hz noise, motion artefacts)	Average per-lead signal coverage ranged from 20.9% to 56.3%. After combining data from all leads (temporal fusion), the overall coverage improved to up to 81.9%. A three-stage artefact detection algorithm was effective in identifying artefacts from 50 Hz noise and motion.
Pagola et al., 2018 [22]	Pilot study	Feasibility of a textile wearable Holter for prolonged cardiac monitoring.	146 stroke patients	3-lead ECG vest and 1-lead ECG chest band	72 h from stroke symptoms onset and during four weeks.	Rate of undiagnosed Atrial Fibrillation (AF) detection, compliance, comfortability, skin lesions,	Both garments had similar comfortability during the day and night. However, the vest group presented a longer time of compliance and time analyzed than the

						and time analyzed.	chest band. The percentage of missed signal was lower in the vest group. The rate of undiagnosed AF detected with textile Holter was 21.9%.
Tsukada et al., 2019 [36]	Observational study	Usefulness of textile electrodes for ECG recording.	66 healthy subjects	T-shirts for men and brassiere for women with textile electrodes sewn to the reverse of the cloth string-shaped electrodes from silk fiber bundles (threads) coated with a conductive polymer, (PEDOT:PSS).	Static (lying, sitting) and dynamic (trunk rotation, stepping); compared to conventional gel electrodes	ECG signal (P, QRS, and T waves), motion artifacts and noise.	P, QRS, and T waves were comparable between the textile and conventional electrodes. No heartbeats were missing from any ECG recordings of either the textile or conventional electrodes under the lying, sitting, or stepping condition. Signal-to-artifact-ratio was better in conventional than textile electrodes and was worst in trunk rotation for both types of electrodes.
Steinberg et al., 2019 [23]	Proof of concept	Assess the signal quality of a wearable ECG sensor system.	15 healthy subjects	Bra or shirt with integrated sensors recording a single-lead ECG.	24-h simultaneous rhythm monitoring using the wearable system with a 3-lead Holter recording.	ECG (P-QRS-T complex).	The wearable ECG sensor's signal quality and accuracy were equivalent to Holter monitoring. Signal coverage of R-R intervals showed a very close overlay between the wearable sensor and Holter signals. The wearable sensor presented high wearing comfort and minimal risk of skin irritation.
Chien-Chin Hsu et al., 2019 [24]	Proof of concept	Test the performance of noncontact textile electrodes.	3 cardiac patients	Noncontact dry electrodes in an elastic chest vest and attached with velcros.	Static (sitting) and dynamic (walking); compared to conventional gel electrodes	ECG	ECG signal quality obtained by the noncontact electrode was similar to the conventional gel electrode. ECG signal quality was also good while walking.
Fouassier et al., 2019 [25]	Pilot study	Evaluate the signal quality of a smart textile compared to a 12-lead Holter recording.	30 healthy subjects	Smart t-shirt composed of 13 textiles electrodes made of silver yarns and hydrogel pads that released water vapour	Static (lying, sitting, standing) and dynamic (walking); compared to 12-lead Holter recording.	ECG (Heart rate, PR, QRS, and QT intervals).	A sinus rhythm was distinguished for all recordings obtained with both smart textile and reference system for all three static conditions. The distinction of P waves, R peaks, and R interval was seen on all ECG tracings with both techniques. The quality of ECG patterns and the overall ECG signal quality was lower in walking conditions for both systems.
Arquilla et al., 2020 [35]	Observational study	Feasibility of a textile-based ECG monitoring	8 healthy subjects	Textile electrodes (silver thread) were sewen in a	Static (sitting); compared to conventional gel	ECG (R-R interval, Heart Rate, comfort)	The sewn electrodes produced clean data, allowing the

				chest-mounted configuration.	electrodes.		measurement of beat-to-beat variability and average HR. No difference in comfort between the adhesive and sewn electrodes was reported.
Li et al., 2020 [18]	Prototype device	Test smart clothing ECG signals.	1 healthy subject	Textile electrodes (silver-coated nylon yarns) knitted into a T-shirt.	Static (lying) and dynamic (jogging).	ECG	The smart clothing showed good performance for measuring ECG signals.
Alizadeh Meghrazi et al., 2020 [13]	Proof of concept	Develop a textile-based multichannel ECG band	6 healthy subjects	Textile electrodes (silver-plated nylon yarns and carbon-coated nylon yarns) knitted in a waistband	Static (sitting and standing) and dynamic (jogging) compared to conventional gel electrodes.	ECG (QRS complex, R peaks)	ECG signals were reliably obtained from different locations on the waist where the shape of the QRS complex was comparable with recordings from the chest using traditional gel electrodes.
Nigussi et al., 2020 [19]	Prototype device	Development of textile electrodes for ECG monitoring	6 healthy subjects	Silver printed textile electrodes from knitted cotton and polyester fabric mounted into a wristband.	Static (sitting) and dynamic (walking); different skin-electrode contact pressures	ECG (P, R, and T peaks and signal intervals like PR, QT, and QRS intervals)	The signals collected by silver printed textile electrodes showed clear R-peaks without missing and false peaks, indicating good waveforms.
Teferra et al., 2021 [34]	Observational study	Evaluate signal quality of textile-based ECG monitoring.	1 healthy subject	Smart vest (t-shirt).	Static (sitting, yawning, deep-breathing, coughing) and dynamic (sitting/standing from a chair, sideways, up movement and climbing stairs); compared to a reference Holter monitor.	ECG (QRS duration and QT intervals), signal to noise ratio	Signal quality was similar between textile-based ECG monitor and Holter. However, the textile-based ECG monitor showed higher accuracy than the Holter monitor for the ECG collected sitting.
Neri et al., (2024) [92]	Observational study	Compare signal quality and user comfort of a novel garment-based single-lead ECG device (YouCare) with a standard Holter monitor.	30 ambulatory patients	Crop top garment embedded polymer-based electrodes, Bluetooth connectivity, cotton/ceramic fabric	24-hour monitoring period, performed activities of daily living.	ECG signal quality (P, QRS, and T) & comfort	YouCare System showed 70% "Good," 12% "Acceptable," and 18% "Not Readable" ECG signals. It had 99.4% R-wave synchronization with Holter and was rated significantly more comfortable than Holter.

2.1 The signal quality of textile-based ECG monitoring compared to gel electrodes

The standard electrocardiogram (ECG) signal comprises morphological features (i.e. P, QRS, and T waves), reflecting atrial and ventricular depolarization and repolarization, and temporal features (i.e. PR, QRS, QT, and RR intervals), representing durations between these events) [5]. These features provide key insights into cardiovascular physiology and pathology, making continuous long-term ECG monitoring essential for detecting cardiovascular disorders and abnormalities [40].

Traditionally evaluated over the long-term using Holter monitors, ambulatory ECG monitoring relies on adhesive gel (Ag/AgCl) electrodes, which provide excellent signal quality [24, 35]. However, long-term use is often limited by skin irritation, gel drying, and electrode detachment due to perspiration [24, 35, 41]. Smart textile electrodes offer a potential solution to these issues by using conductive fabrics, materials, or metals to acquire ECG signals without the need for gels [12].

Demonstration of the accuracy and reliability of smart textile-based ECG monitoring platforms is essential to enhance their adoption in clinical settings. In relation to identifying morphological and temporal ECG features, most studies have focused on the QRS complex, P-wave, T-wave, and R-peak amplitude variations and smart textiles' signal-to-noise ratio. For example, in an early demonstration of the feasibility of textile-based ECG monitoring, Di Rienzo et al. (2005) [15, 89] used a conductive fiber vest to accurately detect arrhythmias and heart rate compared to a traditional ECG recorder, while Paradiso et al. (2005) [14] showed comparable results with a metal-yarn vest. Further research investigated various conductive materials (e.g., silver-coated nylon, stainless steel yarn [26]), electrode placement (chest bands, t-shirts, wristbands [26, 27, 29, 30]), and different textile constructions, demonstrating good signal quality in many studies in agreement with reference devices [13, 17, 19, 21, 23, 26, 29, 30, 35, 92, 93]. However, some studies reported issues such as noise from dry skin [27], signal amplitude discrepancies due to electrode placement [30], and waveform irregularities [43]. While many studies focused on signal quality and accuracy, and some incorporated signal processing algorithms to improve data quality [14, 15, 39, 94], few addressed the integration of textile-based ECG data into clinical practice [42-45].

Critical Analysis:

Eleven of fourteen reviewed studies that assessed the signal quality of textile-based ECG compared to gel electrodes demonstrated good textile-based ECG signal quality, highlighting the technology's promise for long-term monitoring. However, limitations remain: data transmission methods (e.g. Bluetooth, WiFi) often require extensive post-processing; most studies were conducted in controlled laboratory settings with healthy subjects and did not use fully integrated wearable form factors; the clinical validation and long-term feasibility remain insufficiently explored. Future research should address these limitations through more comprehensive real-world studies incorporating diverse populations and integrated clinical workflows to ensure reliable and meaningful data.

2.2 Textile-based ECG monitoring performance during static and dynamic conditions

The inherent flexibility of textile-based ECG systems introduces challenges related to motion artifacts. Di Rienzo et al. (2010) [90] explored the impact of dynamic conditions, examining the impact of motion artifacts on signal quality in telemedicine applications. The electrode-skin interface is particularly susceptible to disruption during dynamic movements, leading to noise and signal degradation, especially with dry or hairy skin [12, 19, 33, 37]. Numerous studies have investigated the impact of both static (sitting, lying, standing) and dynamic (walking, jogging, sit-to-stand) activities on ECG signal quality [16, 20, 24, 25, 31, 32, 36, 38, 39, 42, 93, 94]. For example, Perez de Isla et al. (2011) [95] evaluated a dynamic ECG monitoring system (Nuubo's dynamic ECG) against a conventional treadmill-based ECG monitoring system during exercise electrography, and found comparable performance between the two systems on baseline and peak heart rates. Similar results were also seen by Olmos et al. (2014) [96] for heart rate and maximum PR interval on the tilt table test between Nuubo's technology ECG shirt and conventional ECG monitoring.

While many studies demonstrated adequate detection of QRS complexes and rhythm abnormalities even during moderate dynamic activity [20, 38, 39, 42, 93], motion artifacts significantly impacted signal quality in more strenuous activities [16, 25, 33, 36]. For instance, Di Rienzo et al. (2006, 2013) [39, 91] observed adequate QRS complex detection during walking and pedalling, while Pandian et al. (2008) [20] reported good consistency in RR, QRS, and QT intervals during walking with a textile vest. However, Trindade et al. (2016) [16] noted higher noise amplitude with textile electrodes compared to gel electrodes during walking, and Tsukada et al. (2019) [36] observed increased motion artifacts with trunk twisting.

Strategies to mitigate motion artifacts in these studies included optimizing electrode placement, using compression bands to enhance electrode-skin contact, and employing skin moisturizers or humidification techniques [12, 16, 33]. The use of a wetting device was also shown to improve signal quality in both static and dynamic conditions [32].

Critical Analysis:

Textile-based ECG systems generally perform well under static conditions, achieving comparable or even superior results to traditional gel electrodes in many studies. However, dynamic activities introduce significant noise and motion artifacts, impacting signal quality. While techniques exist to mitigate these issues (electrode placement optimization, compression bands, humidification), further advancements in signal processing and machine learning are needed to reliably extract clinically meaningful data during dynamic conditions [44-46, 94]. Continuous signal quality assessment is crucial for accurate long-term ECG monitoring in real-world settings.

2.3. User's comfort wearing textile-based electrodes

The long-term success of textile-based ECG monitoring hinges on user acceptance, which is intrinsically linked to comfort and ease of use [12, 47]. While high signal quality and accuracy are crucial, a comfortable and unobtrusive system is essential for encouraging prolonged wear and consistent data acquisition [6]. However, user comfort has been under-investigated, with only a few studies addressing this critical aspect as a secondary outcome [22, 23, 35, 48].

Existing studies offer some insights into user perceptions. Pagola et al. (2018) [22] found that a textile vest was preferred over a chest band for long-term use in post-stroke patients, with comparable comfort levels across day and night. Wu et al. (2018) [48] reported that flexible, skincontacting textile electrodes embedded in t-shirts were more comfortable than traditional gel electrodes. Neri et al. (2024) [92] compared a garment-based ECG device to a standard Holter monitor and found that patients rated the garment significantly more comfortable. Steinberg et al. (2019) [23] also noted high comfort and low skin irritation with textile-based ECG sensors integrated into bras and shirts during 24-hour monitoring, while Arquilla et al. (2020) [35] found no significant comfort difference compared to traditional electrodes.

Critical Analysis:

Although preliminary findings suggest textile electrodes offer comparable or superior comfort to traditional methods, this remains a relatively under-researched area. The limited number of studies and small sample sizes hinder definitive conclusions. Future research should prioritize systematic user testing, employing validated questionnaires and incorporating diverse user populations to provide a more comprehensive understanding of comfort-related factors, including textile material, design, and electrode placement. This information is critical for optimizing textile-based ECG system design and promoting wider adoption. Understanding user preferences and expectations regarding comfort and ease of use are also key factors influencing long-term technology adoption.

3. Roadmap of Smart Textiles application for ECG monitoring

The rapid evolution of telemedicine and digital health tools presents significant opportunities to improve cardiovascular disease management [49-51]. Smart textiles offer a promising pathway towards enhanced remote patient monitoring, providing benefits for patients, healthcare providers, and the overall healthcare system. However, successful integration requires addressing several key aspects:

1. Wearable Data Acquisition: This pillar focuses on developing robust and reliable wearable systems capable of accurately monitoring, collecting, and pre-processing ECG data from textile-based sensors. This includes considerations such as sensor design, electrode placement, and signal quality under various conditions.

2. Data Transmission and Communication: Seamless and secure transmission of ECG data from the wearable device to a remote monitoring center (smartphone or PC) is crucial. This necessitates robust and reliable data communication networks, addressing issues such as signal strength, data security, and bandwidth limitations.

3. Cloud-Based Data Analytics and Clinical Integration: A powerful cloud-based analytics platform is needed to process, analyze, and interpret ECG data efficiently, providing clinicians with readily accessible, accurate, and clinically relevant information [2, 6, 9]. This platform must facilitate timely alerts for acute events, support offline data access, and seamlessly integrate with existing EHRs. Data processing and analysis techniques are essential components of this system, requiring sophisticated algorithms to filter noise, identify key patterns, and provide meaningful interpretations [52, 53]. The scalability and reliability of the backend infrastructure, including data storage and retrieval, are essential factors determining the system's performance.

Clinicians require user-friendly clinical portals to visualize and manage this data effectively, enabling timely diagnosis and intervention. Patients and caregivers should have access to relevant information for their self-management and remote health monitoring (Figure 1). Finally, user training and education are critical, particularly for individuals with low digital literacy [55]. Addressing these three pillars will be key to realizing the full potential of smart textiles in improving cardiovascular care.

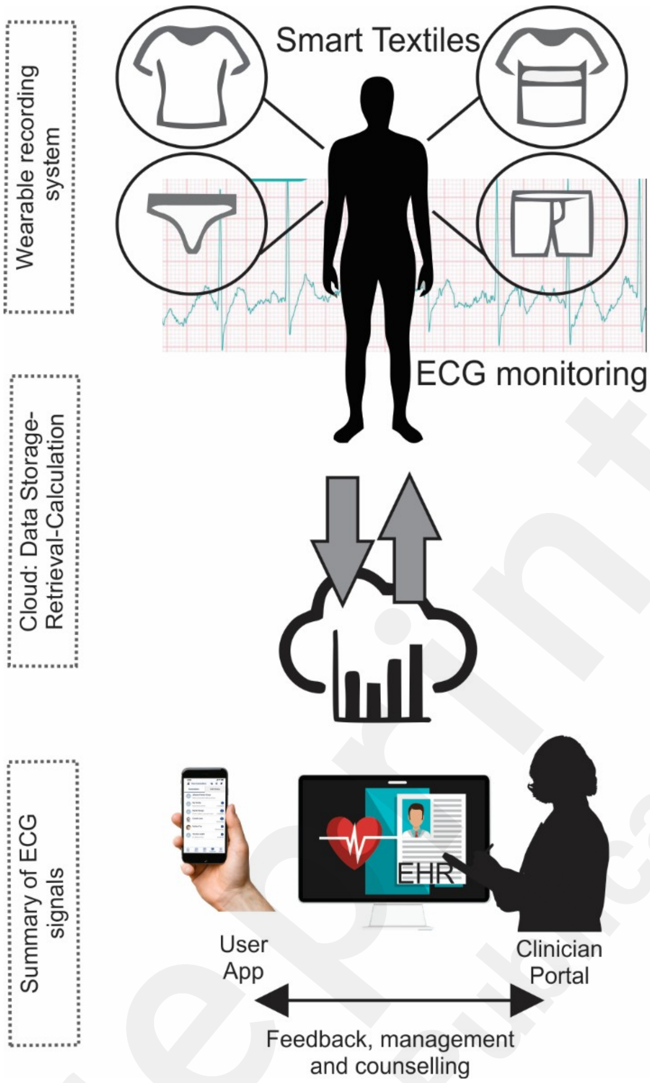

Figure 1: Smart textiles data workflow and integration in clinical practice. Textile-based sensors embedded in clothes/garments continuously measure ECG signals.

3.1Challenges

While textile-based ECG technology shows promise in terms of signal quality, several challenges must be addressed to facilitate its broader adoption in clinical practice. This section outlines key obstacles across three interconnected areas: technology, data management, and clinical workflow integration (Figure 2, Table 2).

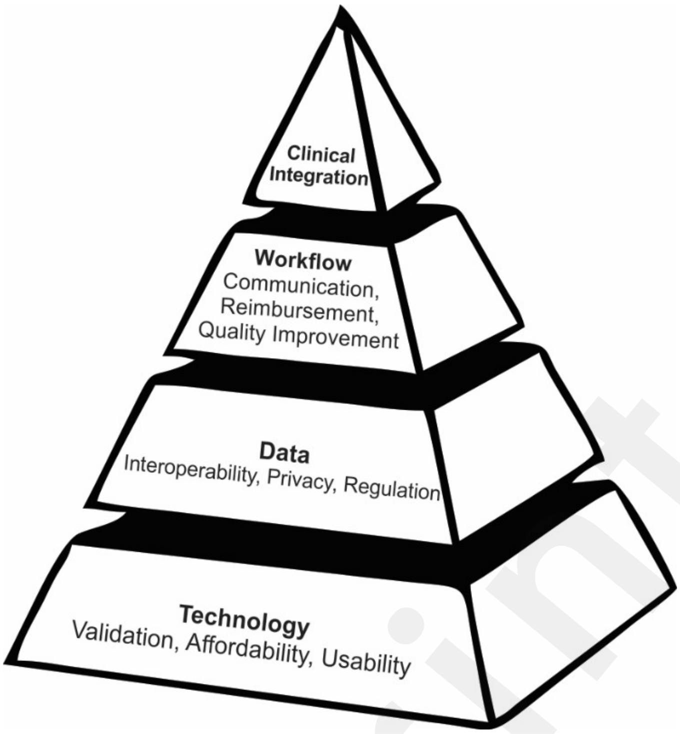

Figure 2: Challenges for smart textile integration into clinical practice.

3.1.1 Technological Challenges:

- **Clinical Validation:** While numerous studies demonstrate the feasibility of textile-based ECG electrodes in terms of signal quality, none have yet achieved routine clinical adoption (Technological Readiness Level 9). A substantial body of clinical data is needed to validate the technology's fidelity, interoperability, safety, and effectiveness as intended [56].
- **Affordability and Cost:** While smart textiles could potentially reduce healthcare costs through optimized patient management and early intervention [44], this remains unsubstantiated. The cost-effectiveness of this technology needs further investigation, considering both initial investment and long-term operational costs [57-59]. Reimbursement policies from insurance companies and governments are crucial for broader accessibility [60, 61].
- **Usability and Acceptability:** Limited research exists on user perceptions and acceptance of smart textile ECG monitoring. Factors like comfort (thermal, tactile, style, pressure), ease of use, perceived value, and the ability to share data with healthcare providers significantly

influence user adoption [61-65]. Further research employing user-centered design methodologies (surveys, focus groups, interviews) is essential [66, 67], using frameworks such as the Technology Acceptance Model to understand user behavior [62, 63].

3.1.2 Data-Related Challenges:

- **Privacy and Security:** The collection and transmission of sensitive physiological data through smart textiles raise significant privacy and security concerns [68]. Robust data protection measures, secure data storage, and transparent data usage policies are essential to safeguard patient information and ensure compliance with relevant regulations [4, 44, 69]. Informed consent and authorized user access are paramount.
- **Interoperability:** Seamless integration of smart textile ECG data with existing EHRs and other healthcare systems is essential for efficient remote patient monitoring [70-72]. This requires consistent data formats, standard communication protocols, and a cloud-based architecture that ensures data exchange and interoperability across different service providers [56].
- **Regulatory Policy:** The rapid evolution of smart textile technology necessitates a review and update of existing regulatory frameworks [73]. Clear standards and guidelines are needed to ensure safety and effectiveness, particularly concerning data privacy and security, in accordance with regulations like HIPAA and FDA guidelines [74]. Transparent policies regarding data collection, usage, and sharing are crucial for building trust and facilitating adoption [75].

3.1.3 Clinical Workflow Challenges:

- **Communication and Feedback:** Effective communication and feedback between patients and healthcare providers are vital components of remote patient monitoring [76]. User-friendly clinical dashboards, timely alerts, and efficient reporting mechanisms are required to ensure timely intervention and improve clinical decision-making [54, 72, 77]. However, challenges include potential delays due to data loss, network issues, and data overload [8, 51].

- **Reimbursement:** Clear reimbursement pathways are necessary to ensure the financial viability of smart textile ECG monitoring within the healthcare system [77, 78]. The cost-effectiveness of the technology must be demonstrated, and sustainable reimbursement models developed, considering various factors such as monitoring duration and service provision [79, 80]. Clinician surveys suggest a need for shared cost responsibility between patients, insurance companies, and the government [81].
- **Quality Improvement:** Integrating smart textile data into established clinical workflows enables continuous learning and improvement through feedback loops and data-driven insights [49, 82-85]. This requires robust data analysis methods, the development of meaningful clinical indicators, and a strong focus on data-driven decision-making within the healthcare system. A structured approach to quality improvement, including infrastructural and organizational changes, is crucial for maximizing the benefits of smart textile technology.

Table 2 - Challenges and recommendations for smart textile integration into clinical practice

Theme	Challenges for clinical integration	Recommendation
Technology	Lack of clinical validation of smart textiles for ECG monitoring. Poor data validity hampers the repeatability of measurements and impairs interoperability and data exchange.	Extensive clinical validation regarding the safety, effectiveness and performance of the smart textile to monitor physiological data over long periods in free-living conditions.
	Affordability and cost may limit the uptake of the smart textile for ECG monitoring	Private insurance companies and Government may partially support the cost of smart textiles for ECG monitoring.
	Absence of information about user needs, perception and acceptance of the smart textile for ECG monitoring.	A comprehensive understanding of users' perceived value, perceived usefulness, perceived ease of use, and satisfaction must be met by health care professionals and users for widespread adoption of smart textile devices. Surveys, interviews and focus groups to address the user acceptability issue.
Data	User privacy and security concerns related to misuse of personal health information during data transfer and real-time data streaming.	Clear guidelines providing the privacy, confidentiality and proper user of electronic medical information. Ensure that users feel comfortable and confident sharing a significant amount of data with data analytic companies, health care providers, and insurance companies.

	Inefficient interoperability among devices, applications, systems, and domains.	Uniform and straightforward data formats; standard communication protocols for information exchange between smart textiles and other platforms.
	Absence of clear regulatory policies governing smart textile for ECG monitoring	Adopt devices cleared/approved by regulatory agencies (i.e., FDA). Expansion of HIPAA policies aligned with remote patient monitoring technologies such as smart textiles.
Clinical workflow	Exchange and communication about actionable or urgent data between health care providers and patients/caregivers, the frequency of data review and the personnel reviewing the data need to be determined. Data overload might hamper appropriate and timely feedback.	Development of clinical dashboard for data reporting. Operationalize and triage the data and define realistic response time. Health care providers can review regularly acquired ECGs during in-person or virtual visits. Timely feedback can be guaranteed if the platform allows the health care provider to set customizable notifications, for example, in case of an abnormal event is detected.
	Reimbursement structures are not fully implemented for remote patient monitoring using smart textiles technologies.	Clear reimbursement models addressing remote monitoring and data review. More studies to assess the costs and cost-effectiveness of remote monitoring are necessary to determine reasonable reimbursement rates.
	Challenges using digital health data gathered from electronic health record systems, personal health records, and other systems (e.g., smart textile) for clinical quality improvement.	Clear regulations to use the smart textile data, allowing it to be aggregated, linked with other forms of data, and leveraged to generate new knowledge and promote clinical quality improvement.

4. Future directions

This review highlights the significant progress in textile-based ECG monitoring, primarily focusing on signal quality. However, translating this technological promise into widespread clinical adoption requires addressing several crucial limitations. While the potential is exciting, challenges persist in integrating smart textile data into current EHR workflows. Concerns remain about clinical validity, patient privacy, cost-effectiveness, timely feedback mechanisms, user-friendliness, and data interoperability. From a healthcare provider's perspective, reliable data extraction, distinguishing actionable data from noise, and understanding ECG prediction algorithms are critical. Effective workflow integration requires establishing data review frequency via a clinical portal, protocols for follow-up communication regarding urgent findings, and a clear remuneration structure. A structured approach, such as the previously proposed ABCD framework [44], can guide the integration of wearable devices into clinical practice. Overcoming these challenges necessitates collaboration among various stakeholders to develop robust evaluation frameworks, implement appropriate regulatory policies, and conduct comprehensive clinical trials. This process must also incorporate continuous learning and improvement based on real-world data from routine patient care. Furthermore, robust evaluation frameworks must incorporate both clinical and patient perspectives [62, 63, 86].

The reviewed studies primarily assessed ECG signal quality in healthy participants within controlled laboratory settings. This limits the generalizability of findings and highlights the need for real-world studies incorporating diverse populations and health conditions. The current proof-of-concept studies and feasibility testing [72, 87], although essential for establishing minimum viable products, do not fully represent the complexities of clinical practice. Integration into mobile apps and clinical portals is also needed. Therefore, definitive conclusions about the effective use and integration of smart textiles in clinical ECG monitoring cannot yet be drawn. A clear, pragmatic, and unified approach to validating this technology is essential [88]. This validation must be an ongoing process, requiring a collaborative environment among manufacturers, technology developers, regulators, and healthcare providers.

In conclusion, smart textiles offer the potential for valuable long-term trends in ECG parameters, improving the detection of transient events and reducing intervention times. However, widespread support and adoption within clinical workflows depend on addressing the identified limitations, incorporating user feedback, and demonstrating the clinical utility and cost-effectiveness of this technology. Only with reliable and meaningful data can textile-based ECG monitoring serve as a valuable diagnostic tool to guide care and improve treatment decisions.

Acknowledgements

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Conflicts of Interest

Clarissa Pedrini Schuch, Gabriela Chaves, Bastien Moineau, Sarah Bennett, Meysam Pirbaglou, Edwin Martin Lobo, and Milad Alizadeh-Meghrazi are current or former employees of Myant Health Corp., a manufacturer of textile-based technologies. Dr. Schuch was also a MITACS intern at Myant during her postdoctoral fellowship at the University of Toronto.

List of abbreviations

Electrocardiogram (ECG)
Silver/Silver chloride electrodes (Ag/AgCl electrodes)
Electronic health record (EHR)
Food and Drug Administration (FDA)
Health Insurance Portability and Accountability Act (HIPAA)

References

[1] Markert C, Sasangohar F, Mortazavi BJ, et al. The use of telehealth technology to support health coaching for older adults: literature review. *JMIR Hum Factors* 2021; 8: 1–10.

[2] Malekian Borujeni A, Fathy M, Mozayani N. A hierarchical, scalable architecture for a real-time monitoring system for an electrocardiography, using context-aware computing. *J Biomed Inform* 2019; 96: 103251.

[3] Soon S, Svavarsdottir H, Downey C, et al. Wearable devices for remote vital signs monitoring in the outpatient setting: An overview of the field. *BMJ Innov* 2020; 6: 55.

[4] Le K, Narayana H, Servati A, et al. Electronic textiles for electrocardiogram monitoring: A review on the structure–property and performance evaluation from fiber to fabric. *Textile Research Journal.* 2022;93(3-4):878-910.

[5] Nigusse AB, Mengistie DA, Malengier B, et al. Wearable smart textiles for long-term electrocardiography monitoring—a review. *Sensors*; 21. Epub ahead of print 2021. DOI: 10.3390/s21124174.

[6] Sana F, Isselbacher EM, Singh JP, et al. Wearable Devices for Ambulatory Cardiac Monitoring: JACC State-of-the-Art Review. *J Am Coll Cardiol* 2020; 75: 1582–1592.

[7] Ashley EA, Raxwal VK, Froelicher VF. The prevalence and prognostic significance of electrocardiographic abnormalities. *Curr Probl Cardiol* 2000; 25: 1–72.

[8] Baig MM, Gholamhosseini H, Connolly MJ. A comprehensive survey of wearable and wireless ECG monitoring systems for older adults. *Med Biol Eng Comput* 2013; 51: 485–495.

[9] Duncker D, Ding WY, Etheridge S, et al. Smart wearables for cardiac monitoring—real-world use beyond atrial fibrillation. *Sensors* 2021; 21: 1–25.

[10] Stoppa M, Chiolerio A. Wearable electronics and smart textiles: A critical review. *Sensors (Switzerland)* 2014; 14: 11957–11992.

[11] Teixeira E, Fonseca H, Diniz-Sousa F, et al. Wearable Devices for Physical Activity and Healthcare Monitoring in Elderly People: A Critical Review. *Geriatrics* 2021; 6: 38.

[12] Majumder S, Mondal T, Deen MJ. Wearable sensors for remote health monitoring. *Sensors (Switzerland)*; 17. Epub ahead of print 2017. DOI: 10.3390/s17010130.

[13] Alizadeh Meghrazi M, Alizadeh Meghrazi M, Tian Y, et al. Multichannel ECG recording from waist using textile sensors. *Biomed Eng Online* 2020; 19: 1–18.

[14] Paradiso R, Loriga G, Taccini N. A wearable health care system based on knitted integrated sensors. *IEEE Trans Inf Technol Biomed* 2005; 9: 337–344.

[15] Di Rienzo M, Rizzo F, Parati G, et al. MagIC system: A new textile-based wearable device for biological signal monitoring. Applicability in daily life and clinical setting. *Annu Int Conf IEEE Eng Med Biol - Proc* 2005; 7 VOLS: 7167–7169.

[16] Trindade IG, da Silva JM, Miguel R, et al. Design and evaluation of novel textile wearable systems for the surveillance of vital signals. *Sensors (Switzerland)*; 16. Epub ahead of print 2016. DOI: 10.3390/s16101573.

[17] Yapici MK, Alkhidir TE. Intelligent medical garments with graphene-functionalized smart-cloth ECG sensors. *Sensors (Switzerland)* 2017; 17: 1–12.

[18] Li M, Xiong W, Li Y. Wearable measurement of ECG signals based on smart clothing. *Int J Telemed Appl* 2020; 2020: 6–10.

[19] Nigusse AB, Malengier B, Mengistie DA, et al. Development of washable silver printed textile electrodes for long-term ECG monitoring. *Sensors (Switzerland)* 2020; 20: 1–16.

[20] Pandian PS, Mohanavelu K, Safeer KP, et al. Smart Vest: Wearable multi-parameter remote physiological monitoring system. *Med Eng Phys* 2008; 30: 466–477.

[21] Dai M, Xiao X, Chen X, et al. A low-power and miniaturized electrocardiograph data collection system with smart textile electrodes for monitoring of cardiac function. *Australas Phys Eng Sci Med* 2016; 39: 1029–1040.

[22] Pagola J, Juega J, Francisco-Pascual J, et al. Yield of atrial fibrillation detection with Textile Wearable Holter from the acute phase of stroke: Pilot study of Crypto-AF registry. *Int J Cardiol* 2018; 251: 45–50.

[23] Steinberg C, Philippon F, Sanchez M, et al. A novel wearable device for continuous

ambulatory ECG recording: Proof of concept and assessment of signal quality. *Biosensors* 2019; 9: 1–13.

[24] Hsu CC, Lin BS, He KY, et al. Design of a wearable 12-lead noncontact electrocardiogram monitoring system. *Sensors (Switzerland)*; 19. Epub ahead of print 2019. DOI: 10.3390/s19071509.

[25] Fouassier D, Roy X, Blanchard A, et al. Assessment of signal quality measured with a smart 12-lead ECG acquisition T-shirt. *Ann Noninvasive Electrocardiol* 2020; 25: 1–7.

[26] Mestrovic MA, Helmer RJN, Kyratzis L, et al. Preliminary study of dry knitted fabric electrodes for physiological monitoring. *Proc 2007 Int Conf Intell Sensors, Sens Networks Inf Process ISSNIP* 2007; 601–606.

[27] Pola T, Vanhala J. Textile electrodes in ECG measurement. *Proc 2007 Int Conf Intell Sensors, Sens Networks Inf Process ISSNIP* 2007; 635–639.

[28] Despang HG, Netz S, Heinig A, et al. Wireless long-term ECG integrated into clothing. *Biomed Tech* 2008; 53: 270–278.

[29] Kannaian T, Neelaveni R, Thilagavathi G. Design and development of embroidered textile electrodes for continuous measurement of electrocardiogram signals. *J Ind Text* 2013; 42: 303–318.

[30] Vojtech L, Bortel R, Neruda M, et al. Wearable textile electrodes for ECG measurement. *Adv Electr Electron Eng* 2013; 11: 410–414.

[31] Gonzales L, Walker K, Keller K, et al. Textile sensor system for electrocardiogram monitoring. In: *2015 IEEE Virtual Conference on Applications of Commercial Sensors (VCACS)*. IEEE, pp. 1–4.

[32] Weder M, Hegemann D, Amberg M, et al. Embroidered electrode with silver/titanium coating for long-term ECG monitoring. *Sensors (Switzerland)* 2015; 15: 1750–1759.

[33] Pani D, Dessi A, Saenz-Cogollo JF, et al. Fully Textile, PEDOT:PSS Based Electrodes for Wearable ECG Monitoring Systems. *IEEE Trans Biomed Eng* 2016; 63: 540–549.

[34] Teferra MN, Hobbs DA, Clark RA, et al. Preliminary Analysis of a Wireless and Wearable Electronic-Textile EASI-Based Electrocardiogram. *Front Cardiovasc Med*; 8. Epub ahead of print 2021. DOI: 10.3389/fcvm.2021.806726.

[35] Arquilla K, Webb AK, Anderson AP. Textile electrocardiogram (Ecg) electrodes for wearable health monitoring. *Sensors (Switzerland)* 2020; 20: 1–13.

[36] Tsukada YT, Tokita M, Murata H, et al. Validation of wearable textile electrodes for ECG monitoring. *Heart Vessels* 2019; 34: 1203–1211.

[37] Balsam P, Lodziński P, Tymińska A, et al. Study design and rationale for biomedical shirt-based electrocardiography monitoring in relevant clinical situations: ECG-shirt study. *Cardiol J* 2018; 25: 52–59.

[38] Coyle S, Lau KT, Moyna N, et al. BIOTEXBiosensing textiles for personalised healthcare management. *IEEE Trans Inf Technol Biomed* 2010; 14: 364–370.

[39] Di Rienzo M, Rizzo F, Meriggi P, et al. Applications of a textile-based wearable system for vital signs monitoring. *Annu Int Conf IEEE Eng Med Biol - Proc* 2006; 2223–2226.

[40] Rodrigues MJ, Postolache O, Cercas F. Physiological and behavior monitoring systems for smart healthcare environments: A review. *Sensors (Switzerland)* 2020; 20: 1–26.

[41] Marozas V, Petrenas A, Daukantas S, et al. A comparison of conductive textile-based and silver/silver chloride gel electrodes in exercise electrocardiogram recordings. *J Electrocardiol* 2011; 44: 189–194.

[42] Teferra MN, Ramos JS, Kourbelis C, et al. Electronic textile-based electrocardiogram monitoring in cardiac patients: a scoping review. *JBI database Syst Rev Implement reports* 2019; 17: 1958–1998.

[43] Li M, Xiong W, Li Y. Wearable measurement of ECG signals based on smart clothing. *Int J Telemed Appl*; 2020. Epub ahead of print 2020. DOI: 10.1155/2020/6329360.

[44] Bayoumy K, Gaber M, Elshafeey A, et al. Smart wearable devices in cardiovascular care: where we are and how to move forward. *Nat Rev Cardiol*; 0123456789. Epub ahead of print 2021. DOI: 10.1038/s41569-021-00522-7.

[45] Chatterjee S, Thakur RS, Yadav RN, et al. Review of noise removal techniques in ECG signals. *IET Signal Process* 2020; 14: 569–590.

[46] Smital L, Haider CR, Vitek M, et al. Real-Time Quality Assessment of Long-Term ECG Signals Recorded by Wearables in Free-Living Conditions. *IEEE Trans Biomed Eng* 2020; 67: 2721–2734.

[47] Serhani MA, El Kassabi HT, Ismail H, et al. ECG monitoring systems: Review, architecture, processes, and key challenges. *Sensors (Switzerland)*; 20. Epub ahead of print 2020. DOI: 10.3390/s20061796.

[48] Wu W, Pirbhulal S, Sangaiah AK, et al. Optimization of signal quality over comfortability of textile electrodes for ECG monitoring in fog computing based medical applications. *Futur Gener Comput Syst* 2018; 86: 515–526.

[49] Nwaru BI, Friedman C, Halamka J, et al. Can learning health systems help organisations deliver personalised care? *BMC Med* 2017; 15: 1–8.

[50] Molinari G, Molinari M, Di Biase M, et al. Telecardiology and its settings of application: An update. *J Telemed Telecare* 2018; 24: 373–381.

[51] Slotwiner DJ, Tarakji KG, Al-Khatib SM, et al. Transparent sharing of digital health data: A call to action. *Hear Rhythm* 2019; 16: e95–e106.

[52] Yang Z, Zhou Q, Lei L, et al. An IoT-cloud Based Wearable ECG Monitoring System for Smart Healthcare. *J Med Syst*; 40. Epub ahead of print 2016. DOI: 10.1007/s10916-016-0644-9.

[53] Hill DD, Garcia HMC. The Integration of Patient Health Record Generated from Wearable and Internet of Things Devices into Health Information Exchanges. 2021; 15: 112–116.

[54] Kildea J, Battista J, Cabral B, et al. Design and development of a person-centered patient portal using participatory stakeholder co-design. *J Med Internet Res* 2019; 21: 1–16.

[55] Gordon WJ, Landman A, Zhang H, et al. Beyond validation: getting health apps into clinical practice. *npj Digit Med* 2020; 3: 14.

[56] Pustiek M, Beristain A, Kos A. Challenges in Wearable Devices Based Pervasive Wellbeing Monitoring. In: *2015 International Conference on Identification, Information, and Knowledge in the Internet of Things (IIKI)*. IEEE, pp. 236–243.

[57] Bergmo TS. Economic evaluation in telemedicine – still room for improvement. *J Telemed Telecare* 2010; 16: 229–231.

[58] Chan M, Estève D, Fourniols J-Y, et al. Smart wearable systems: Current status and future challenges. *Artif Intell Med* 2012; 56: 137–156.

[59] Karunathilake SP, Ganegoda GU. Secondary Prevention of Cardiovascular Diseases and Application of Technology for Early Diagnosis. *Biomed Res Int* 2018; 2018: 1–9.

[60] Patel S, Park H, Bonato P, et al. A review of wearable sensors and systems with application in rehabilitation. *J Neuroeng Rehabil* 2012; 9: 1–17.

[61] Ferguson C, Inglis SC, Breen PP, et al. Clinician perspectives on the design and application of wearable cardiac technologies for older adults: Qualitative study. *JMIR Aging* 2020; 3: 1–8.

[62] Gao Y, Li H, Luo Y. An empirical study of wearable technology acceptance in healthcare. *Ind Manag Data Syst* 2015; 115: 1704–1723.

[63] Abu-Dalbouh HM. A questionnaire approach based on the technology acceptance model for mobile tracking on patient progress applications. *J Comput Sci* 2013; 9: 763–770.

[64] Bove LA. Increasing Patient Engagement Through the Use of Wearable Technology. *J Nurse Pract* 2019; 15: 535–539.

[65] Wu W, Pirbhulal S, Sangaiah AK, et al. Optimization of signal quality over comfortability of

textile electrodes for ECG monitoring in fog computing based medical applications. *Futur Gener Comput Syst* 2018; 86: 515–526.

[66] Vaportzis E, Clausen MG, Gow AJ. Older adults perceptions of technology and barriers to interacting with tablet computers: A focus group study. *Front Psychol* 2017; 8: 1–11.

[67] Moineau B, Myers M, Ali SS, et al. End-user and clinician perspectives on the viability of wearable functional electrical stimulation garments after stroke and spinal cord injury. *Disabil Rehabil Assist Technol* 2019; 0: 1–10.

[68] Torous JB, Chan SR, Gipson SY-MT, et al. A Hierarchical Framework for Evaluation and Informed Decision Making Regarding Smartphone Apps for Clinical Care. *Psychiatr Serv* 2018; 69: 498–500.

[69] Kotz D, Gunter CA, Kumar S, et al. Privacy and Security in Mobile Health: A Research Agenda. *Computer (Long Beach Calif)* 2016; 49: 22–30.

[70] Ndlovu K, Mars M, Scott RE. Interoperability frameworks linking mHealth applications to electronic record systems. *BMC Health Serv Res* 2021; 21: 1–10.

[71] El-Sappagh S, Ali F, Hendawi A, et al. A mobile health monitoring-and-treatment system based on integration of the SSN sensor ontology and the HL7 FHIR standard. *BMC Med Inform Decis Mak* 2019; 19: 97.

[72] Genes N, Violante S, Cetrangol C, et al. From smartphone to EHR: a case report on integrating patient-generated health data. *npj Digit Med* 2018; 1: 23.

[73] August NY, Et PM, Herzeca LF. E-Textiles : Regulating The Future Of Fashion.

[74] Accenture Federal Services. *Conceptualizing a Data Infrastructure for the Capture, Use, and Sharing of Patient-Generated Health Data in Care Delivery and Research through 2024 Draft White Paper for a PGHD Policy Framework*. 2016.

[75] The Office of the National Coordinator (ONC) for Health Information Technology. Connecting Health and Care for the Nation. *ONC Rep* 2015; 1–9.

[76] Elm JJ, Daeschler M, Bataille L, et al. Feasibility and utility of a clinician dashboard from wearable and mobile application Parkinson's disease data. *npj Digit Med*; 2. Epub ahead of print 2019. DOI: 10.1038/s41746-019-0169-y.

[77] Gordon WJ, Landman A, Zhang H, et al. Beyond validation: getting health apps into clinical practice. *npj Digit Med*; 3. Epub ahead of print 2020. DOI: 10.1038/s41746-019-0212-z.

[78] Chan M, Estève D, Fourniols JY, et al. Smart wearable systems: Current status and future challenges. *Artif Intell Med* 2012; 56: 137–156.

[79] Centers for Medicare & Medicaid Services (CMS). Physician Fee Schedule. 2021; 1–33.

[80] Smuck M, Odonkor CA, Wilt JK, et al. The emerging clinical role of wearables: factors for successful implementation in healthcare. *npj Digit Med* 2021; 4: 45.

[81] Manninger M, Zweiker D, Svennberg E, et al. Current perspectives on wearable rhythm recordings for clinical decision-making: the wEHRAbles 2 survey. *EP Eur* 2021; 1–8.

[82] Menear M, Blanchette MA, Demers-Payette O, et al. A framework for value-creating learning health systems. *Heal Res Policy Syst* 2019; 17: 1–13.

[83] Mason AR, Barton AJ. The emergence of a learning healthcare system. *Clin Nurse Spec* 2013; 27: 7–9.

[84] Friedman CP, Wong AK, Blumenthal D. Policy: Achieving a nationwide learning health system. *Sci Transl Med* 2010; 2: 1–4.

[85] Friedman CP, Rubin JC, Sullivan KJ. Toward an Information Infrastructure for Global Health Improvement. *Yearb Med Inform* 2017; 26: 16–23.

[86] Venkatesh, Thong, Xu. Consumer Acceptance and Use of Information Technology: Extending the Unified Theory of Acceptance and Use of Technology. *MIS Q* 2012; 36: 157.

[87] Shah SS, Gvozdanovic A. Digital health; what do we mean by clinical validation? *Expert Rev Med Devices* 2021; 18: 5–8.

[88] John C. Mankins. Technology readiness levels. *J Chem Inf Model* 2004; 53: 1689–1699.

[89] Di Rienzo M, Rizzo F, Parati G, Ferratini M, Brambilla G, Castiglioni P. A textile-based wearable system for vital sign monitoring: applicability in cardiac patients. *Comput Cardiol*. IEEE; 2005. p. 699–701.

[90] Di Rienzo M, Meriggi P, Rizzo F, Castiglioni P, Lombardi C, Ferratini M, et al. Textile technology for the vital signs monitoring in telemedicine and extreme environments. IEEE *Trans Inf Technol Biomed* 2010;14(3):711–7.

[91] Di Rienzo M, Racca V, Rizzo F, Bordoni B, Parati G, Castiglioni P, et al. Evaluation of a textile-based wearable system for the electrocardiogram monitoring in cardiac patients. *Europace* 2013;15(4):607–12.

[92] Neri, L., Corazza, I., Oberdier, M.T. *et al.* Comparison Between a Single-Lead ECG Garment Device and a Holter Monitor: A Signal Quality Assessment. *J Med Syst*, 2024; 48(57): 1-7.

[93] Romagnoli M, Alis R, Guillen J, Basterra J, Villacastin JP, Guillen S. A novel device based on smart textile to control heart's activity during exercise. *Australas Phys Eng Sci Med*. 2014;37(2):377-84.

[94] Yu X, Boehm A, Neu W, Venema B, et al. A wearable 12-lead ECG T-shirt with textile electrodes for unobtrusive long-term monitoring – Evaluation of an ongoing clinical trial. In:

Eskola, H., Väisänen, O., Viik, J., Hyttinen, J. (eds) EMBEC & NBC, 2017. *IFMBE Proceedings*, vol 65. Springer, Singapore.

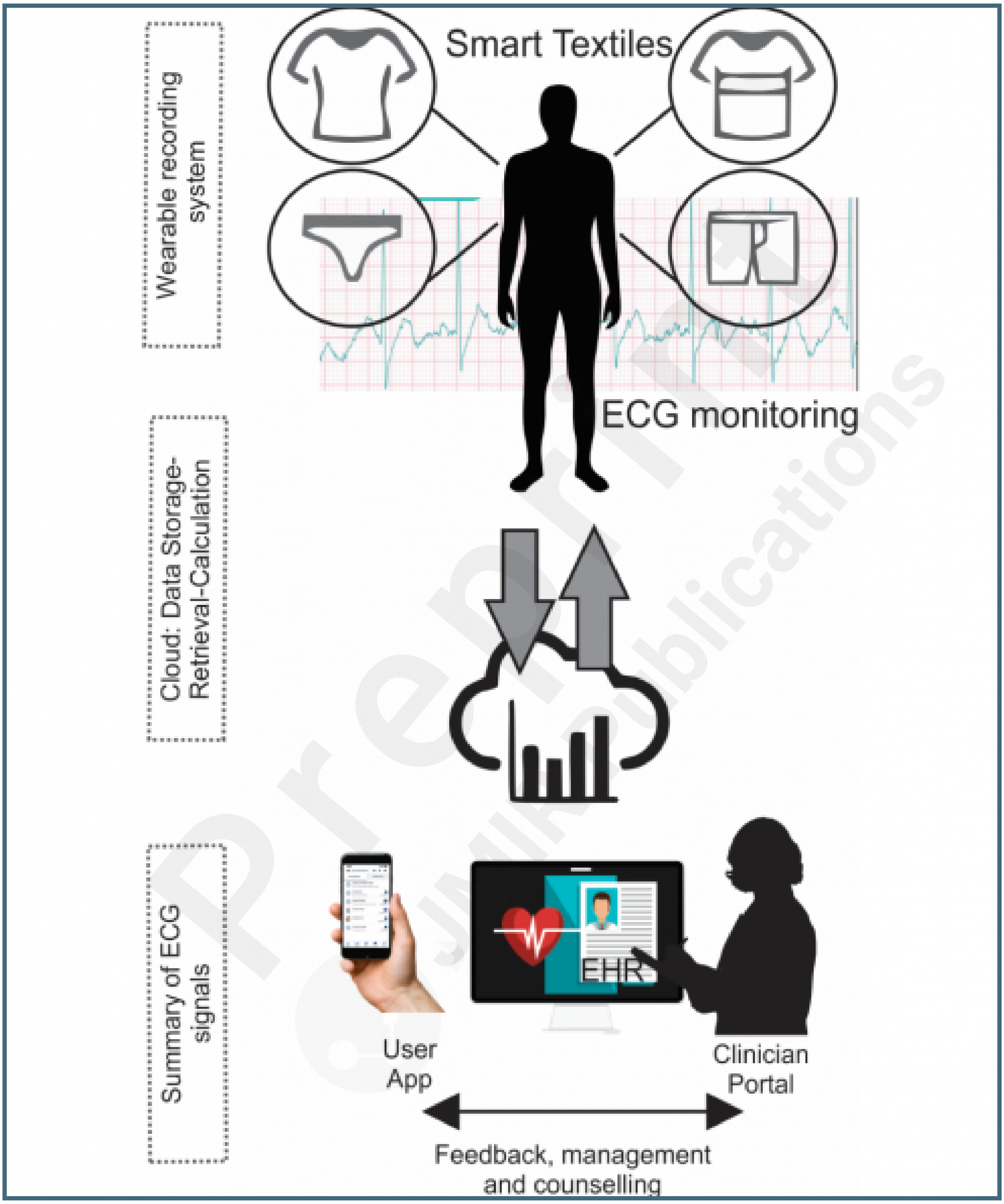
[95] Perez de Isla L, Lennie V, Quezada M, Guinea J et al. New generation dynamic, wireless and remote cardiac monitorization platform: A feasibility study. *International Journal of Cardiology*, 2011;153(1): 83 - 85.

[96] Olmos C, Franco E, Suárez-Barrientos A, Fortuny E, et al. Wearable wireless remote monitoring system: An alternative for prolonged electrocardiographic monitoring. *International Journal of Cardiology*, 2014;172(1): e43 - e44.

Supplementary Files

Figures

Smart textiles data workflow and integration in clinical practice. Textile-based sensors embedded in clothes/garments continuously measure ECG signals.



Challenges for smart textile integration into clinical practice.