



Empa

Materials Science and Technology

Smart Textile Systems for Real-Time Monitoring of Physiological Responses for Health and Performance

Textile International Forum and Exhibition (TIFE) 2026

NTUH International Convention Centre, Taipei

September 16, 2026

Dr. Simon Annaheim

Excellence times Six – the Institutions of the ETH Domain



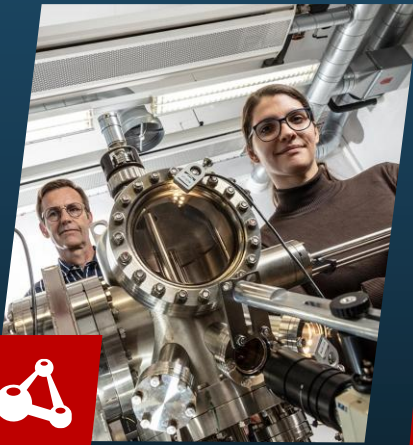
The Cockpit for our Research



The UN Sustainable Development Goals – tackling the prime challenges of our time.



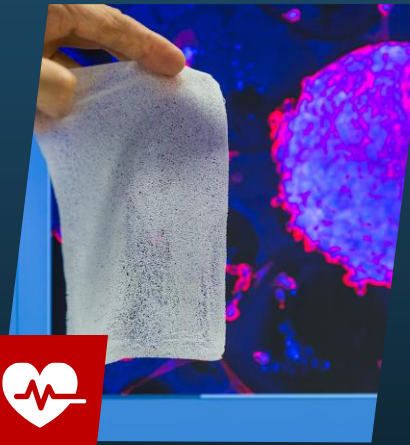
Our Response – in four Research Focus Areas



**Nanoscale Materials
& Manufacturing
Technologies**



Built Environment

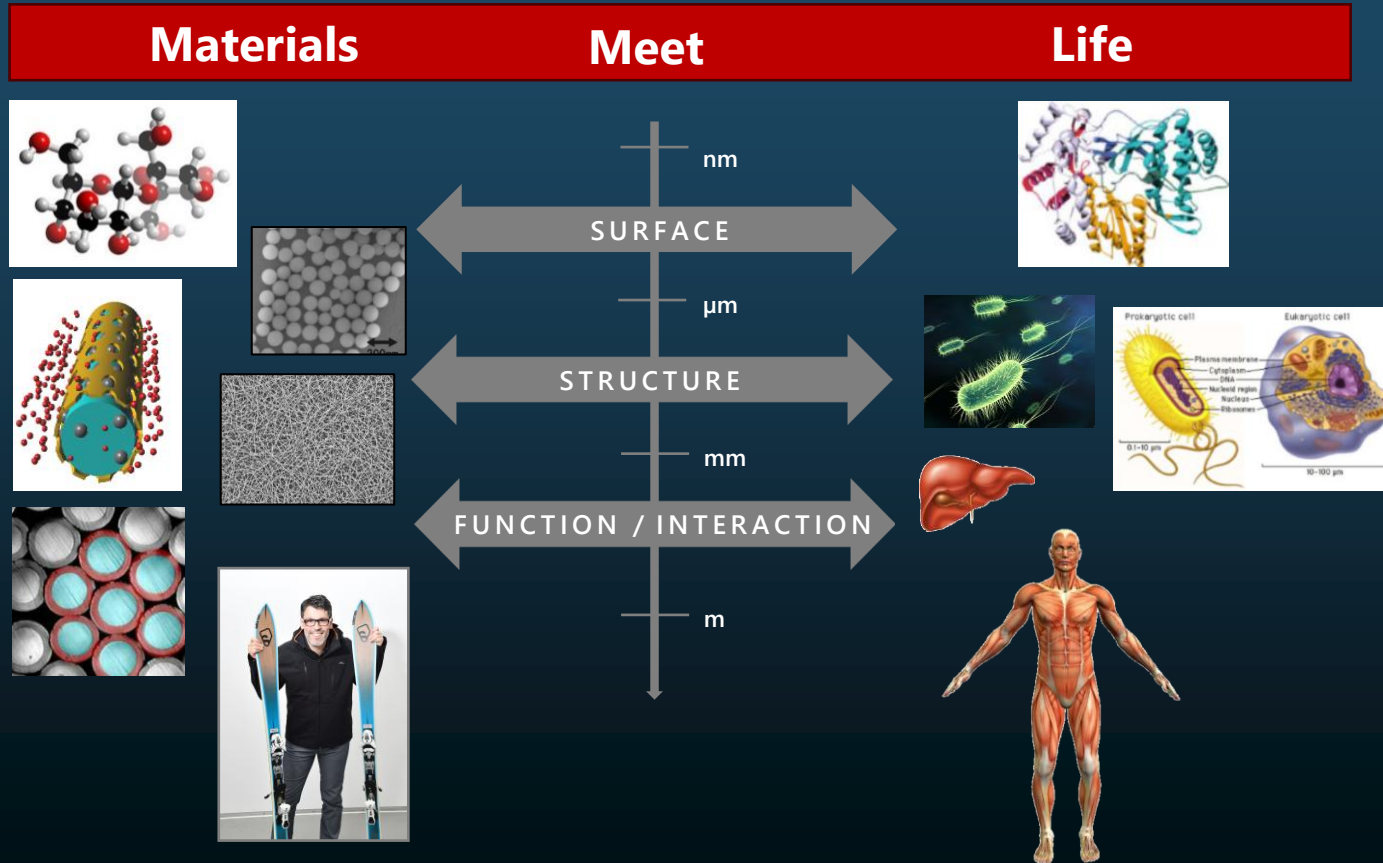


Health



**Energy, Resources &
Emissions**

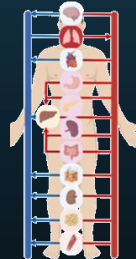
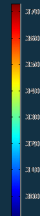
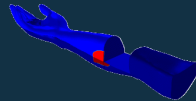
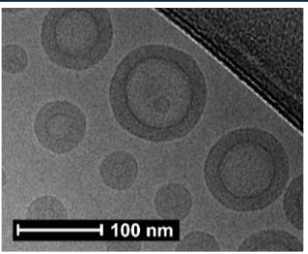
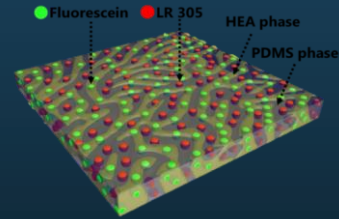
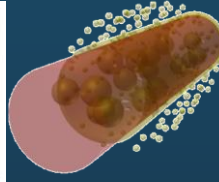
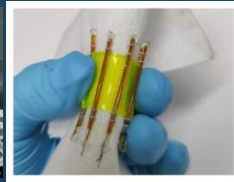
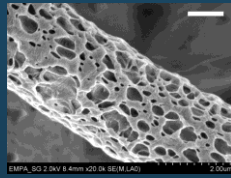
Departement Materials Meet Life



Laboratory for Biomimetic Membranes and Textiles



We design soft materials to monitor and support body functions

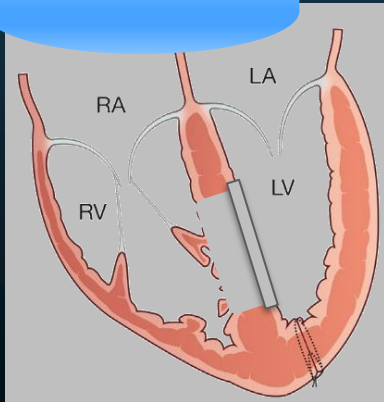
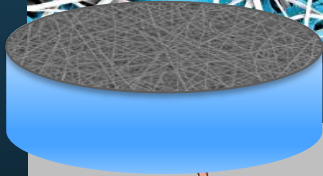
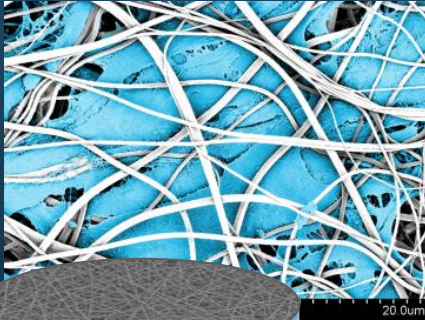


We pioneer manikins and digital twins for tailoring biomimetic solutions

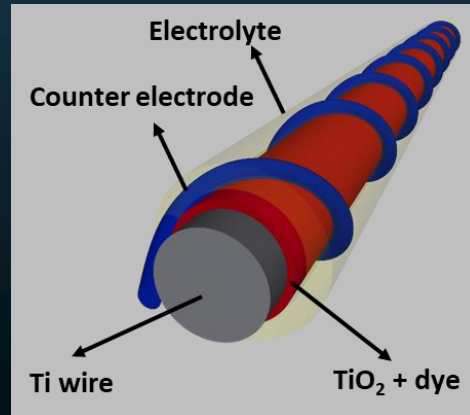
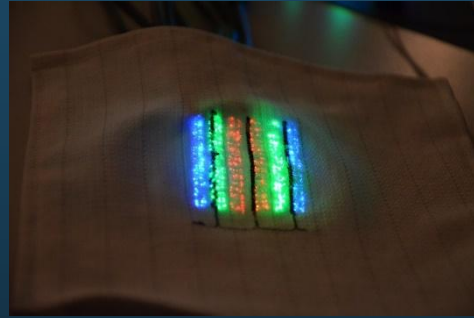
Key research topics of the lab



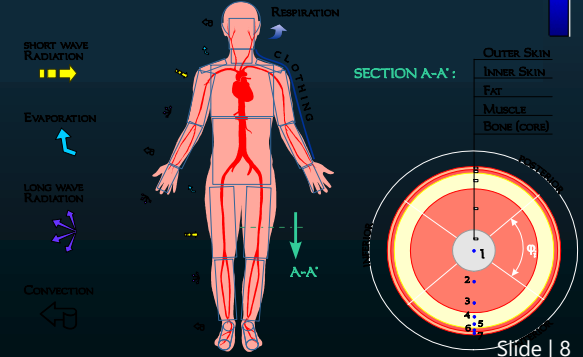
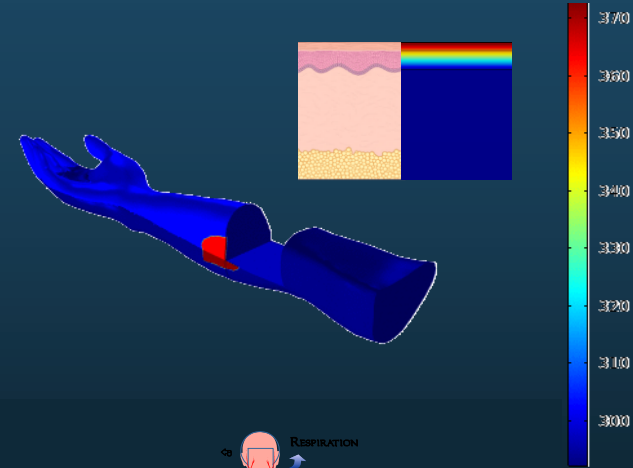
Medical Textiles



Wearables and Biosensing



Digital Health Solutions





Continuous Vital Sign Monitoring

Real-time physiological data — from the hospital bedside to the worksite to the sideline



Patients

Earlier detection of clinical deterioration



Workers

Preventing heat stress & overexertion injury



Athletes

Optimizing recovery & training readiness

One continuous signal, three settings where a missed change matters



Patients: Catching Deterioration Before It Becomes a Crisis

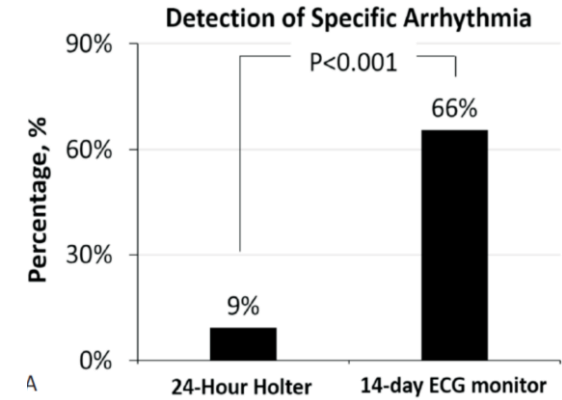


Fewer missed events

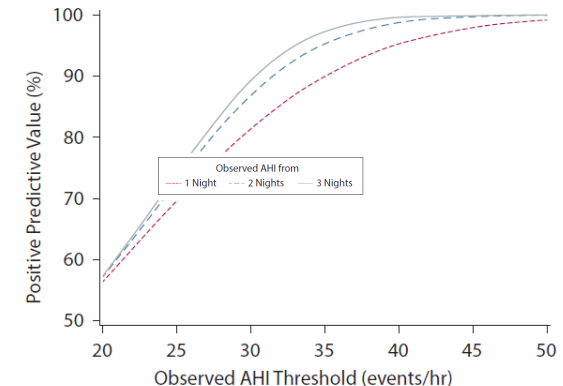
Continuous monitoring flags abnormal vitals between nurse rounds — catching metabolic crises and oxygen-desaturation episodes that periodic (roughly every 4–8 hour) spot-checks can miss.

Better outcomes

Continuous vital-sign monitoring (CVSM) is associated with reduced mortality, ICU transfers, rapid-response-team activations, and hospital length of stay versus intermittent checks.



Chua et al., Acta Cardiol Sin, 2020



Punjabi et al., CHEST, 2020



Occupational Safety: Detecting Heat & Physical Strain in Real Time



A serious toll

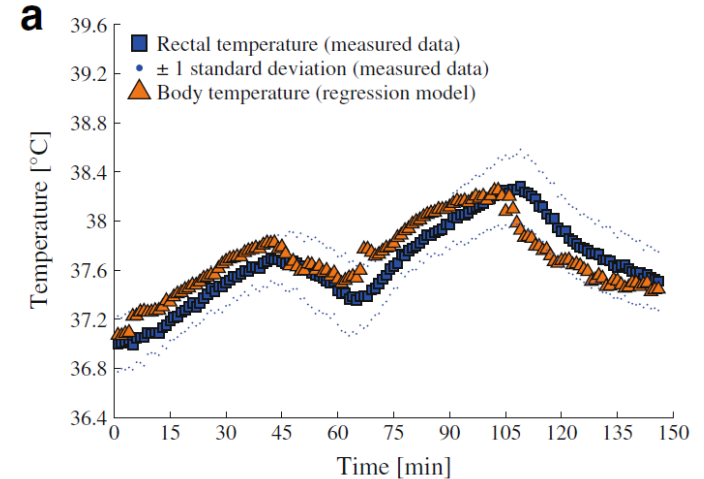
Occupational heat exposure caused 479 U.S. fatalities from 2011–2022, including 43 deaths in 2022 alone (up 19% year-over-year), alongside an estimated 170,000+ heat-related injuries annually.

What gets tracked

Wearables track heart rate, core and skin temperature (the strongest predictor of heat-illness risk), respiratory rate, and fluid loss, alongside ambient temperature and humidity.

From reactive to proactive

Real-time alerts let workers rest, rehydrate, or slow down before symptoms escalate; aggregated data lets employers redesign high-risk tasks, schedules, and cooling protocols.



Niedermann et al., *Int. J. Biometeorol.*, 2014



Athletes: Guiding Training Load & Recovery



A window into readiness

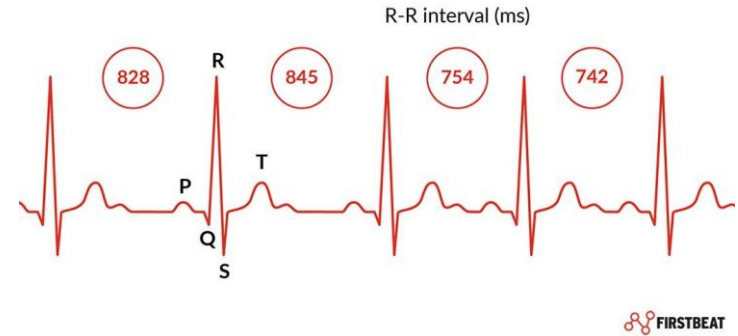
Heart-rate variability (HRV) reflects combined physical, mental, and chemical stress on the autonomic nervous system — a broader readiness signal than GPS or training-load data alone.

Recovery-guided programming

HRV typically drops after intense sessions and returns to baseline within about 72 hours, letting coaches prescribe demanding work when it's normal or elevated, and lighter work when it's depressed.

Outperforming fixed plans

HRV-guided training has outperformed pre-planned programs for developing aerobic performance (better running velocity and VO2max) — though its use for predicting injury risk is not yet validated.





Sensor Requirements for Continuous Monitoring

What a sensor — especially a textile-based one — must deliver to monitor reliably, on the body, day after day



Accuracy & Signal

Clinical-grade, gap-free data the algorithm can trust



Wearability & Durability

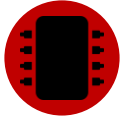
Comfortable, stretchable, and washable enough for daily use



Power & Connectivity

Battery life and secure transmission that hold up outside the lab

A sensor only monitors continuously if it survives being worn, washed, and moved in — every day



What Any Continuous-Monitoring Sensor Must Deliver



Clinical-grade accuracy

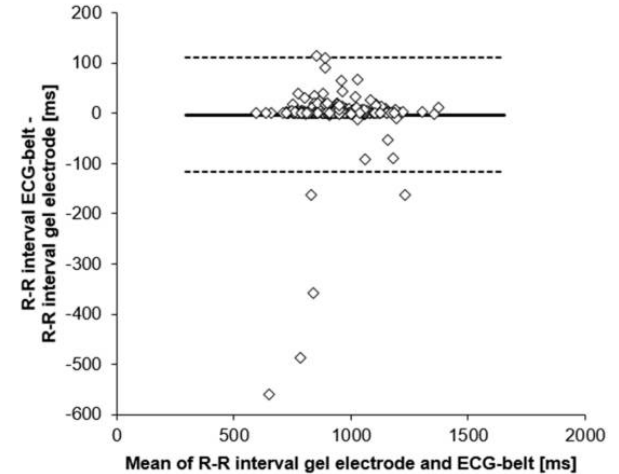
Readings must be benchmarked against reference medical equipment to quantify error and identify sources of noise — the baseline every other requirement builds on.

Uninterrupted data capture

Gaps in continuous data are often unusable and get discarded outright, so minimizing dropout matters as much as raw accuracy when algorithms depend on the stream.

Comfort, power & connectivity that sustain compliance

Devices must stay lightweight and unobtrusive enough for extended wear, with battery life and secure wireless transmission that hold up outside the clinic or lab.





Textile Sensors: Built Into the Fabric Itself



Mechanical compatibility with the body

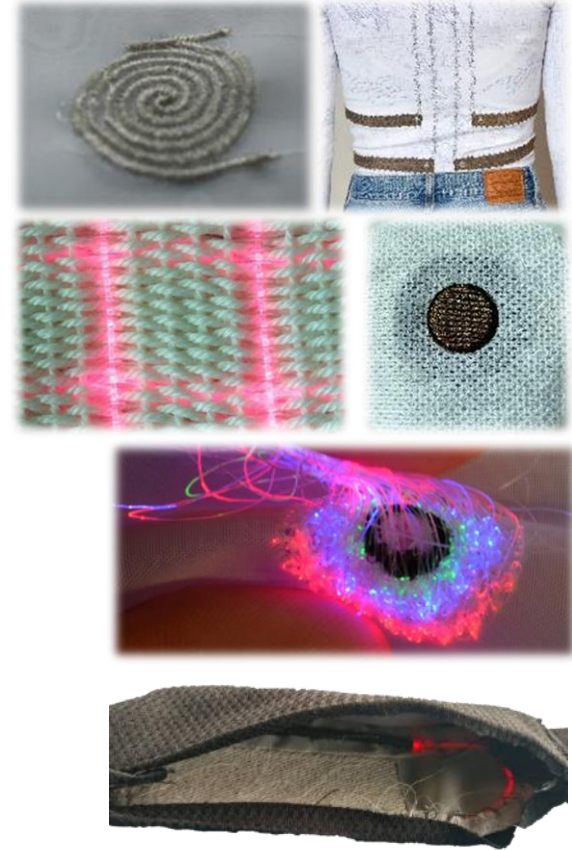
The sensor must stretch, bend, and move with the garment — knitted structures generally outperform woven ones during activity because their elasticity reduces slip between skin and electrode.

Stable, low-impedance skin contact

Signal quality depends on consistent electrode-skin contact; moderate contact pressure lowers impedance and noise without causing discomfort over hours of wear.

Fabrication method shapes performance

Sensors are integrated by weaving, knitting, embroidery, or printing conductive yarns and inks directly into the textile — each method trades off conductivity, durability, and manufacturability differently.





Textile Sensors: Surviving Real-World Use



Material choice determines lifespan

Conductive material matters as much as design: in wash testing, copper-based electrodes corroded and failed after as few as 10 wash cycles, while silver-based electrodes remained stable and maintained signal quality.

Washing is a combined chemical and mechanical stress test

Repeated laundering combines fabric agitation, bending, and detergent exposure — durable sensors are typically qualified for 25–50+ wash cycles before performance degrades.

Standardized durability testing

Martindale abrasion (10,000 cycles), pilling tests, and chemical-immersion testing let manufacturers predict wash durability without laundering full garment prototypes.



Textile-Based Sensing for Continuous Vital Sign Monitoring

Weighing what textile sensors make possible against what still stands in the way



Opportunities

Comfort & compliance · Multi-parameter sensing · Scalable manufacturing



Challenges

Signal & motion artifacts · Durability under wash & wear · Standards & regulatory path

The fabric is ready to sense — the question is whether it can do so reliably, every day, at scale



What Textile Sensing Makes Possible



Comfort that sustains continuous wear

Soft, breathable, garment-like sensors hold skin contact for hours without the discomfort or clinical look of rigid devices — turning 24/7 monitoring into something people actually keep wearing.

Clinical-grade signals, tolerant of movement

A knitted sensing sleeve recently matched clinical-standard blood-pressure accuracy while staying reliable through movement, rotation, sweating, and re-wearing — without needing precise electrode placement.

Manufacturing that rides existing textile infrastructure

Weaving, knitting, embroidery, and printing are established garment-industry processes, offering a scalable route to production rather than an entirely new manufacturing base.





What Still Gets in the Way



Signal quality moves with the body

Electrode-skin contact shifts with posture, sweat, and motion, and integrating electronics into fabric without disturbing its mechanical or electrical behavior stays technically difficult across coating, printing, and spinning methods.

Durability has a ceiling

Conductive coatings and yarns degrade with washing and repeated flexing; some retain conductivity for only around 45 wash cycles — well short of the years of reliable performance clinical use would demand.

Prototype-to-product is a bigger leap than it looks

Knitting, weaving, and embroidery scale in principle, but connecting textile to electronics — soldering, adhesives, embroidery, connectors — each carries trade-offs, and standardized, automated production at volume remains underdeveloped.



Closing the Gap to Clinical & Commercial Use



Power remains the weak link

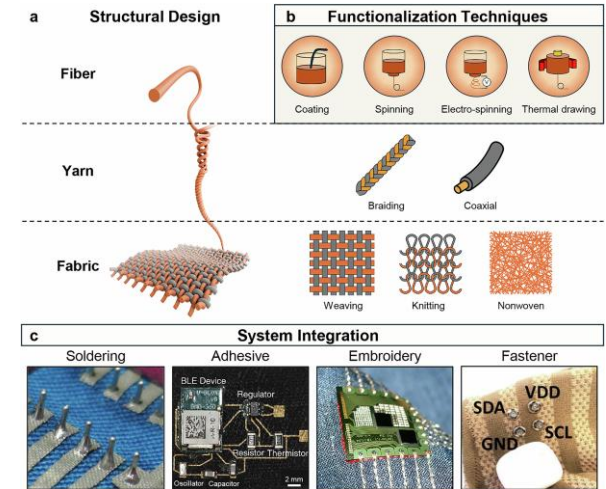
Triboelectric, piezoelectric, and thermoelectric energy harvesting show promise, but none yet deliver enough power for continuous high-demand sensing — flexible batteries and supercapacitors are still commercially immature.

No shared rulebook yet

There is no industry-wide standard for wash durability, electrical consistency, or biocompatibility testing, which slows comparison across devices and complicates the path through medical-device regulation.

Evidence is catching up to the engineering

Long-term, real-world durability and clinical-equivalence data remain limited; showing outcomes on par with — or better than — conventional wearables is the next hurdle before broad clinical deployment.



the gap that materials science, textile engineering, and clinical validation must close together



Textile Electrodes for Continuous Monitoring

From the limits of Ag/AgCl gel electrodes to knitted, dry textile sensors — validated in continuous patient monitoring



The Challenge

Ag/AgCl gel electrodes cause skin irritation, biocompatibility issues, and moisture buildup



The Solution

Knitted, silver-metallized E-fibre electrodes — OEKO-TEX certified, no gel, no aggressive chemicals

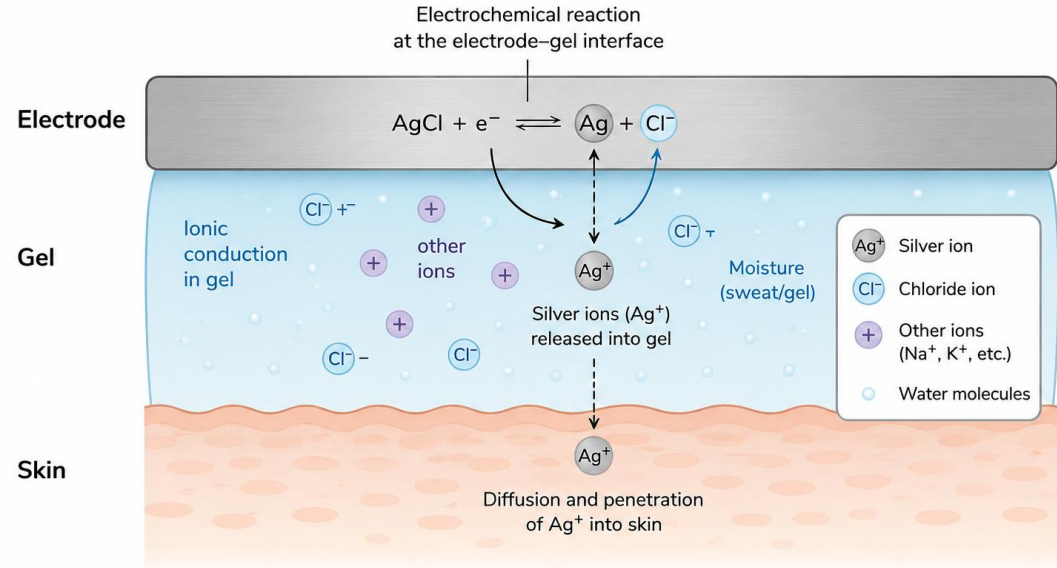


Clinical Validation

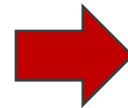
Signal quality comparable to gel electrodes in continuous ECG monitoring, validated in patients

A knitted textile can do what a gel electrode does — without the gel

The continuous monitoring challenge of Ag/AgCl electrodes



- ❖ Biocompatibility issues:
- ❖ Penetration of Ag^+ into the skin
- ❖ Everyday adhesive removal
- ❖ Moisture accumulation

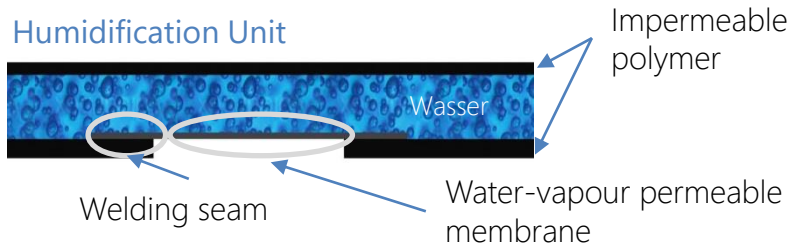


Skin irritation & discomfort

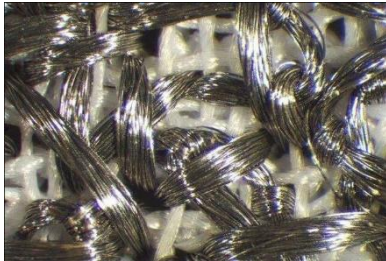




Our textile-based solution (E-Fibre)



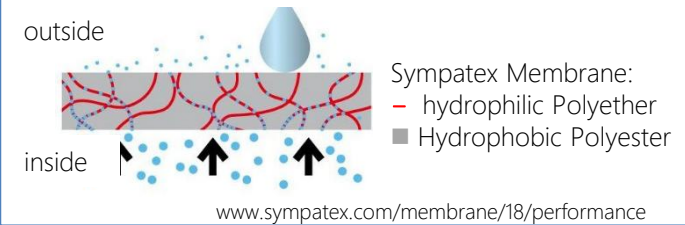
Knitted Textile Electrode



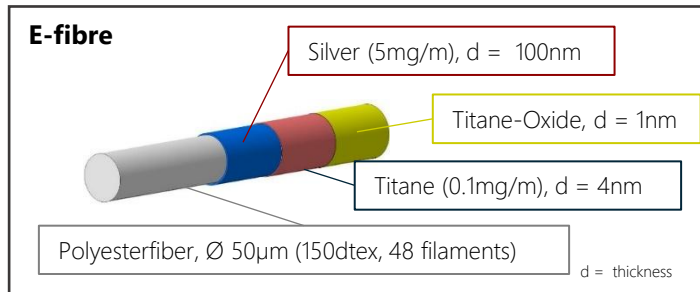
Textile Characteristics of the Electrode

- ❖ flexible
- ❖ porous
- ❖ High surface-to-volume ratio
- ❖ Comfortble skin-contact

Water-vapour premeable membrane



E-fibre



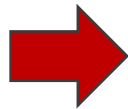
Textile electrodes



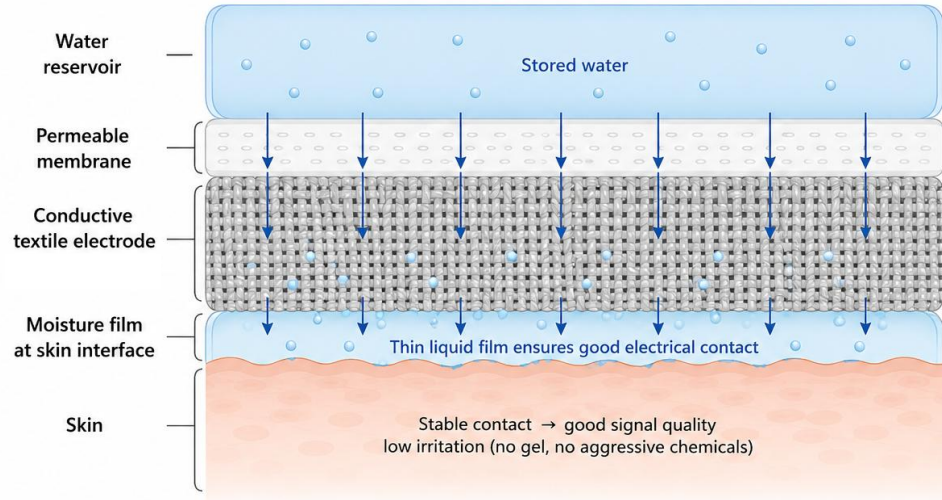
Nahtlos

Biocompatibility issues solved:

- ✓ No electrochemical reaction
- ✓ Can be used for up to 14 days
- ✓ Moisture release control



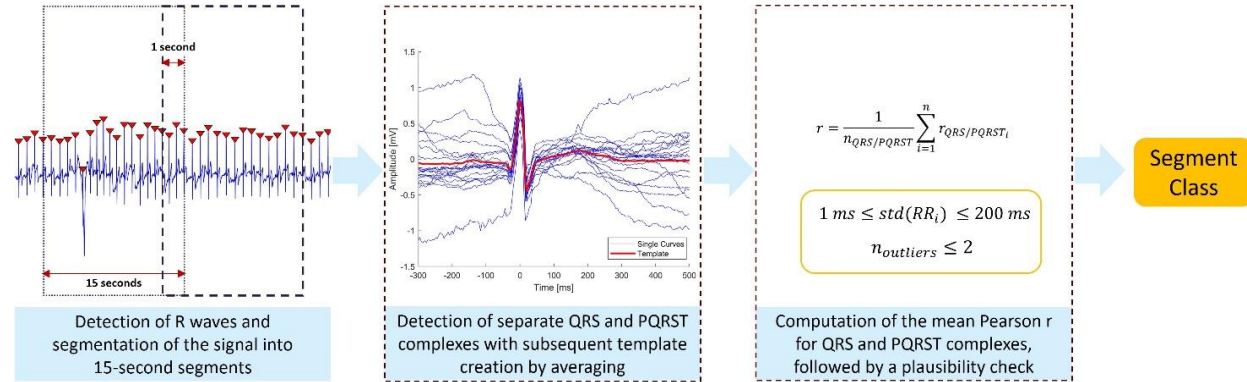
No skin irritation



A knitted fabric metallized with silver. The conductive textile is OEKO-TEX® STANDARD 100 certified and can therefore be worn next to the skin.

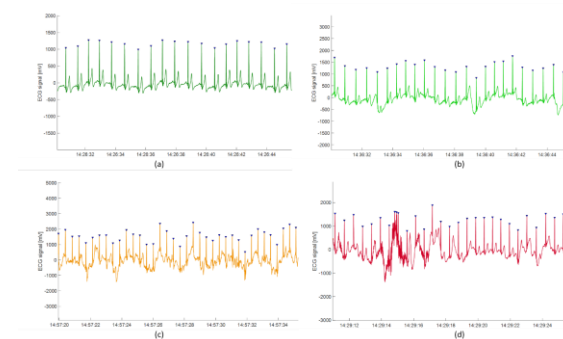


Signal quality assessment (ECG)



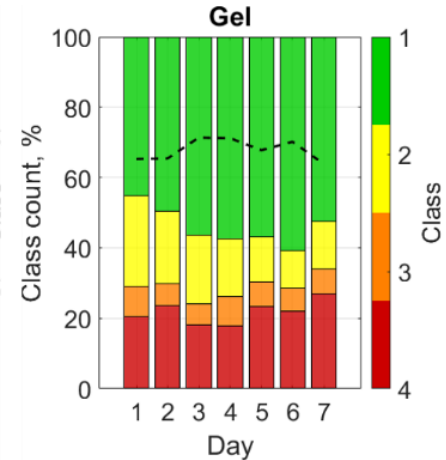
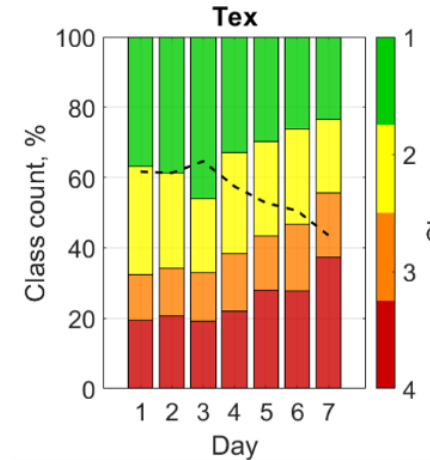
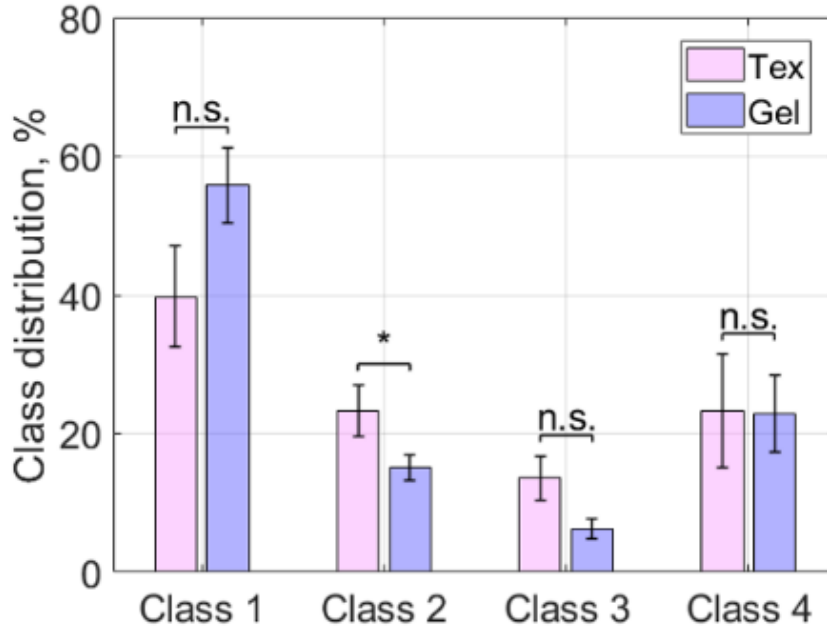
Class	PCC of QRS complex	PCC of PQRS complex	Plausibility criteria
1	≥ 0.98	≥ 0.98	True
2	≥ 0.98	< 0.98	True
3	< 0.98	< 0.98	True
4	any	any	False

Validation of classification based on 3 datasets (n = 242, n = 44, n = 9)



Continuous ECG-monitoring in Patients

Signal quality assessment



n=13
Maevskaia et al., in preparation

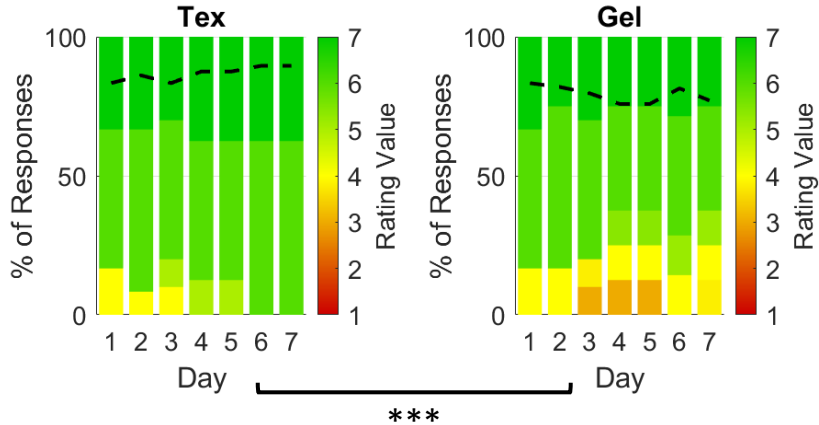
Continuous ECG-monitoring in Patients

Wearing Comfort and Skin Irritation

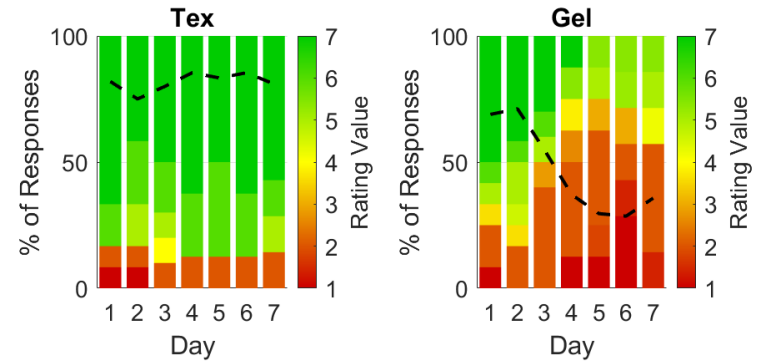


hoch Health
Ostschweiz

It is comfortable to wear the electrodes



Electrodes lead to NO skin irritation



Rating from 1 (not agree) to 7 (fully agree)

n=13
Maevskaia et al., in preparation



Rulebooks for Textile-Based Vital Sign Sensors

Standardization and the regulatory path to FDA and EU MDR clearance



Test the Textile

IEC 63203 — electrical & wash durability of the fabric itself



Meet Device Standards

IEC 60601, ISO 10993, IEC 62304, ISO 14971
— regardless of form factor



Clear a Regulator

FDA and EU MDR — two different games with different clocks

Passing the textile test is necessary — it is not the same as clearing a medical device



Rulebook I: Testing the Textile Itself

A standards body finally exists

IEC Technical Committee 124 now publishes the IEC 63203 series specifically for e-textiles — a shared, comparable way to test wearable textile electronics instead of every lab inventing its own method.

What it actually tests

Published parts include IEC 63203-201-3/-4 (electrical resistance of conductive textiles under a simulated microclimate — heat and moisture, like skin contact) and IEC 63203-204-1/-2 (2023–2025, washing durability of e-textile systems).

Where it stops

These standards validate the textile-and-electronics substrate — not clinical accuracy, biocompatibility, software, or how a regulator should classify the finished product.

the emerging e-textile test series — covers
electrical & wash durability, not clinical
performance



Rulebook II: Standards Every Medical Device Must Meet

Safety & risk

IEC 60601-1 (plus -1-2 for electromagnetic compatibility) covers electrical safety, and ISO 14971 governs risk management — written for rigid enclosures, but applied all the same to a knitted sensor.

Biocompatibility & software

ISO 10993-1 governs skin-contact biocompatibility, and IEC 62304 governs software lifecycle wherever an algorithm turns raw signal into a reading — both apply regardless of form factor.

Cybersecurity, increasingly

IEC 82304-1 and cybersecurity expectations (NIST-aligned for FDA; the EU Cyber Resilience Act and NIS2 for connected devices) now sit alongside the classic safety standards for any connected sensor.

6 Standards

the core safety, biocompatibility, software & risk standards a textile sensor must satisfy before classification even starts



What This Means for a Textile Sensor Program

Marketing language is a US-only lever

The identical hardware can be a wellness product or a Class II medical device depending on the claims made — a framing option EU MDR does not allow.

Passing textile tests isn't passing device review

IEC 63203 proves the fabric survives washing and stays electrically stable; the medical-device file — safety, biocompatibility, software, clinical evidence — still has to be built on top of that.

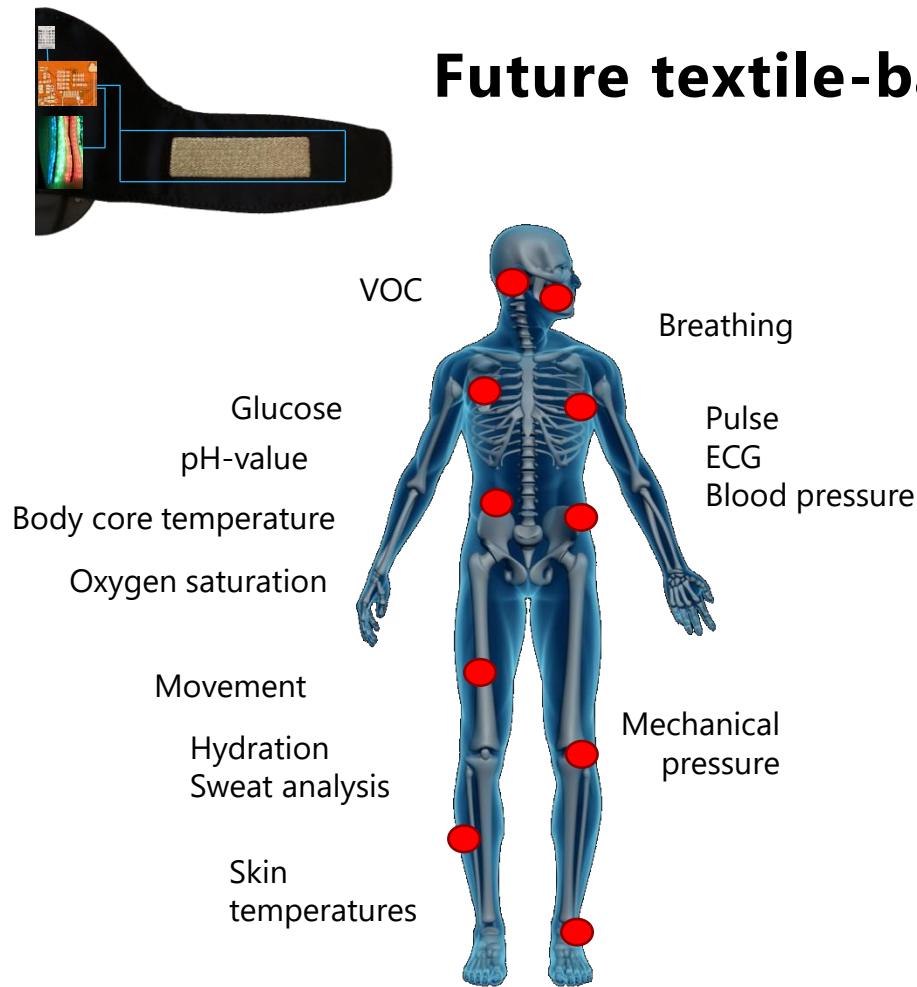
Build to the stricter bar first

Programs targeting both markets typically build their clinical evaluation to EU MDR's higher bar first, since that evidence is more reusable downstream than the reverse.

3–9 vs 8–14+ mo

typical FDA 510(k) timeline vs. EU MDR Class IIa/IIb Notified Body review

Future textile-based monitoring opportunities



Textile-based sensors for digital health solutions

❖ **Key success factors**

- ❖ Reliability and accuracy of signals
- ❖ Biocompatibility of sensors
- ❖ Unobtrusive nature and high wearing comfort
- ❖ Applicability for telemedical applications

❖ **Early detection** due to continuous monitoring

❖ **Appropriate assessments** due to screening at home

❖ **Individualized therapies** due to patient follow-up at home

ACKNOWLEDGEMENTS

Thank you!



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