BJMB
Brazilian Journal of Motor Behavior
Systematic review and meta-analysis articles

Modularity in wearable devices: Impacts on development, usability, and maintenance – a systematic review

ANDRÉ C. M. SILVA[1] | ERIC D. P. SANTOS[2] | KAUÊ O. ANJOS[2] | GABRIEL S. BARROS[3] | WALTER T. L. JUNIOR[1] | MARIA E. KUNKEL[1]

[1] Science and Technology Institute, Federal University of São Paulo, São José dos Campos, SP, Brazil
[2] Centro Universitário Senac, SP, Brazil
[3] Faculdade de Informática e Administração Paulista, SP, Brazil

Correspondence to: Maria Elizete Kunkel
Federal University of São Paulo, São José dos Campos, SP, Brazil. ORCID ID: 0000-0003-1711-9289
Rua Talim 330, Vila Nair, CEP 12231280, São José dos Campos, SP, Brazil
email: elizete.kunkel@unifesp.br
https://doi.org/10.20338/bjmb.v19i1.518

HIGHLIGHTS

- Modular wearables improve comfort, customization, and adaptability
- Modularity simplifies maintenance and enables easier upgrades
- Modular design streamlines development, but conversion remains challenging
- Modular systems support sensor integration and interoperable data collection

ABBREVIATIONS

BLE	Bluetooth Low Energy
BSN	Body Sensor Network
CAD	Computer-Aided Design
DARPA	Defense Advanced Research Projects Agency
DOT	Diffuse Optical Tomography
EEG	Electroencephalography
EMG	Electromyography
fNIRS	Functional Near-InfraRed Spectroscopy
HD-DOT	High-Density Diffuse Optical Tomography
IMU	Imersion Measurement Unit
I2C	Inter-Integrated Circuit
LED	Light-Emitting Diode
MFPMU	Miniature foldable pouch motor unit
MTTR	Mean Time To Repair
MND	Modular Neutron Detectors
NFC	Near-Field Communication
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RQ	Research Questions
sEMG	Surface Electromyography
SMEB	Soft Modular Electronic Blocks
SU	Sensor Unit
TPU	Thermoplastic Polyurethane
UX	User Experience
WBAN	Wireless Body Area Network

PUBLICATION DATA

Received 26 09 2025
Accepted 30 12 2025
Published 13 02 2026

BACKGROUND: Wearable devices integrate sensors and computational systems into daily life, supporting health, sports, and rehabilitation. Modularity, defined as the division of functions into interoperable subsystems, has emerged as a strategy to enhance personalization, usability, and lifecycle management.
AIM: This systematic review examined how modular design strategies have been applied to wearable devices and evaluated their impacts on development, user experience, and maintenance.
METHODS: A structured search in PubMed, IEEE Xplore, ScienceDirect, and Wiley (2019–2025) identified 15,208 records. Following PRISMA guidelines, 25 studies met eligibility criteria, including modular hardware wearables with functional implementation. Study quality was assessed using a custom 12-item checklist.
RESULTS: All studies (25/25; 100%) described attachment strategies such as snaps, hook-and-loop fasteners, magnetic couplers, or customized geometries. Modularity improved development in 80% of studies, supporting distributed architectures, wireless integration, and scalable workflows, though conversion of monolithic systems remained a challenge. Positive impacts on user experience were reported in 64% of studies, particularly through ergonomic adaptability, comfort, and configurability. Maintenance benefits were highlighted in 36% of studies, with modular systems enabling quick repairs, upgrades, and reuse of electronic and textile components. Importantly, modularity facilitated integration of neurophysiological tools (sEMG, fNIRS, EEG), enhancing sensor placement flexibility and artifact reduction in applied contexts.
INTERPRETATION: Evidence consistently supports modularity as a foundational strategy to improve adaptability, usability, and sustainability of wearable devices. While its potential for portable neurophysiological assessment is promising, further validation in sports, rehabilitation, and everyday environments is urgently needed.

KEYWORDS: Wearables | Modularity | Development process | User experience | Maintenance

INTRODUCTION

Wearables are technological devices designed to be worn on the body, integrating seamlessly with daily life to promote continuous interaction and comfort. Unlike handheld electronics such as smartphones and tablets, wearable technologies function as extensions of the human body, embedding sensors and computational capabilities into clothing, accessories, or even directly onto the skin [1]. The history of wearable devices can be traced back to 1961, when mathematicians Thorp and Shannon developed a compact apparatus to predict roulette wheel outcomes [2]. Despite containing only twelve transistors, this early system demonstrated the potential of real-time human augmentation, using a toe switch for input and a concealed earpiece for feedback [1,2]. Such pioneering efforts established the conceptual foundation for wearable systems capable of enhancing human perception and interaction with the environment [3].

In the 1980s, leading academic institutions like Massachusetts Institute of Technology (MIT), Carnegie Mellon, and Georgia Institute of Technology accelerated research in this field [1]. Among early innovators, Steve Mann created wearable photography systems composed of helmets, backpacks, and integrated cameras [1,4]. His work illustrated how wearable technology could be embedded into personal identity, reinforcing his vision of technology as an existential extension of the user. Meanwhile, other researchers emphasized usability, developing hands-free tools for industrial workers and sensor-based systems that adapted to ambient changes [1,5].

By the 1990s, wearable technology had achieved institutional recognition, exemplified by the American Defense Advanced Research Projects Agency (DARPA) workshop "Wearables in 2005" and Boeing's first dedicated conference. These events brought together academia, industry, and military stakeholders to explore applications such as augmented reality, health monitoring, and situational awareness [1,3-5]. However, despite academic interest, commercial viability remained limited. The company Xybernaut, founded in 1990 to deliver exclusive wearable solutions, collapsed due to financial instability [1]. It was only in the 2010s and 2020s that wearables matured into consumer-friendly products, featuring continuous operation, environmental sensing, and real-time notifications [3,4], now evident in smartwatches, fitness trackers, and extended reality headsets.

The primary goal of wearable technology is to augment individual capabilities through seamless and intuitive integration, providing a personalized flow of information under user control [6]. Effective design must therefore address physiological and ergonomic demands, ensuring that devices adapt to functional needs without compromising movement or comfort. In addition, wearable devices have shown great potential to support people with disabilities by enabling compensation of motor or sensory limitations and enhancing independence in daily activities. For example, smart orthoses, lightweight exoskeletons, and biometric monitoring devices illustrate how modular solutions can be applied in rehabilitation and motor performance contexts [8]. From a motor behaviour perspective, wearable technologies are increasingly recognized as tools that assess and influence movement organization, motor variability, and task performance across contexts. By embedding sensors and actuators directly on the body, these systems enable continuous observation of motor behaviour during functional tasks, supporting the study of motor control, motor learning, and adaptation in real-world environments. In this sense, wearable devices extend laboratory-based motor behaviour analysis to daily activities, sports, and rehabilitation settings.

A promising design strategy to meet these requirements is the use of modular architecture, defined as the organization of a system into interchangeable functional units, allowing flexibility, scalability, and personalized adaptation [9-11]. Beyond its technical role, modularity can directly influence motor behavior outcomes by facilitating user-specific adjustments and supporting rehabilitation processes. It serves three major purposes: managing system complexity, enabling parallel and asynchronous development, and reducing the impact of uncertainties during design [9-11]. In wearables, modularity can be illustrated through clothes with detachable components, such as a jacket with removable sleeves, tailored to user preferences and environmental conditions [10].

Two dimensions of modularity are particularly relevant: "Modularity-in-design", which allows partitioned and distributed development across specialized modules [11], and "Modularity-in-use", which enables end-users to configure and personalize devices according to individual needs [11]. A notable example is the IKO Creative Prosthetic System, an award-winning project in which children assemble their own prosthetic arms using LEGO™ pieces [12], combining both dimensions of modularity.

Despite its promise, little is known about how modularity supports the design of wearable devices for advanced applications such as portable neurophysiologic assessment. Modular integration of electroencephalography (EEG), electromyography (EMG), or functional near-infrared spectroscopy (fNIRS) sensors, for instance, could facilitate adaptability in sports, rehabilitation, and daily monitoring, while simplifying device maintenance and scalability in clinical contexts. This systematic literature review therefore investigates the implications of modularity in the design of wearable devices, with a specific focus on its influence across three core dimensions: development, user experience, and maintenance. We hypothesize that modularity introduces significant advantages in adaptability, repairability, and user-centered customization, particularly in domains directly linked to motor control. In this context, rehabilitation is understood as an applied process aimed at restoring, reorganizing, or optimizing motor behaviour, and conceptualized as a continuum of motor control processes involving sensorimotor integration, movement coordination, and functional task execution. To test this hypothesis, we systematically analyzed peer-reviewed studies, synthesizing evidence on the role of modular architecture in wearable innovation.

METHODS

The study was conducted and reported in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-

Analyses (PRISMA) [13-14]. We performed a systematic investigation structured in three stages: planning, execution and reporting (Figure 1). The search strategy included databases such as PubMed, Scopus, IEEE Xplore, and ScienceDirect, covering publications from 2019 to 2025, restricted to English-language articles. The inclusion and exclusion criteria were defined a priori, considering only peer-reviewed studies that directly addressed modularity in wearable devices. The process was guided by four Research Questions (RQ) focused on modularity in wearable devices: attachment strategies (RQ1), influence on the development process (RQ2), impact on user experience (RQ3), and implications for maintenance (RQ4). Each question and its motivation are summarized in Table 1.

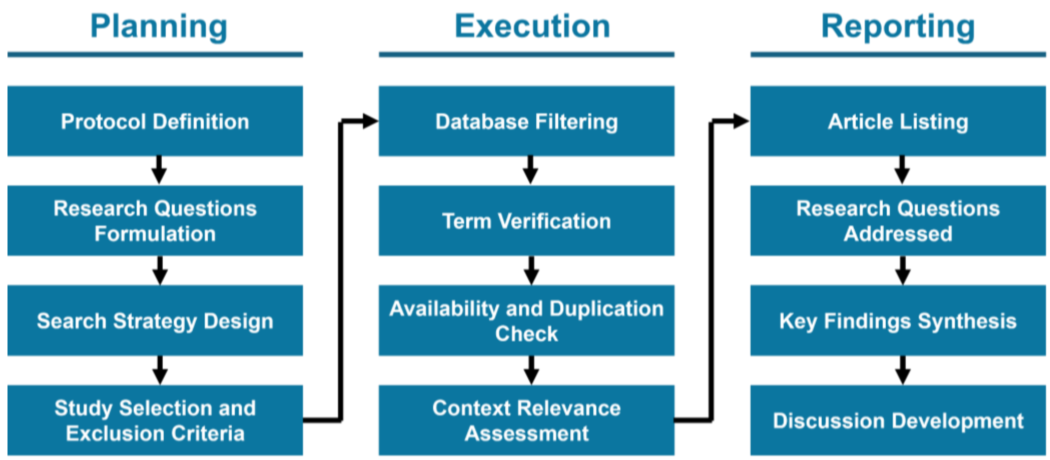

Figure 1. Workflow of the Systematic Literature Review.

Table 1. Key Research Questions Addressing Modularity in Wearable Technology.

Questions	Motivation
RQ1: What attachment strategies are used to implement modularity in wearable devices?	Identify mechanisms that enable modules to be attached/detached, highlighting practical implementations
RQ2: How does modularity influence the development process of wearable devices?	Examine how engineers/designers leverage modularity in design and construction workflows
RQ3: How does modularity affect the user experience of wearable devices?	Explore effects on interaction, customization, and satisfaction from the end-user perspective.
RQ4: How does modularity facilitate maintenance?	Assess implications for post-development activities such as repairs, replacements, and system updates.

Search strategy

Searches were performed in four electronic databases covering engineering, computing, and biomedical literature: IEEE Xplore, PubMed, Science Direct and Wiley Online Library. To retrieve publications related to modular wearable computing systems, we used the Boolean string: ("Wearable" AND "Device" AND "Modular") OR ("Wearable" AND "Computer" AND "Modular"). Filters limited results to peer-reviewed journal articles, English language, and publications years 2019 - 2025.

Eligibility criteria

The studies were eligible if they met the following criteria: (1) the term “Wearable” appears in the title; (2) the term "Modular" appears in the title or abstract; and (3) the full text is available. We excluded studies that were inaccessible, not computer-based, or that did not address hardware modularity or lacked features of modularity-in-use (i.e., end-user configuration/personalization).

Study quality and risk of bias assessment

We assessed the methodological quality of the included studies using a custom 12-item checklist, specifically designed for evaluating research on modular wearable devices. The checklist covered the following four domains:

- D1: Reporting Rigor: Clarity of research questions and outcomes; completeness of device description, including its modular architecture; details on materials, assembly, and attachment mechanisms.
- D2: Internal Validity: Alignment between measured outcomes and the study's claims (e.g., usability, comfort); evidence of device validation or benchmarking; and efforts to control bias (e.g., counterbalancing, assessor blinding, protocol availability).

- D3: External / Ecological Validity: Description of participant sample and selection criteria; realism of the testing environment; and handling of motion or ambient artifacts. For neurophysiological devices, this included specifics on electrode placement, signal preparation, sampling, filtering, and synchronization.
- D4: Reproducibility and Modularity: Availability of materials needed for replication (e.g., schematics, bill of materials, Computer-Aided Design (CAD) files, firmware); analysis of how modular design choices impacted outcomes and interoperability; and evidence of maintainability (e.g., repair/upgrade procedures, replacement time, durability).

Each item was scored as either "Yes" (2 points), "Partial / Unclear" (1 point), "No" (0 points) or "Not Applicable" (excluded from scoring). The total score for each study was converted into a percentage and used to classify studies as either "High quality" (≥ 75%), "Moderate quality" (50–74%) or "Low quality" (< 50%).

Data extraction and synthesis

For each study we recorded bibliographic data, device domain (health/rehab, sports, daily/industrial), study type (prototype, bench, user, field), and modularity descriptors. Outcomes were mapped to the RQs:

- RQ1 – Attachment: materials/interfaces, joining/locking, geometry, tooling, donning/doffing, failures/artifacts.
- RQ2 – Development: workflow, prototyping cycles, integration, reuse/upgrade paths, constraints (e.g., converting monolithic designs), and basic KPIs.
- RQ3 – User Experience (UX): comfort/fit, customization, ease of use, usability scales, task performance, adverse effects.
- RQ4 – Maintenance: repairability (e.g., Mean Time To Repair (MTTR)), replaceability, durability/lifecycle, upgrade procedures, documentation/spares.
- Neurophysiology tags (when applicable): electroencephalography, electromyography, functional near-infrared spectroscopy; placement, sampling, preprocessing/artifact handling, synchronization, field use.

When applicable, neurophysiology-related tags were also extracted, EEG, EMG or fNIRS with details on sensor placement, sampling, preprocessing and artifact handling, synchronization, and field use. This structured approach ensured consistency in data collection and facilitated cross-study comparison, thereby strengthening the reliability of the evidence synthesized in the following Results section.

RESULTS

Study selection, quality assessment, and synthesis approach

A total of 15,208 records were retrieved by the initial search (Figure 2). After applying language, publication type, and date filters 2019 - 2025; peer-reviewed journals; English), 5,241 records remained. From these, 61 records met the keyword condition ("Wearable" in the title and "Modular" in the title/abstract). Following the removal of duplicates and inaccessible documents, 48 unique records were screened. Title, abstract, and conclusion screening identified 20 studies that satisfied all eligibility criteria and were assessed in full text. An updated search was then conducted with additional restrictions (publication year ≥2025, open access, and focus on neurophysiology). This yielded 5 further eligible studies, resulting in a final sample of 25 studies included in the review.

The methodological quality and risk of bias of the included studies were assessed using a custom 12-item checklist developed specifically for research on modular wearable devices (Table 2). Overall, most studies demonstrate moderate to high methodological rigor, with common limitations related to small sample sizes and incomplete reporting of long-term outcomes. The complete list of included studies and their contribution to each research question (RQ1–RQ4) is presented in Table 3. For each study, we extracted descriptors related to study design, target population, type of modular wearable device, domain of application, and reported outcomes, ensuring alignment with the predefined research questions. The findings were synthesized descriptively using absolute counts (n) and percentages (%). A meta-analysis was not feasible due to the considerable methodological heterogeneity across studies, including differences in study populations, device designs, outcome measures, and experimental protocols. To provide clarity, results are organized and reported below according to each research question (RQ1–RQ4).

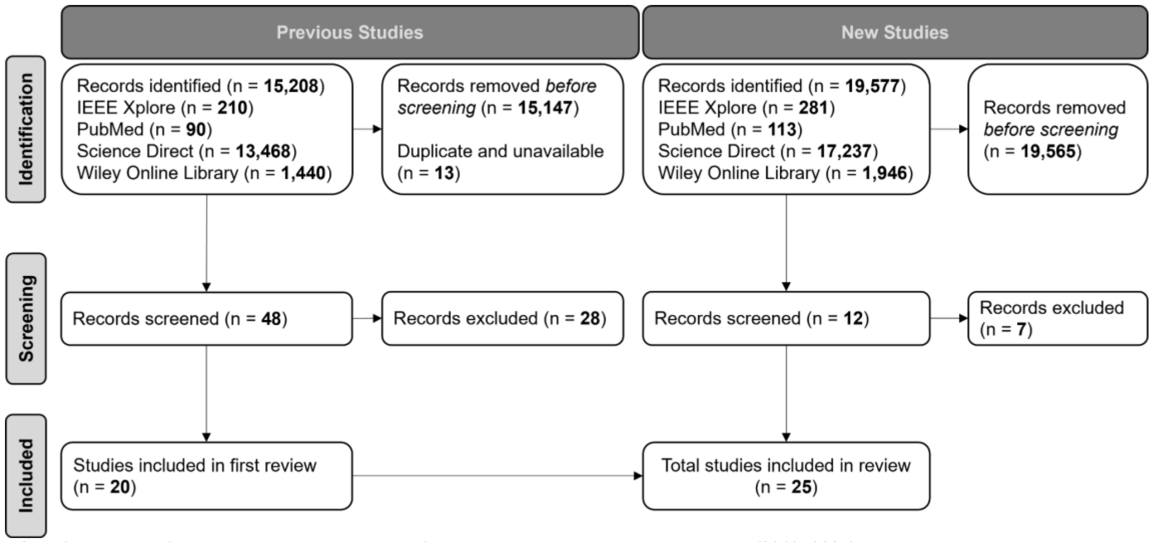

Figure 2. PRISMA flow diagram for previous and new study identification, screening, eligibility, and inclusion (2019–2025).

Table 2. Study quality scores.

Article	D1	D2	D3	D4	(%)	Classification
Abdelhady et al., 2019 [14]	8	6	4	3	87,5	High Quality
Cerone et al., 2019 [15]	8	6	4	2	83,33	High Quality
Garcia-Macias, 2019 [16]	6	3	1	2	50	Moderate Quality
Haghi et al., 2019 [17]	8	6	4	2	83,33	High Quality
Ochs et al., 2019 [18]	8	6	4	2	83,33	High Quality
Xiloyannis et al., 2019 [19]	8	6	4	3	87,5	High Quality
Yoon et al., 2019 [20]	8	6	4	3	87,5	High Quality
Alam et al., 2020 [21]	7	6	5	2	83,33	High Quality
Bützer et al., 2021 [22]	8	6	4	2	83,33	High Quality
Frijia et al., 2021 [23]	8	6	6	3	95,3	High Quality
Abad et al., 2022 [24]	8	6	4	3	79,17	High Quality
Voropai & sarana, 2022 [25]	8	6	4	2	83,33	High Quality
Liu et al., 2022 [26]	8	4	3	2	70,83	Moderate Quality
Ngo et al., 2022 [27]	8	6	3	2	79,17	High Quality
Zaltieri et al., 2022 [28]	8	6	5	3	91,67	High Quality
David et al., 2023 [29]	8	6	3	3	83,33	High Quality
Gollob et al., 2023 [30]	8	6	2	3	79,17	High Quality
Najafikhoshnoo et al., 2023 [31]	8	5	4	3	83,33	High Quality
Sanz-pena et al., 2023 [32]	8	6	3	3	75	High Quality
Uchitel et al., 2023 [33]	8	5	6	2	87,5	High Quality
Guo et al., 2024 [34]	8	3	3	3	70,83	Moderate Quality
Li et al, 2024 [35]	8	6	5	4	95,83	High Quality
Gambo et al., 2025 [36]	8	6	6	3	95,83	High Quality
Wu et al., 2025 [37]	8	5	2	3	75	High Quality
Zhang et al., 2025 [38]	8	6	3	3	83,33	High Quality

D1: Reporting Rigor; D2: Internal Validity; D3: External/Ecological Validity; D4: Reproducibility and Modularity

Table 3. Mapping of research questions (RQ1–RQ4) to evidence from wearable modularity studies.

Studies	RQ 1 Attachment	RQ 2 Development	RQ 3 User Experience	RQ 4 Maintenance
Abdelhady et al., 2019 [15]	3D-printed enclosures; Flexible insole material; IMUs on shank/thigh. Force Sensitive Resistor sensors insole.	Modular division (force, motion, communication); custom protocol integration; replicable modules; supports hardware upgrades.	Discomfort from external microcontrollers; interconnecting wires reduce usability.	Replication and upgrade pathways enable sensor fusion and hardware evolution.
Cerone et al., 2019 [16]	Miniaturized 32-channel amplifier SU directly connected to electrodes; small/light geometry reduces bulk.	Modular Body Sensor Network with multiple synchronized SUs; each node handles conditioning, sampling, and wireless transmission.	Simplified setup, portable, interfaces with mobile devices; reduced motion artifacts via local circuitry.	Scalability through addition of SUs for monitoring multiple muscles.
Garcia-Macias, 2019 [17]	Commercial off-the-shelf modules (Arduino Nano) embedded in knee pads, bracelets, hats, belts; tiny geometry for integration	Scalable from single device to WBAN; integrates with smartphones, positioning systems, and smart objects.	Hands-free use; ankle band perceived as more natural/less tiring than wristband; no training required.	Expandable WBAN by adding modules; adaptable design supports system integration.
Haghi et al., 2019 [18]	Multi-layer stack (5 printed circuit boards) joined via board-to-board connector with shared pins.	Centralized processing with distributed sensors; task-specific layers; Z-axis expansion addresses form factor constraints.	Lightweight wrist-worn device; smartphone app allows user customization of active sensors.	Lightweight wrist-worn device; smartphone app allows user customization of active sensors.
Ochs et al., 2019 [19]	MNDs with controller area network dongles; low-profile modules in moderator casing.	Modular platform integrated into lightweight systems; 16 MNDs connected to master board via communication dongles.	Interfaces with Android devices for intuitive real-time monitoring.	Upgrades planned with dual-sided Microstructured Semiconductor Neutron Detectors; adjustable arrangement of modules to improve sensitivity and mitigate artifacts.
Xiloyannis et al., 2019 [20]	Modular units with electromagnetic clutches and Bowden cables for power transmission.	“One-to-Many” paradigm—multiple degrees of freedom controlled by modules powered by a single motor; reduces control complexity.	Jerky movements from clutch discretization; negative biological torque in descent required user effort against exosuit.	Potential upgrade with magneto- rheological clutches for smoother torque modulation.
Yoon et al., 2019 [21]	SMEBs bonded via oxygen plasma; rapid assembly (<5 s) on skin; strain-relief design for stability.	Modularized into three SMEB types (sensor, interconnect, circuit) enabling tailored layouts.	Soft, conformal contact ensures comfort and imperceptible wear; customization improves signal accuracy.	Easy substitution or addition of SMEBs for repair, upgrades, or functional changes.
Alam et al., 2020 [22]	Chest-worn electrocardiogram and wrist-worn IMU sensors.	Modular classification-regression pipeline with independent layers; context classifier transferable across applications.	Designed for unobtrusive use and usability with wearable sensors.	Context classifiers can be updated to adapt to new contexts or feature spaces.
Bützer et al., 2021 [23]	Bowden cables, clip-on mechanism, Velcro straps/glove/fingerlings; 3D-printed parts for prototyping.	Iterative prototyping with usability tests; modular actuation unit compatible with different hand modules.	Lightweight, sleek design; multiple fixation options for comfort; palm uncovered for sensory feedback; customizable modules based on hand anthropometrics.	Clip-on modules replaceable without disturbing cables; battery compartment adaptable; fingers removable; Bowden cables limited to ~3200 cycles.
Frijia et al., 2021 [24]	Independent hexagonal modules (“tiles”) clipped into neoprene cap; optical fibers with disposable light-guides; Velcro straps.	Dense modular network of sources/detectors; docks connected to hub via flexible cable; challenges with HD-DOT scalability.	Lightweight (195 g), infant-friendly neoprene cap ensures comfort and good optical coupling; tolerated well by infants.	Docks repositionable within cap for flexible array design and upgrades.

Abad et al., 2022 [25]	Fingertip modules with nail clips, rubber bands for grip; open-palm/backhand thimble design; sockets, plugs, and flat flexible cables.	Iterative prototyping from single- to five-fingertip design; modular sockets/plugs enable integration.	Adjustable to any hand size; secure, flexible fit; open-palm design supports hand tracking.	Easy part replacement via detachable sockets/cables; expandable with haptic or flex sensors.
Voropai, Sarana, 2022 [26]	Custom 3D-printed ear pads with embedded electronics; conductive textile electrodes; mounted on commercial headphones.	Modular structure enables flexibility, e.g., swapping 50 Hz for 60 Hz notch filter.	Over-ear headphones ensure comfort; dry textile electrodes eliminate skin prep and discomfort.	Headphones and filters are easily replaceable due to modular design.
Liu et al., 2022 [27]	Small reconfigurable sensing modules; high-density arrays to overcome miniaturization limits.	Design strategies include modular devices, flexible hybrid electronics, and materials innovation; modules can be combined or reconfigured.	Wireless operation enhances comfort; customizable for varied anatomies and measurement needs.	Hybrid modular design supports reuse, upgrades, and expansion of sensing areas.
Ngo et al., 2022 [28]	Stacked modules (EMG, Electrical impedance myography, microcontroller, communication) interconnected via connectors; compact box worn on belt.	Subsystems separated into modules for easier development/debugging; integrated as sensor nodes in Posture and Activity Network by MedIT Aachen BSN.	Lightweight, wearable, wireless design for comfort.	Scalable system: modules can be replaced or combined for upgrades, e.g., multi-frequency bioimpedance.
Zaltieri et al., 2022 [29]	Flexible dumbbell-shaped polymer modules anchored to elastic bands with hooks and loops.	Two elastic bands each with multiplexed sensing modules; modular anchoring system supports adaptability.	Lightweight, adaptable to any anthropometry; easier for patients with limited mobility vs. smart T-shirts.	Removable modules enable band cleaning; Fiber Bragg grating-polymer integration enhances durability and flexibility.
David et al., 2023 [30]	Textile glove with Velcro straps, elastic tubes, and wiring harness; sensors detachable for washing; heavy components placed proximally in arm bag.	Applied Verein Deutscher Ingenieure 2206 mechatronic design; modular subfunctions (mechanical, electrical, IT) integrated via Arduino.	Textile glove minimizes restriction; proximal placement improves comfort; adaptable to a wide range of hand sizes; adjustable sensor positions.	Detachable electronics for easy replacement; glove washable; modularity allows selective sensor use.
Gollob et al., 2023 [31]	Vacuum-Powered Artificial Muscle with modular cells, anchoring clips, rings, and flexible membrane; cells clipped/deactivated via grooves.	Dynamic model with model-informed open-loop control; adjustable actuator length supports growth over treatment period.	Soft, lightweight, body-conforming system; more comfortable than rigid devices; potential risk from off-axis knee loads.	Cells can be unclipped for workspace adaptation; modularity enables growth adjustment without full replacement.
Najafikhoshnoo et al., 2023 [32]	Disposable pH sensor module and reusable NFC communication module; flexible skin-like styrene-ethylene-butylene-styrene substrate.	Two-unit modular design (sensor + electronics); 3D-printed nanomaterials on flexible substrates; NFC enables battery-free operation.	Comfortable, stretchable design; low-cost, easy-to-use system for home monitoring.	Disposable sensor easily replaceable; reusable electronics module extends system lifecycle.
Sanz-pena et al., 2023 [33]	Modular robotic ankle foot orthosis with four sub-assemblies (Exo-Foot, Exo-Tibia, connectors, support); bolted joints; nylon-carbon fiber via 3D printing.	Additive manufacturing workflow; actuator system with encoders/load cells; Simulink real-time control.	Additive manufacturing workflow; actuator system with encoders/load cells; Simulink real-time control.	Rubber sole and distal tibia components are easily replaceable; low-cost replication via additive manufacturing.
Uchitel et al., 2023 [34]	Hexagonal modules docked into neonatal EasyCap; disposable light-guide; Velcro chin strap.	Dense modular network of sources/detectors; dock chain connected to hub via flexible cable.	Flexible EasyCap improves fit/comfort for newborns; tolerated for long sessions (≤ 2 h); quick fitting (< 5 min).	Repositionable docks enable flexible array design and cortical coverage.
Guo et al., 2024 [35]	Flexible modules with magnetic attachments, board-to-board connectors, silicone encapsulation.	Partitioned into mainframe (control) + functional modules; I2C interface loads modules dynamically.	Flexible band ensures comfort, secure fit, and even weight distribution; customizable functionalities/forms.	Magnetic modularity enables easy replacement, upgrades, and reconfiguration of modules.

Li et al, 2024 [36]	EEG-fNIRS modules with electrodes, LEDs, detectors; connected via wires and copper-plated disk; secured by TPU fixing belt.	Separate acquisition modules linked to main board; EEG signals fed in parallel to ADS1299.	Lightweight (21.8 g), comfortable for long-term monitoring; flexible belt ensures close skin fit.	Modular design supports expansion to whole-brain monitoring by adding modules.
Gambo et al., 2025 [37]	3D-printed polylactic acid enclosure with adjustable forearm mount.	Three-component system (wearable, API, gesture recognition model); modular event-driven API enables scalable integration.	Compact, adjustable arm-mounted design for comfort.	Artificial Intelligence engines and Application Programming Interface support dynamic model loading/ unloading, enabling updates and model switching.
Wu et al., 2025 [38]	Tattoo-like modular sensors printed via direct ink writing from polyvinyl alcohol, silk fibroin, and multi-walled carbon nanotubes; self-healing material enables joining after application.	Modular assembly tailored to body geometry and loading direction; customizable sensor patterns.	Conformal, adhesive-free wear; increased signal-to -noise ratio; stretchable, moisture-adaptive material prevents slippage.	Self-healing, reusable, and reshaped multiple times without performance loss.
Zhang et al., 2025 [39]	MFPMU (TPU membrane) connected to 3D-printed bones via grooves; secured with Velcro straps.	Standard heat-sealing fabrication; three MFPMUs per finger to actuate joints; segmented design addresses alignment constraints.	Adapts to finger joint extension for comfort; avoids unnecessary force; segmented design prevents skin restriction.	MFPMUs replaceable in ~30 s; standardized fabrication reduces tooling complexity.

RQ1 - Attachment materials/interfaces, joining/locking, geometry, tooling, donning/doffing, failures/artifacts); RQ2 - Development (workflow, prototyping cycles, integration, reuse/upgrade paths, constraints); RQ3 - User experience (UX) (comfort/fit, customization, ease of use, usability scales, task performance, adverse effects); and RQ4 - Maintenance (repairability (Mean Time To Repair, (MTTR)), replaceability, durability/lifecycle, upgrade procedures, documentation/spares). Body Sensor Network (BSN); Electroencephalography (EEG); Electromyography (EMG); Functional Near-InfraRed Spectroscopy (fNIRS); High-Density Diffuse Optical Tomography (HD-DOT); Imersion Measurement Unit (IMU); Inter-Integrated Circuit (I2C); Light-Emitting Diode (LED); Miniature foldable pouch motor unit (MFPMU); Modular Neutron Detectors (MND); Near-Field Communication (NFC); Soft Modular Electronic Blocks (SMEB); Sensor Unit (SU); Thermoplastic Polyurethane (TPU); Wireless Body Area Network (WBAN).

RQ1: Attachment strategies for modular wearables

All included studies (25/25; 100%) reported at least one attachment strategy enabling addition, removal or reconfiguration of modules. Attachment strategies were defined as specific mechanisms that facilitate modularity, allowing components to be secured to or attached from the main wearable system. These strategies address the need for reliable joining, comfort, easy donning/doffing, and tailored fit for diverse anatomies through five categories: Flexible Anchoring and Support; Mechanical Clamps, Clips and Magnetic Locking; Internal Electrical/Layered Joining; Remote Actuator Coupling Interfaces and Direct Surface Adhesion/Bonding. The number of times each category is presented across the included studies, along with their percentage of portrayal through all 25 studies, can be visualized in Figure 3.

The leading strategy is Flexible Anchoring and Support, which was portrayed in 10/25 (40%) studies. This category encompasses textile-based systems and adjustable closures, such as elastic bands, straps, gloves, fingerlings, harnesses, and Velcro® strips, used primarily for securing the device to the body and adapting to different sizes or anatomies. Closely following were Internal Electrical/Layered Joining, which were portrayed in 9/25 (36%) studies. This method focuses on electronic architecture, utilizing specialized electrical interfaces like board-to-board connectors, sockets, flexible flat cables, and optimized communication protocols like Inter-Integrated Circuit (I2C) or serial peripheral interfaces to stack and connect functional printed circuit boards layers or modules, as seen in systems where modules are stacked and interconnected through internal connectors.

The third most common strategy was Mechanical Clamps, Clips, and Magnetic Locking, portrayed in 8/25 (32%) studies. This strategy involves using physical components like clips, press-fit grooves, snap mechanisms, or magnetic joints to achieve a firm, rapid, and repeatable module-to-module or module-to-interface connection. Remote Actuator Coupling Interfaces were reported in 3/25 (12%) studies, defined as dedicated structural connections designed for transmitting power or force from an off-board or remote actuation unit, typically employing cable transmissions or Bowden cables. Lastly, Direct Surface Adhesion/Bonding was utilized in 2/25 (8%). This category involves the utilization of material properties or chemical reactions to achieve close, adhesive-free conformity and bonding directly onto the skin or soft substrate, often resulting in tattoo-like applications.

An illustrative example of an interesting device application is provided by Li et al. [36] (Figure 4), who developed a hybrid EEG-fNIRS patch integrating electrodes, light sources, and detectors into lightweight (21.8 g) modules mounted on a flexible Thermoplastic Polyurethane (TPU) belt for brain EEG-fNIRS monitoring, specifically supporting the co-located acquisition of EEG and fNIRS signals, to facilitate easy cognition and emotion detection in the prefrontal area. The belt ensured stable forehead attachment and comfort, while claw-shaped dry EEG electrodes eliminate the need for skin preparation. The co-located modular design, with EEG electrode positioned between the fNIRS source and detector, enables synchronous recording of neuronal and hemodynamic activity from the same brain region. This compact and ergonomic system supports long-term monitoring of cognitive and emotional tasks in the prefrontal cortex with minimal spatial interference, demonstrating the potential of attachment strategies for advanced multimodal neurophysiological monitoring.

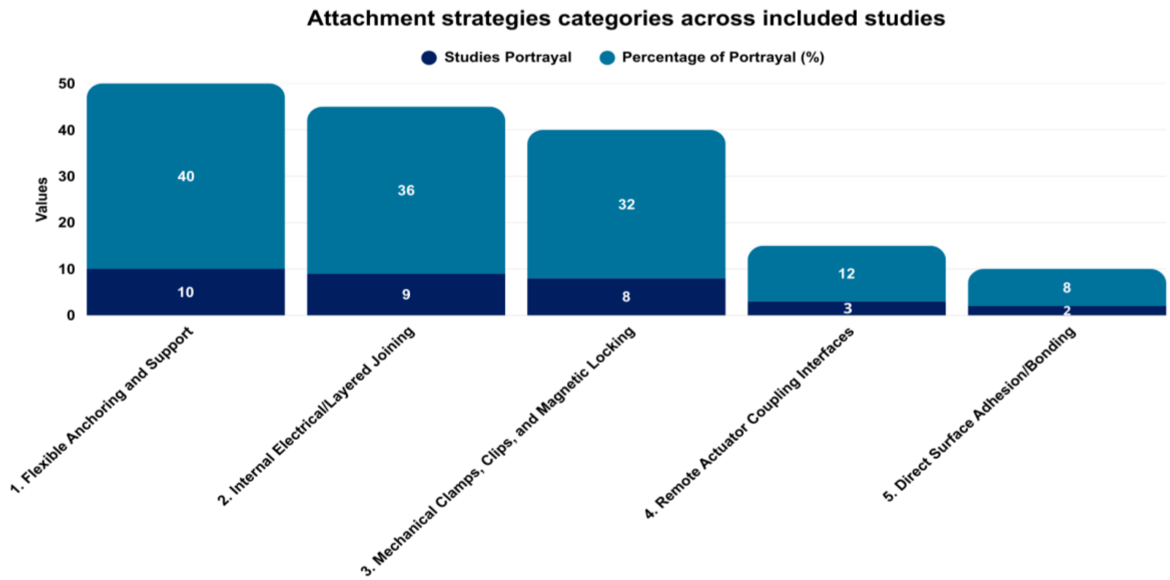

Figure 3. Frequency of attachment categories across included studies. 1. Flexible Anchoring and support are portrayed in 10/25 (40%) studies (textile-based systems, elastic bands, straps, gloves, fingerlings, harnesses, adjustable closures, Velcro® strips). 2. Mechanical Clamps, Clips, and Magnetic Locking portrayed in 8/25 (32%) studies (clips, press-fit grooves, snap mechanisms, magnetic joints). 3. Internal Electrical/Layered Joining portrayed in 9/25 (36%) studies (board-to-board connectors, sockets, flexible flat cables, inter-integrated circuits, serial peripheral interfaces). 4. Remote Actuator Coupling Interfaces portrayed in 3/25 (12%) studies (cable transmissions, Bowden cables). 5. Direct Surface Adhesion/Bonding portrayed in 2/25 (8%) studies (adhesive and tattoo-like applications). Illustration created with the assistance of artificial intelligence. This image is merely illustrative and is not included in, nor part of, the article on which it is based.

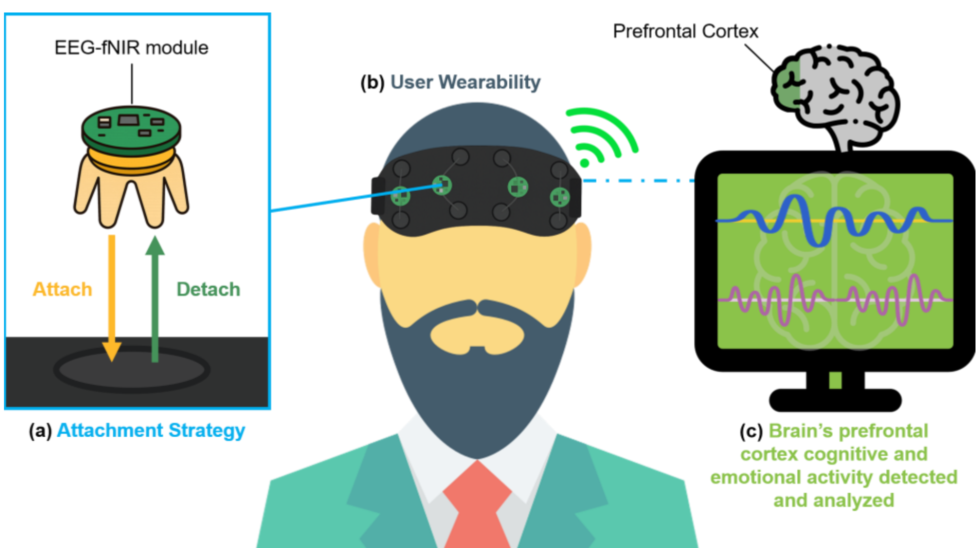

Figure 4. Li et al.'s device function, wearability and modular attachment strategy. (a) The Electroencephalography Functional Near-InfraRed Spectroscopy (EEG-fNIR) modules can be attached and detached from the wearable headband platform. (b) The headband design allows users to wear it on the front head, where signals from the prefrontal cortex can be remotely stored. (c) Signals collected from the device can be read for cognitive and emotional brain behaviour analysis. Illustration created with the assistance of artificial intelligence. This image is merely illustrative and is not included in, nor part of, the article on which it is based.

RQ2: Influence of modularity on the development process

Overall, 20/25 (80%) studies reported development-related benefits associated with modularity. Three recurring themes emerged from the perspective of designers and engineers.

Conversion and integration challenges

This theme is recurrent in 7/25 (28%) studies. Some designers utilize modularity to overcome integration hurdles, such as achieving rapid assembly and connection [21], for instance, using magnetic suction mechanisms [35]. Modular components also simplify the integration required for customization based on anatomy [38]. Integrating modular architecture into wearable systems can present initial challenges, especially when the device was not originally conceived as modular [23]. Adapting an existing structure into separate functional units often requires redesign and additional assembly steps, increasing early development effort (e.g., one study involving infrared spectroscopy wearables highlighted that increasing the number of optical tomography channels made device assembly significantly more complex [27].

Wireless communication and systems integration

5/25 (20%) modular wearable systems adopted wireless communication protocols (e.g., Bluetooth, Wi-Fi, and cloud-based services to support asynchronous, distributed modules and reduce on-body wiring [17,19,25,34,37]). While not mandatory, wireless connectivity facilitates dynamic module integration and distributed data processing. In the Uasisi proximity sensor developed by Garcia-Marcias [17], a cloud server handled intensive processing, and Bluetooth Low Energy (BLE) enabled user-driven acquisition and integration of additional modules, promoting asynchronous configurability.

Distributed architecture and reuse

Modularity enabled distributed systems, allowing components to function independently or collaboratively within a single device architecture [22-23]. At least 18/25 (72%) studies demonstrated systems where modules could be reconfigured or replaced without compromising the device's core function [17-19,21,23-25,28-30,32,34]. Alam et al. [22], for example, designed a wearable capable of gathering three distinct data inputs, each dependent on how the user wore the device for inferring respiratory parameters, such as breathing rate (BR) and minute ventilation (VE), using a modular and generalizable classification-regression pipeline, thereby enabling continuous monitoring and potential risk assessment for chronic cardiopulmonary conditions, like asthma. This modular flexibility supported context-aware applications and organized data interpretation [17].

The findings on development show a strong trend towards creating scalable and transferable systems with clear, independent workflows. Researchers often divide systems into distinct functional blocks, such as sensing, processing, and communication, to simplify debugging, facilitate replication, and allow for independent updates [15-16,28]. Integration is typically achieved through standardized communication protocols like I2C and serial peripheral interfaces for intra-device communication and wireless protocols like Bluetooth or custom radio frequency for data transmission to a host device (e.g., a smartphone or personal computer) [15-16,28]. This creates a Body Sensor Network (BSN) where multiple sensor nodes can operate synchronously [16,28]. Many designs include a central hub or microcontroller (e.g., Arduino, ESP-32) that aggregates data from various modules before transmission, often using custom data packets to ensure high-fidelity communication [15,30,37].

A prime example from the neurophysiology field is the wearable system for High-Density sEMG detection by Cerone et al. [16] for applications requiring high portability and robustness to movement artifacts, enabling new research frontiers in the non-invasive analysis of the neuromuscular system. This system features a modular architecture where miniaturized 32-channel Sensor Units (SUs) act as nodes in a BSN to monitor different muscles synchronously (Figure 5). Each SU is a self-contained module that performs signal conditioning, sampling (in 2048 sps), and wireless Wi-Fi transmission to a mobile device or personal computer. Multiple SUs is synchronized via a common pulse signal, ensuring coherent data acquisition across the network. The system's design avoids lengthy cables between electrodes and amplifiers by placing the conditioning circuitry directly at the detection site, which significantly reduces motion artifacts, a critical challenge in dynamic EMG recordings. This modular and wireless integration simplifies the experimental setup and makes high-density EMG practical for applied and clinical settings outside the lab.

RQ3: Effects of modularity on user experience

16/25 (64%) studies reported specific UX advantages linked to modularity. Two core advantages were repeatedly emphasized.

User configurability and control

Modular design offers high degrees of user autonomy over both hardware and software aspects [18]. In at least 6/25 (24%) cases, it was up for the user to decide how the device was going to be controlled, and which parts would be activated during the experience [17-19,23,38]. Hardware parts could be manually manipulated [22], and software configured through smartphone applications [17-19]. For example, the wearable gas sensor by Haghi et al. [18], integrated multiple sensor layers that could function independently. A smartphone application allowed users to activate specific layers, tailoring the device's performance to various environmental conditions.

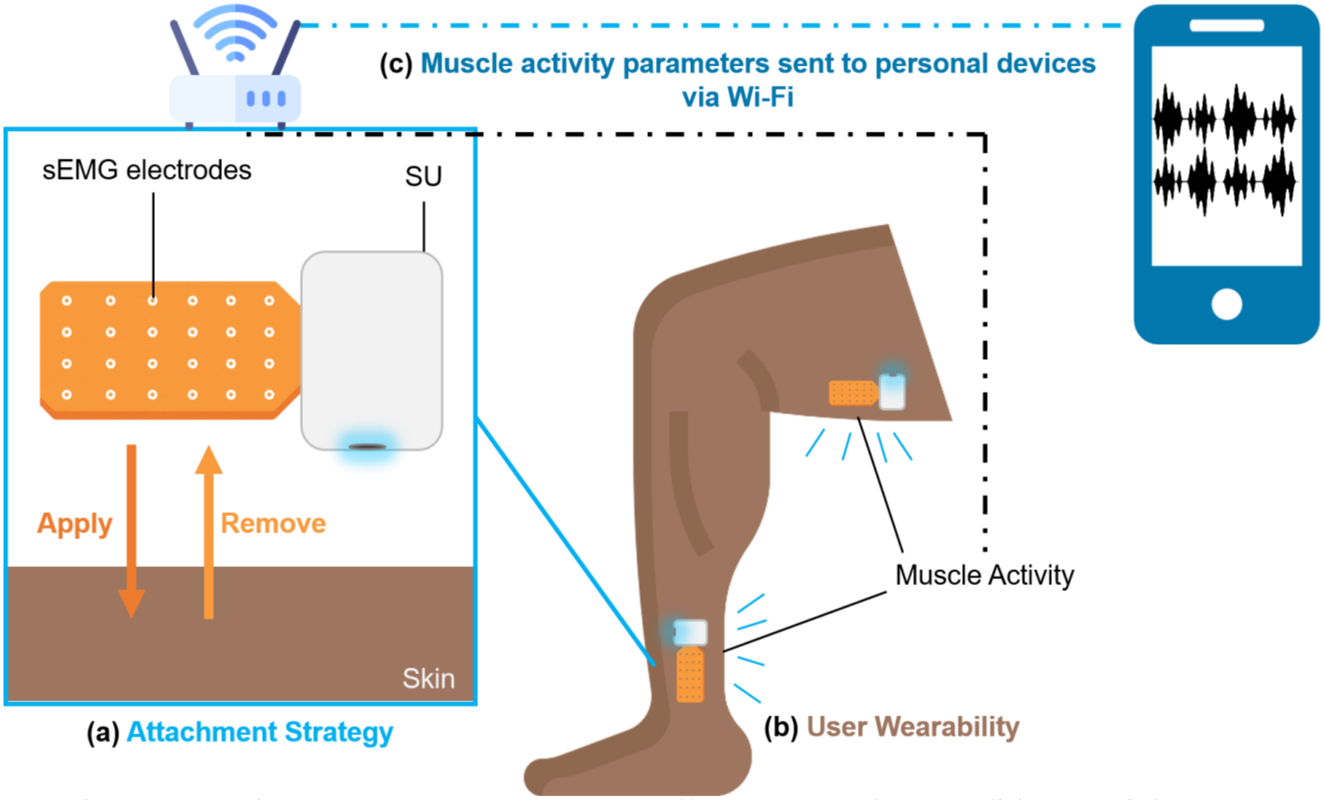

Figure 5. Cerone et al.'s device function wearability and modular attachment strategy. (a) The device consists of a sensor unit (SU) attached to Surface Electromyography (sEMG) electrodes, and it interacts directly with the user's skin and can be positioned on various body parts. (b) When the user's muscles are relaxed or tensioned, the electrical activity produced by all electrodes is detected by their respective SUs. (c) The SUs share muscle activity data through Wi-Fi transmission. All data from all sensors can then be visualized through any personal computing device. Illustration created with the assistance of artificial intelligence. This image is merely illustrative and is not included in, nor part of, the article on which it is based

Ergonomic / anatomical adaptation

Another key benefit identified was enhanced adaptability of modular devices to users' anatomical variations, often allowing the user themselves to adjust the system [28]. A minimum of 15/25 (60%) studies proposed flexible, customizable devices that reduced sizing constraints [21,25,27-31]. The RELab tenoexo hand exoskeleton, developed by Bützer et al. [23], designed for hand movement rehabilitation, featured removable and adjustable finger modules for optimizing assistance and adaptability to the individual user by allowing customization based on specific hand anthropometrics and kinematic profiles, and permitting the easy removal of individual finger modules when assistance is only required for selected digits.

Regarding user experience, modularity is leveraged to enhance comfort, customization, and ease of use, which are critical factors for user acceptance. Designs are tailored to fit a wide range of anthropometries, often using adjustable straps, customizable 3D-printed parts, or flexible materials that conform to the body [30-31,33]. For instance, systems are designed to be lightweight, with heavier components like batteries and processors often placed proximally on the arm or in a separate unit to minimize perceived weight on the hand or head [23,30]. Customization extends to functionality, where users can select or configure specific sensor modules via a smartphone app or swap modules to suit different tasks, such as monitoring different gases or selecting specific grasp types [18,23]. This adaptability makes the devices more practical for daily life and long-term use [21,35].

The wearable High-Density Diffuse Optical Tomography (HD-DOT) system for infant neuroimaging by Uchitel et al. [34] is an example of modular design enhancing user experience in a sensitive population (Figure 6). The system uses multiple independent, lightweight (~6 g) sensor "tiles" clipped into a flexible neonatal EasyCap for allowing the system to conform to the scalp and providing wide cortical coverage through a dense network of sources and detectors, thereby enabling functional neuroimaging at the cot-side with minimal preparation or disturbance to newborn infants. This modular cap is more comfortable and better tolerated by newborns than rigid alternatives, accommodating variable head shapes and allowing for long-duration studies (up to 2 hours) at the cot-side in a clinical setting. The design facilitates an efficient fitting process (< 5 min), minimizing disruption to the infant. By using a flexible cap and modular tiles, the system achieves good optical coupling without causing significant discomfort, as evidenced by high data retention rates and the ability to conduct studies on vulnerable newborns during natural sleep.

Figure 6. Uchitel et al.'s device function wearability and modular attachment strategy. (a) The sensor tile is built with a clip mechanism that can fit into specific parts of the cap. (b) Each sensor tile can be positioned in different parts of the cap, enabling adaptability for multiple head shapes. (c) The cap platform is thought to be a comfort resource, so that brain activity supervision and imaging can be performed while the baby is deep asleep. Illustration created with the assistance of artificial intelligence. This image is merely illustrative and is not included in, nor part of, the article on which it is based

RQ4: Maintenance, repairability, and upgrades

Unlike development and user experience, the influence of modularity on maintenance was discussed less frequently. 9/25 (36%) studies explicitly discussed maintenance-related advantages. However, all mentions concerning post-deployment adjustment, part replacement, debugging and repairs were consistently linked to modular characteristics [18,25-28,30-31]. Removable components enabled each subsystem to be fixed separately from the device, without compromising its activity [18,28-29]. In a study by Voropai and Sarana [26], a heart monitoring system was designed to be clipped onto a set of headphones for implementing a convenient and practical wearable heart rate monitoring system that utilizes the mastoid area near the ears as a natural mount point, allowing the device to monitor for the presence of a user and automatically initialize measurement in the background for continuous daily use. Its analog notch filters could be easily swapped out, ensuring fast replacement and greater user comfort. This case exemplifies how modularity simplifies both functional updates and hardware service.

The overall findings for maintenance indicate that modularity is a key strategy for creating durable, reusable, and upgradeable systems. Many devices are designed with replaceable components, such as disposable sensors, detachable electronics for washing textile parts, or easily swappable modules for different functionalities [23,31-32]. For example, a system might feature a reusable electronics module with a disposable pH sensor, or a glove where all electronic parts can be removed before washing [30,32]. This approach simplifies repairs, as a single damaged unit can be replaced without discarding the entire system39. Furthermore, modular architecture provides clear upgrade paths; new sensor technologies or improved processing units can be integrated by simply adding or replacing a module, ensuring the system remains current without a complete redesign [19,28].

The soft wearable modular assistive glove by Zhang et al. [39] effectively portrays modularity for maintenance (Figure 7). The glove is composed of Miniature foldable pouch motor units (MFPMUs) connected to 3D-printed "bones" to actuate finger joints to flex when inflated by generating a bending motion and simultaneously elongating to accommodate the physiological extension of the skin at the finger joints when rotating. The purpose of this device is to induce hand movement for users with poor movement actuation of their hands. A key feature of this design is that the MFPMUs are detachable. If a unit is damaged, the user can disconnect the silicone tube, push the unit out of its groove, and install a replacement in under 30 seconds. This replaceability greatly simplifies maintenance and extends the device's lifespan. The standardized fabrication process for the MFPMUs also eliminates the need for numerous different molds, making it easier to produce spare parts. This design choice ensures that the device is not only functional but also practical for long-term use by allowing for quick and straightforward repairs.

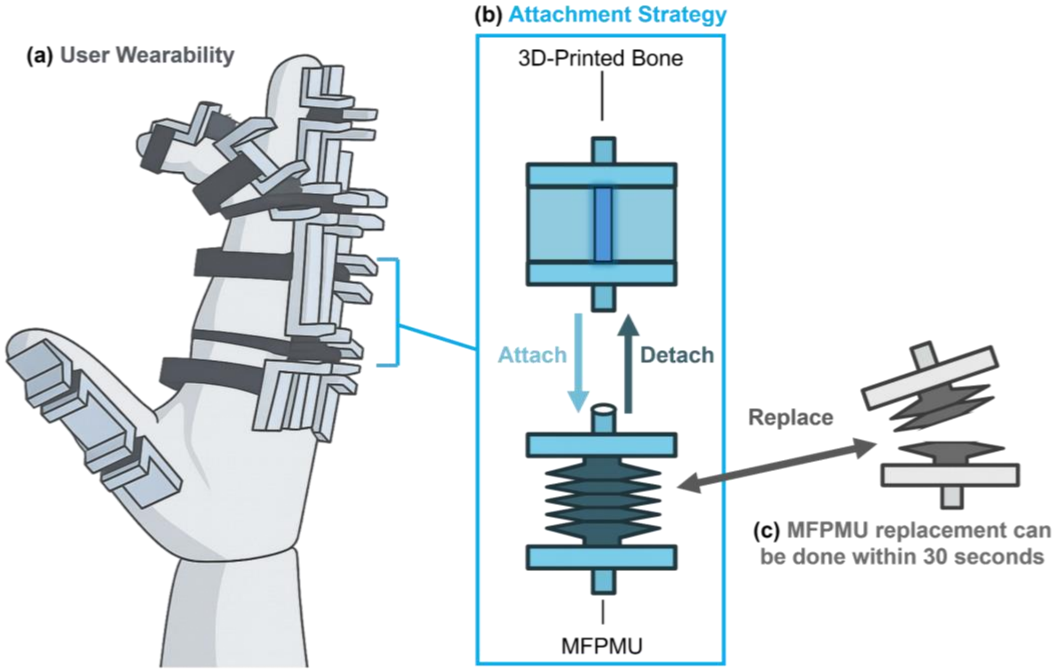

Figure 7. Zhang et al.'s device function wearability and modular attachment strategy. (a) People with poor or no hand movement can use the device to induce finger contortion. The functional parts are held to the user's hand through adhesive strips. (b) The functional parts of the device, being the 3D-Printed bones and the Miniature foldable pouch motor units (MFPMUs), are what enable the user to perform finger movements. Each MFPMU can be attached or detached from the 3D-Printed bone. (c) In case a MFPMU breaks or presents a malfunction, it can be replaced by another one within 30 seconds. Illustration created with the assistance of artificial intelligence. This image is merely illustrative and is not included in, nor part of, the article on which it is based.

Summary of findings

Several included works involved or directly enabled portable neurophysiology, notably sEMG [16,28,33] and fNIRS/DOT [24,27,34]. Modularity facilitated sensor placement flexibility, channel scaling, and artifact management (e.g., motion/sweat), while distributed architecture eased synchronization with biomechanical measures in applied environments (sports, rehabilitation, and daily activities). Across 25 studies, modularity consistently supported attachment/reconfiguration (100%) and was frequently associated with benefits in development (80%), user experience (64%), and maintenance (36%). Common constraints included the initial overhead of converting monolithic designs and balancing quick-change interfaces with mechanical stability in real-world use. These patterns set the stage for the Discussion, where we interpret how modular architectures can enhance portable neurophysiologic assessment and identify priority gaps for validation in applied settings.

DISCUSSION

The section synthesizes the key findings for each RQ, contextualizing them in terms of their scientific and practical significance.

Attachment strategies

Although different strategies for component integration are described in the literature, material-based solutions remain central to achieving modularity in wearable devices. The review found that elastic adjustment mechanisms [29-30,34] and personalized additive manufacturing (3D printing) [15,18,26,32] are commonly employed. These approaches align with the need for wearables to adapt to the user's physical and functional requirements [7]. By enabling flexible and personalized configurations, these materials contribute to user comfort and usability, reinforcing the core objective of wearability [6]. In this sense, material properties act as enablers of modularity by supporting both structural and ergonomic customization.

Development process factors

The development of modular wearable systems presents both challenges and opportunities, particularly related to the design of distributed and wireless subsystems. While modular transformation can be demanding when applied to pre-existing systems [27], our review showed that designers often leverage wireless communication to enhance data flow and control [22-23]. These findings support the relevance of the "modularity-in-design" concept, previously discussed in the Introduction. The reviewed devices reflect the principles of complex systems engineering [17-18,22-23], benefiting from modularity's capacity to manage complexity and enable parallel development workflows [10,12].

User experience factors

From the user's perspective, modularity consistently produced positive experiences, particularly in terms of interaction flexibility and ergonomic adaptability. The reviewed studies emphasized user empowerment through control over device components and settings [20,23], as well as adjustability for diverse body types and needs [21,25,27-31]. These results exemplify the "modularity-in-use" paradigm, in which users actively engage with the device's configuration, both physically and functionally [11]. Moreover, this form of customization reinforces the "option value" of modularity, extending decision-making power to the end-user [9,20]. This aligns with the foundational purpose of wearable technologies: to enhance human capability and autonomy through personalized tools [1,4,6].

Ease for maintenance factors

Maintenance-related findings echoed many of the patterns observed in the development and user experience domains. The core modularity principles, management of complexity, parallel functionality, and robustness against failure, are equally relevant in post-deployment scenarios [9,11]. As scientific prototypes, most reviewed devices benefited from modularity by allowing isolated testing, debugging, and replacement of components without compromising the overall system [18,25-26,30-31]. For example, a malfunctioning module could be repaired or replaced independently, avoiding the need to reconstruct the entire device [18,28-29]. This not only improves efficiency but also supports long-term sustainability in wearable design. Therefore, modularity proves to be an academically and technically favorable approach for lifecycle management.

Comparative showed that high-quality studies more consistently reported positive outcomes related to development robustness, user experience, and maintenance feasibility, supported by clearer modular architectures and explicit strategies for repairability and upgrades. In contrast, moderate-quality studies were largely limited to proof-of-concept demonstrations, with reduced validation, and less systematic reporting of long-term usability or maintenance-related outcomes.

From a sustainability perspective, modular maintenance has relevant economic and systemic implications. By enabling part-level replacement rather than full system disposal, modular wearables can reduce lifecycle costs, extend device longevity, and support faster repairs with reduced downtime, which is particularly relevant for clinical and public healthcare settings.

Study limitations

This review has several limitations that should be acknowledged. Addressing these gaps represents an important direction for future research in modular wearable systems:

1. Substantial methodological heterogeneity was observed across the included studies, including differences in device types, experimental protocols, outcome measures, and validation strategies, which precluded quantitative meta-analysis.

2. Most studies focused on prototype-based or early-stage systems, often evaluated under controlled or short-term conditions, limiting generalization to real-world use.

3. Longitudinal evaluations assessing durability, long-term user adherence, and maintenance performance were largely absent.

4. There is a lack of standardized metrics for assessing maintenance-related outcomes, such as repair time, component lifespan, and lifecycle cost, which constrains cross-study comparison and evidence synthesis.

CONCLUSION

This review demonstrates that modularity offers concrete advantages for the design, usability, and maintenance of wearable devices. Across 25 studies, modular architecture consistently supported attachment flexibility, ergonomic adaptation, distributed development workflows, and simplified maintenance through part replacement. Together, these findings confirm modularity as a central strategy for enhancing adaptability, user autonomy, and long-term sustainability in wearable technologies. Importantly, several works revealed its potential for integrating neurophysiological monitoring tools, highlighting opportunities for application in rehabilitation, sports, and daily living. However, current evidence remains limited to prototypes and short-term evaluations. Future research should prioritize standardized validation protocols, longitudinal studies, and cross-domain applications to establish the reliability of modular designs in real-world contexts. By advancing these directions, modularity can become a cornerstone of next-generation wearable systems, supporting both technological innovation and human-centered healthcare.

REFERENCES

1. Malmivaara M. The emergence of wearable computing. In: McCann J, Bryson D, editors. *Smart Clothes and Wearable Technology*. Finland: Woodhead Publishing; 2009. p. 3-24. doi: 10.1533/9781845695668.1.3
2. Thorp E. Optimal gambling systems for favorable games. *Rev. Inst. Int. Stat.* 1969;273-293. doi: 10.2307/1402118

3. Starner T, et al. Augmented Reality through Wearable Computing. *Presence: Teleoperators & Virtual Environments*. 1997;6(4):386-398. doi: 10.1162/pres.1997.6.4.386
4. Mann S. Smart Clothing: The "Wearable Computer" and WearCam. *Pers. Technol*. 1997;1(1):21-27. doi: 10.1007/bf01317885
5. Rhodes B. The Wearable Remembrance Agent: A System for Augmented Memory. *Pers. Technol.* 1997;1:218-224. doi: 10.1007/bf01682024
6. Mann S. Wearable computing as a means for personal empowerment. *Proc. 3rd Int. Conf. on Wearable Computing (ICWC)*. 1998;51-59.
7. Bryson D. Designing smart clothing for the body. *Smart Clothes and Wearable Technology*. Derby: Elsevier Ltd; 2009. p. 95-107. doi: 10.1533/9781845695668.1.95
8. Fazan LH, Kunkel ME, Stringhini D. Improving computer access for individuals with upper limb deficiency through extensionist actions. *Rev. Bras. Ext. Univ*. 2024;15:71-84. doi: 10.29327/2303474.15.1-7
9. Baldwin C, Clark K. The Option Value of Modularity in Design - An Example from Design Rules, Volume 1: The Power of Modularity. *SSRN Electron. J*. 2002;1:1-14. doi: 10.2139/ssrn.312404
10. Chen Y, Li M. Modular design in fahion industry. *J. Arts Humanit.* 2018;7(3):27-32. doi: 10.18533/journal.v7i3.1271
11. Baldwin C, Clark K. Modularity in the Design of Complex Engineering Systems. *Complex Engineered Systems: Science Meets Technology*. Boston: Springer; 2006. p. 175-205. doi: 10.1007/3-540-32834-3_9
12. Brulé E, Valentin F. Of open bodies: challenges and perspectives of an open design paradigm. *Future Focused Thinking - DRS International Conference*. 2016;27-30. doi: 10.21606/drs.2016.160
13. Kitchenham B. Procedures for performing systematic reviews. Keele, UK, Keele University; 2004.
14. Page M, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ, 2021;372:n71. doi: 10.1136/bmj.n71
15. Abdelhady M, Bogert A, Simon D. A high-fidelity wearable system for measuring lower-limb kinetics and kinematics. *IEEE Sens. J.* 2019;19(24):12482–12493. doi: 10.1109/JSEN.2019.2940517
16. Cerone G, Botter A, Gazzoni M. A modular, smart, and wearable system for high density semg detection. *IEEE Trans. Biomed. Eng.* 2019;66(12):3371–3380. doi: 10.1109/TBME.2019.2904398
17. Garcia-Marcias J. Uasisi: A modular and adaptable wearable system to assist the visually impaired. *Procedia Comput. Sci.* 2019; 151:425-430. doi: 10.1016/j.procs.2019.04.058
18. Haghi M, Stoll R. Thurow K. Pervasive and personalized ambient parameters monitoring: a wearable, modular, and configurable watch. *IEEE Access*. 2019;7: 20126–20143. doi: 10.1109/ACCESS.2019.2897845
19. Ochs T, et al. Wearable detector device utilizing microstructured semiconductor neutron detector technology. *Radiation Physics and Chemistry*. 2019; 155:164–172. doi: 10.1016/j.radphyschem.2018.08.028
20. Xiloyannis M, et al. Design and validation of a modular one-to-many actuator for a soft wearable exosuit. *Front. Neurorobot*. 2019; 13:39. doi: 10.3389/fnbot.2019.00039
21. Yoon J, et al. Soft modular electronic blocks (smebs): a strategy for tailored wearable health-monitoring systems. *Advanced Science*. 2019;6(5):1807682. doi: 10.1002/advs.201801682
22. Alam R, Peden D, Lach J. Wearable respiration monitoring: interpretable inference with context and sensor biomarkers. *IEEE J. Biomed. Health Inform*. 2020;25(6):1938-1948. doi: 10.1109/JBHI.2020.3035776
23. Bützer T, Lambercy O, Arata J, Gassert R. Fully wearable actuated soft exoskeleton for grasping assistance in everyday activities. *Soft Robot*. 2021;8(2):128-143. doi: 10.1089/soro.2019.0135
24. Frijia E, et al. Functional imaging of the developing brain with wearable high-density diffuse optical tomography: a new benchmark for infant neuroimaging outside the scanner environment. *NeuroImage*. 2021; 225:117490. doi: 10.1016/j.neuroimage.2020.117490
25. Abad A, Reid D, Ranasinghe A. A novel untethered hand wearable with fine-grained cutaneous haptic feedback. *Sensors*. 2022;22(5):1924. doi: 10.3390/s22051924
26. Voropai A, Sarana V. A wearable heart rate monitoring system based on over-ear headphones. *Journal of Medical Engineering Technology*. 2022;46(7):604–607. doi: 10.1080/03091902.2022.2080884
27. Liu S, Xue B, Yan W, Rwei A. Recent advances and design strategies towards wearable near-infrared spectroscopy. *IEEE Open Journal of Nanotechnology*. 2022; 4:25-35. doi: 10.1109/OJNANO.2022.3226603
28. Ngo C, et al. A wearable, multi-frequency device to measure muscle activity combining simultaneous electromyography and electrical impedance myography. *Sensors*. 2022;22(5):1941. doi: 10.3390/s22051941
29. Zaltieri M, et al. Preliminary assessment of a flexible multi-sensor wearable system based on fiber bragg gratings for respiratory monitoring of hemiplegic patients. *Int. J. Environ. Res. Public Health*. 2022;19(20):13525. doi: 10.3390/ijerph192013525
30. David J, Helbig T, Witte H. Senglove—a modular wearable device to measure kinematic parameters of the human hand. *Bioengineering*. 2023;10(3):324. doi: 10.3390/bioengineering10030324
31. Gollob S, et al. A length-adjustable vacuum-powered artificial muscle for wearable physiotherapy assistance in infants. *Front. Robot. AI.* 2023; 10:1190387. doi: 10.3389/frobt.2023.1190387
32. Najafikhoshnoo S, et al. A 3d nanomaterials-printed wearable, battery-free, biocompatible, flexible, and wireless ph sensor system for real-time health monitoring. *Adv. Mater. Technol.* 2023;8(8):2201655. doi: 10.1002/admt.202201655

33. Sanz-Pena I, Jeong H, Kim M. Personalized wearable ankle robot using modular additive manufacturing design. *IEEE Robot. Autom. Lett*. 2023;8(8):4935–4942. doi: 10.1109/LRA.2023.3290529
34. Uchitel J, et al. Cot-side imaging of functional connectivity in the developing brain during sleep using wearable high-density diffuse optical tomography. *NeuroImage*. 2023; 265:119784. doi: 10.1016/j.neuroimage.2022.119784
35. Guo H, Shen D, Chen Y, Feng X. Flexible modular strategy for tailored, human–machine fusion wearable electronics. *Wearable Electronics*. 2024;1:244-250. doi: 10.1016/j.wees.2024.10.001
36. Li B, et al. Hybrid Integrated Wearable Patch for Brain EEG-fNIRS Monitoring. *Sensors*. 2024;24(15):4847. doi: 10.3390/s24154847
37. Gambo A, et al. An End to End Wearable Device and System for Indefinite, Continuous, Real Time Gesture Recognition of Directional and Shape Based Arm Gestures. *IEEE Access*. 2025;13:153436-153463. doi: 10.1109/ACCESS.2025.3602871
38. Wu X, Noroozi R, Quiquero D, Poepping T. Customizable and self-adaptive tattoo-like wearable strain sensor for human-machine interface. *Chem. Eng. J.* 2025;510:161456. doi: 10.1016/j.cej.2025.161456
39. Zhang T, Zheng K, Tao H, Liu J. A soft wearable modular assistive glove based on novel miniature foldable pouch motor unit. *Adv. Intell. Syst.* 2025:2500274. doi: 10.1002/aisy.202500274

Citation: Silva ACM, Santos EDP, Anjos KO, Barros GS, Lima Junior WT, Kunkel ME. (2025). Modularity in Wearable Devices: Impacts on Development, Usability, and Maintenance – A Systematic Review. *Brazilian Journal of Motor Behavior*, 19(1):e518.

Funding: This research was supported by the National Council for Scientific and Technological Development (CNPq, Brazil) (Projects 443769/2023-0 and 312022/2025-5) and the Funding Authority for Studies and Projects (FINEP, Brazil) Rede INOVATA (Project 2174/22).
Competing interests: The authors have declared that no competing interests exist.
DOI: https://doi.org/10.20338/bjmb.v19i1.518