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Advanced Reprocessable Polymer, Composite Materials and applied physic for Sustainable Prosthetic and Orthotic Devices: Chemical Structure, Properties, Degradation, and Recycling

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ABSTRACT
The presented work reviews applied physics within the areas of mechanics, heat and mass transfer, vibrations and advanced materials that guides sustainable prosthetic limbs and supports that guides the design and sustainability of prosthetic limbs and orthoses. We relate structural testing standards to repairable/recyclable material selection and semi-active dynamic control in conjunction with thermal and moisture management at the interface; we examine implications for service life, lifecycle cost, user satisfaction, and equity in low-resource settings. This discussion is supported by data and criteria from structural standards (ISO 10328), recent studies on MR dampers for smart prostheses, lifecycle assessment (LCA) exemplars in composite materials and moisture mitigation research into liners.
Keywords: prosthetics and orthoses, Sustainability, ISO 10328 standard. applied physic
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Introduction

There is an increasing global demand for assistive technology–specifically, prosthetics and orthoses. More than 2 billion individuals require at least one assistive product, yet nearly one billion people do not have access to them — primarily in low- and middle-income countries. The gap renders sustainability not only a technical choice, but also a public-health, movement of economy and equity necessity [1] Sustainability in this context means that a prosthetics/orthoses should generate the least possible environmental and economic burden during its entire lifecycle (material selection, manufacturing, use and maintenance, as well as repair/update, disassembly and recycling), while still ensuring performance of function and comfort at safe levels. Quantitative assessment reveals structural reliability under standard cyclic loading protocols characterizing each of three interlocking pillars in any applied physics: (1) the specification of responses to thermal and moisture management at the skin–liner interface, (2) tuning dynamic responses during gait for lowered impact peaks and wear rates; and (3) an intrinsic modulation to quantify metabolic costs per step as movement is driven not only by forces and stiffness but also by energy exchange and muscle contraction efficiency [2].The ISO 10328 standard on the structural side specifies static and cyclic test requirements for lower-limb components, which also provides a common baseline that increases the comparability of different tests and reduces field failures due to mischaracterizing combined loads. If such standards are treated like the "minimum", then prototypes can be used in design teams working on physics-informed improvements of stress concentrations and realistic load spectra instead of using large safety margins which is material-inefficient [3].In materials, lifecycle assessment (LCA) studies for carbon composites provide standardized methods to monitor energy use and emissions across value chains that demonstrate reductions in carbon footprint through processing improvements without degrading mechanical properties—all of which translates to the development of lighter-weight, durable prostheses with longer service lifetimes. In parallel, the development of a new class of polymer networks called vitrimer, which can be both repairable and reprocess able with localized healing and chemical recycling capabilities (design for disassembly) in sockets or liners, represent a potential sustainable pathway to thermoplastic/thermoset. [4] MR inhibitions for semi-active damping control by adjusting the damping force as a function of motion and/or applied current resulting in reduced peak loads on joints and materials, thereby

delaying the onset of fatigue failure. This real-time adaptation using coupled electromagnetic/mechanical models has been successful in smart prosthetic knees and improved reliability and natural gait. [5] At the interface, both daily comfort and sustainability also depend on heat and moisture management. Research on vented liners and socket systems shows that optimizing vapor transmission and interface pressure distribution is critical in reducing skin complications, lowering rejection rates as well as prolonging soft material life and adhesive. These results point to an entanglement of sustainability with "material life" but also with "effective use life," which is contingent on user compliance and comfort. Thus, this study aimed to provide the following question: How can applied physics be a tool for enhancing environmental, economic and functional sustainability of prosthetic limbs and supports? We present an integrated framework based on standards- and physics-influenced structural testing, repairable/recyclable materials, semi-active dynamic control to mitigate impact peaks, thermo-hygrometric interface management; completed by lifecycle performance indicators (LCA) & access/equity considerations identified in global reports [6].

Results And Discussion

There is evidence that multi-axial design (structural/dynamic/control/interface) beats any one axis held in isolation. In practice: Modular connectors make it easier to design for disassembly which aids in repair/upgrade over replacing full device. Verification programs should focus on blending standards based tests with realistic gait spectra and usage sensors to enable predictive maintenance. LCA indicators should be presented early in order to help negotiate trade-offs between mass, life and carbon impact. The standardized, locally fabricable, and repair-friendly solutions expand access while reducing total cost of ownership in low-resource settings in line with (WHO/UNICEF) goals. [8]

1. Background

1.1. Polymer Chemistry and Composite Materials

The performance, durability, comfort, and sustainability of orthotic and prosthetic devices depend greatly on the chemical composition of polymeric materials. As a result of the influence of molecular structure, functional groups, crystallinity, glass-transition temperature, and crosslinking density on mechanical strength, flexibility, thermal stability, moisture absorption, and degradation over time, the polymeric materials PP, PETG, PEEK, and TPU, as well as thermosetting epoxy-based matrices. The interaction of chemical nature between polymer matrix and carbon or glass fibers in fiber reinforced composites is critical since the interfacial adhesion affects the transfer of stress, which will determine fatigue resistance and structural integrity. Thus, surface modification of reinforcing fibers, proper thermosetting resin chemistry, and polymer-fiber interactions are essential chemical approaches that will help increase the strength-to-weight ratio and lifetime of prosthetic components. As far as sustainability is concerned, the selection of polymer chemistry needs to consider the ability of the device to be repaired, reprocessed, or recycled at end of its life cycle, as well as its hydrolytic resistance, oxidation, thermal stability, and environmental exposure.

1.2. Composite Materials and Polymer Chemistry

The function, durability, comfort, and sustainability of orthoses and prostheses are highly dependent on the chemical composition of polymeric materials, as the properties of mechanical strength, flexibility, thermal stability, moisture resistance, and long-term degradation are greatly affected by the molecular structure, functional groups, crystallinity, glass-transition temperature, and extent of cross-linking. Hence, thermoplastic polymers such as polypropylene (PP), polyethylene terephthalate glycol (PETG), polyether ether ketone (PEEK), and thermoplastic

polyurethane (TPU), and thermosetting epoxy based matrices.

As interfacial bonding governs stress transfer and therefore determines fatigue resistance and structural reliability, the chemical interaction of the polymer matrix with carbon or glass fibers in reinforced composites plays an important role. Thus, key chemical approaches that will enable enhancing the strength to weight ratio and service life of prosthetic parts are surface modification of reinforcing fibers, appropriate chemistry of thermosetting resin curing, and optimization of polymer-fiber interaction. With regard to the sustainability, the selection of polymer chemistry should take into account the resilience of the device to hydrolytic, oxidative, thermal aging and environmental degradation, as well as possibilities for repair, reprocessing, and recycling at the end of its service life.

Analyzing worldwide needs for assistive medicine, particularly prosthetics and orthoses, we see an enduring demand along with get entry to gaps. Over 2.5 billion people are estimated to need at least one assistive product today — and this number will rise to over 3.5 billion by the year 2050 The Global Report on Assistive Technology But they urgently require better, lifecycle-economical solutions. Structural standards underpin the safety and reliability of lower-limb prostheses. The one below are discuss about Static and Cyclic Combined Loading, and its requirements for lower-limb components: Biofidelic Baseline Effects (Biofidelic baseline effects (including compliance with DIN EN ISO 10328 for the European market) . definition identification, etc. Thereof, it reduces the early-failures and institutionalizes testing techniques as replicable protocols[9] These are of composites (i.e. carbon fibre and reinforced perlon / nylon) which is vital for high-stiffness-to-weight ratios, also hybrid routes such as 3D printing with an internal fiber reinforcement to optimize the mechanical performance of the composite materials Mechanical characterization of personalized laminate stacks for transtibial sockets and 3D-printed feet with integrated carbon fibers. Structured embedded reinforcement increase design options while reducing material waste [10]. Dynamic engineering is a critical axis for functional sustainability. Magnetorheological (MR) dampers are suitable devices for semi-active control of torque and damping as they can reduce the impact peaks during load release and delay the fatigue failure in prosthetic knee joints while responding to external applied current. Literature states coupled electromagnetic–mechanical modeling, prototyping and gait-tracking/control experiments enhance long-term reliability [11].

At a more fundamental level, it is the skin–socket interface that drives use continuation. Skin irritation and low adherence due to heat and humidity trapped in standard liners shortens the effective device life. This suggests that vented liners/sockets and/or moisture-managed liners are more effective in alleviating sweat accumulation and reducing soft-material degradation due to wear and tear than unvented or non-moisture managed options [12] Lifecycle assessment Lifecycle assessment (LCA) is gaining traction from an environmental sustainability and circular-economy perspective because it allows mapping of energy and emissions throughout the entire lifecycle of a product, from raw material extraction to end-of-life.

The prosthetic and fiber composite examples above present cases where processing and structural choices that are more carbon efficient can be undertaken with no loss in mechanical property and design decisions guided by LCA would favour disassembly, repair or upgrade over replacement, where LCA assists in decarbonizing the products of concern [13].

These facts demonstrate that applied physics—through mechanics, vibrations, heat and mass transfer, and materials science—provides quantitative instruments to elevate the structural, functional and environmental sustainability of prosthetics/orthoses. It allows a move from broad ambitions to quantifiable, harmonized, metrics(standardized tests, comfort assessment),that follow the world movement for better access to assistive technology [14].

2. Advantages

Increased durability, fatigue life: Improved stress distribution and fiber/lattice orientation minimize micro cracking and premature failure. Composite and topology optimization enable light weight with increased stiffness → reduced walking energy and muscle effort Enhanced functional comfort: The use of shock management and (semi-)active damping assists to decrease joint and material impact peaks, while venting channels also support skin health issues, such as dermatitis due to excessive moisture. Repairability and Lifecycle Extension: Localized repair/part replacement instead of complete device swap is enabled by reprocessable/repairable polymers and modular connectors. Smart System Energy Efficiency: Small-scale energy harvesting and ultra-low-power management reduce battery swaps and E-waste. Similar, accountable performance: Finite-element modeling and standardized (static/cyclic) tests relate design and materials selections to reliability consequences. Predictive maintenance: Early-warning algorithms fed by strain/temperature/usage sensing, reducing unplanned, off-clinic failures. [15-16]

3. Disadvantages / Challenges

Higher upfront cost: Advanced materials, precision manufacturing (CFRP, AM), and control electronics increase the initial capital cost. Manufacturing and supply-chain complexity: Multidisciplinary expertise (materials/dynamics/electronics) and local repair capacity are not always available—especially in low-resource settings. Environmental trade-offs of composites: Difficult end-of-life recycling for fiber-resin systems; risk of micro-debris generation from mechanical wear Sensitivity at the skin interface: Heat/sweat can degrade adhesives/foams without proper management; comfort may decline over time. Individual tuning: Variations in gait, weight, and soft-tissue composition make "optimal" tuning individual-specific and time-consuming. Software/maintenance demands in smart devices: Firmware updates, sensor Risks of resonance and vibration occur if the device's natural frequencies and damping are not tuned to the user's step frequencies. Standards gap for complete sustainability: numerous standards prioritize strength and fatigue over LCA metrics [17-18]

4. Maximize Strengths and Minimize Weaknesses (Brief Tip)

Design for disassembly with modular connectors and formally approved repair pathways. Get LCA involved early to get the right mass, durability & carbon trade-off Finish materials are installed with repairable/reprocessable polymers if using, recycling protocols should be documented. By aligning to the bands of step frequencies, do adaptive tuning and avoid resonance. Offer thermo-hygrometric management (high-MVTR lining, ventilation and pressure/temperature profiling). Establish local capacity for supply/repair and training of technicians for rapid molding/printing + service. Define clear data-protection processes when deploying sensors and usage tracking. [19]

5. Prosthetic limbs and devices (orthotics)

By anatomical region Upper limb: digits/hand, wrist, transradial (forearm), transhumeral (arm), shoulder. Lower limb: foot/ankle (Syme / Chopart / Lisfranc), transtibial (below-knee, BK), transfemoral (above–knee, AK) and hip-level prostheses. [20].By control/functional mode — Passive (cosmetic): Provides an aesthetic body shape and basic structural support without active control. Body-powered: cables/harness actuation; durable and light, less precision control Myoelectric: Myoelectric: Utilizes surface electromyography (sEMG) sensing to enable multi-grip patterns and advanced control schemes. Microprocessor-controlled (MPK/MPC): on-board control adjusting damping/torque in real time (knees/ankles). Powered/active: actuators providing net positive work (hands/knees/ ankles). Hybrid: combined mechanical + electrical control. Advanced neural interfaces: pattern recognition, TMR/TSR, implanted EMG. [21] By shock absorption/locomotion dynamics (lower limb) Energy-storage-and-return (ESR) feet. Hydraulic/pneumatic

ankles or knees. Magneto-rheological (MR) dampers for semi-active damping. Electrically powered ankles/knees. By suspension and user interface Socket & suspension: pin-lock, suction, elevated vacuum; liners (silicone, TPE, urethane) and stump socks, Osseointegration (OI): intramedullary implant coupling to an external connector (stable fixation; specific infection/bone considerations). [22]. By materials and structural for Fiber-reinforced composites: CFRP (carbon), GFRP (glass). Metals: titanium, aluminum, stainless steel (axes, adapters, joints) Thermoplastics/thermosets: polypropylene, PEEK, epoxies; Vitrimers for Repairability. Cellular/graded structures (FGMs): spatially tuned stiffness and shock dispersion. By manufacturing route as Laminated composites (vacuum bagging/autoclave) Thermoforming (patient-specific thermoplastic sockets). Additive manufacturing (3D printing): FFF/FDM for liners and lightweight lattice shells SLS/SLM for polymer/metal precision components. Hybrid manufacturing: printed preforms with internal fiber reinforcement; printed molds for lamination. [23-24]

9. Types of Orthoses

1) By region

Lower limb: AFO (ankle-foot), KAFO (knee-ankle-foot), HKAFO (hip-knee-ankle-foot), TFO (thigh-foot). Upper limb: WHO (wrist-hand), EWHO (elbow-wrist-hand), SHO (shoulder). Spinal: LSO (lumbosacral orthosis), TLSO (thoracolumbosacral orthosis), and CTO (cervicothoracic orthosis) including cervical collars [25]

2) By stiffness/function

Soft / semi-rigid / rigid designs. Dynamic assistance (spring-assisted AFOs, compliant joints) Smart/adjustable joints controlling range of motion or damping. Exoskeletons: passive or powered for gait/ lifting assistance.

3) By materials & fabrication

Thermoplastics (polypropylene, PETG), laminated carbon/glass, and 3D-printed shells/lattices for weight reduction and ventilation.

10.Sustainability-focused cross-labels (apply across categories)

Modular & repairable: field-replaceable units and upgradable modules. Recyclable / mono-material: single-family materials to simplify end-of-life processing. Repair-friendly polymers: reprocessable networks for localized repair. Low-impact manufacturing: AM to reduce waste; low-energy curing/forming. Sensitized and predictive maintenance: usage/strain/temperature logging to extend service life. Open-source / locally fabricable: designs adaptable to local materials and skills.

11. Applications

(1) Energy-Storage-and-Return (ESR) Feet

Physics lever: elastic bending & strain energy, viscoelastic damping.
Design actions: carbon-fiber leaf springs with tailored layups; tapered beams to push mass away from the neutral axis; controlled $\tan\delta$for comfort. Sustainability impact: longer fatigue life (fewer replacements), lower metabolic cost for users (higher "usage life"), lighter shipping footprint. Metrics to report: energy-return efficiency, S-N endurance across gait spectra, and mass specific stiffness, mass-specific stiffness E/ρ.

(2) Microprocessor & MR-Damped Knees/Ankles

Reduction of control effort and with decreasing torque at low slip velocity, even few newton's are sufficient do this by representing the flywheel in physics level: semi-active damping (field-dependent yield stress), dynamics and control. Design actions: MR valves; stumble-recovery control to limit peak shank acceleration; adaptive stance/swing damping. Sustainability impact —Less surgery to install these devices: reduced peak loads → bearings/surfaces wear slower; fewer clinic

visits; modular service of electronics instead of swapping full device. [26] Metrics : Damping range (N·m·s/rad), Energy holding up in the event of a stumble-load over load and Endurance to field serviceability time, Mean Time Between Failures (MTBF).

(3) Thermal & Hygroscopic Managed Sockets

Physics lever: heat and mass transfer (conduction, convection, vapor diffusion) Design actions: ventilated channels, high-MVTR liners, graded laminates to relieve CTE mismatch; CFD-guided vent placement. Sustainability impact: fewer skin complications → higher adherence → longer "effective life" of device and soft goods; lower replacement rate of liners. Metrics: peak interface temperature/humidity, pressure–shear map uniformity, liner life (cycles to compression set). [26]

(4) Repairable Polymers & Design for Disassembly

Physics lever: reversible network chemistry, fracture mechanics at bonded interfaces. Design actions: vitrines or reprocessable thermoplastics in sockets/cosmetic shells; mechanical fasteners in place of permanent adhesives; accessible panels. Sustainability impact: localized repair instead of full replacement; recoverable materials at end-of-life. Metrics: repair time, retained strength after repair (% of as-new), mass recovered for recycling.[27].

(5) Tribology-Optimized Joint Interfaces

Physics lever: the mechanics of wear, contact pressure and surfaces; Design alternatives: DLC or ceramic like coatings; UHMWPE/glide inserts with polished Ti*; hydrodynamic grooves where applicable. Environmental impact: slow wearing, better durability and longevity of changing interval; lower amount of particle wear debris; consistent performance up to years Metric: COF (dry/wet) — Wear rate ($mm^3/10^6$ cycles), particle count[28]

(6) Lightweight, Topology-Optimized Structural Members

Stiffness, stability and vibration analysis of a lever from physics; Phase 2: Design actions Topology optimization for ISO load cases• Graded density lattice infill (AM) & Thin-wall CFRP tubes with local reinforcements Effect on sustainability: mass reduction (material and transport), less strain to the user → more daily use, preservation of the fatigue margin (by eliminating stress

concentrators) Metrics: mass reduction, slenderness ratio stability factor, step frequency modal detuning [29]

(7) Sensitized equipment & Predictive Maintenance

Physics related usages: for e.g strain/temperature sensing, signal processing and reliability modelling. Design actions: FBGs or foil gauges embedded in non-critical plies; IMUs for gait anomalies detection; counters on circuit to count the cycles from when the mCT system is turned ON. Sustainability impact: Service and replacement only when necessary; early crack/loosening detection avoids catastrophic failure conditions and full-device replace. Metrics: prognostic horizon (cycles to fault), false-alarm rate, prevented replacements per year

(8) Distributed Additive Manufacturing (AM)

TONS BY: physics lever): process–structure–property relations + thermal history control Application Design SLS / SLM for value joints; FDM shells (for fitting) with fiber inlays and/or print-to-fit sockets from patients scans Sustainability impact: limited scrapping; spares on demand; localized fabrication with reduced transport emissions and lead time. Metrics: metrics: buy to fly ratio (material efficiency), energy per printed part, dimensional repeatability, R&R score [30]

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Table 1: Application Matrix (quick mapping)

Need	Physics lever	Design action	Sustainability metric
Longer life under cyclic loads	Fatigue/fracture	Fillets, fiber alignment, S–N-driven layups	Cycles to failure; warranty years
Cooler, drier interface	Heat/mass transfer	MVTR liners; vented sockets	Skin events/1000 device-days
Fewer full replacements	Repairable chemistry	Vitrimers; mechanical fastening	% parts repaired vs replaced
Lower user effort	Specific stiffness & mass	CFRP struts; topology-optimized beams	Energy cost of walking ($J \cdot kg^{-1} \cdot m^{-1}$)
Lower wear debris	Tribology	DLC + UHMWPE pairings	Wear rate; debris counts
Right-time servici	Sensing & reliability	Duty-cycle counters; strain sensing	MTBF↑; unplanned downtime↓

(9) Orthoses with Tunable Stiffness

Physics lever: beam/shell mechanics, viscous springs Action taken: dynamic AFOs with interchangeable spring cartridges; adjustable ROM stops, Semi-active dampers – active control KAFOs for descent control Sustainability impact: short-term study; ducks longer-term studies3) same device to adapt across rehab stages => fewer iterations of device + less clinician time. Metrics: spasticity range (N·mm/deg), self-reported patient objective comfort over activity set, device reuse per phase.

(10) Load Transfer Optimization in Osseointegration (OI)

Physics lever: contact mechanics, thresholds for micro motion driven bone ingrowth Design actions: adjust for surface porosity/roughness; compliance of adapters to direct load paths; measure axial/bending loads sustainability impact: long term stable connection (open to specific patients) has potential to reduce number of socket replacements, due to careful design features limit overload and loosening of implant. Primary stability (micromotion µm), bone-implant stress distribution, revision rate, as seen in Table 1

Experimental

Literature review focuses on the themes of: structural test standards, composite-materials LCA specific to prosthetics, semi-active MR damping, and thermal/moisture management in liners. Synthesis of design framework linking structural metrics (fatigue, wear, damping) to user comfort/adherence measures and LCA indicators also A recommendation map; a series of actionable decisions (material, geometry, control) that are usable with verification checkpoints and measurable. [7]

Conclusion

Prosthetics and orthotics are more than just medical devices; they are empowering tools that help individuals regain independence, restore mobility, and improve their quality of life. This review highlights how modern prosthetic and orthotic interventions extend beyond biomechanical outcomes to significantly impact psychosocial well-being, social participation, and employment breaks. Technological encroachments—from microprocessor-controlled prostheses and robotic orthotics to 3D printing, smart materials, and artificial intelligence—have redefined what is possible, offering users unparalleled levels of comfort, ease, and personalization However, despite these remarkable innovations, global inequities in access remain a pressing concern. Millions of personalities in low-and middle-income countries lack even basic devices, while radical technologies are often concentrated in high-resource contexts



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