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Review

A review of composite materials for enhancing support, flexibility and strength in exercise

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ABSTRACT

Composite materials are increasingly being used in sports and exercise equipment due to their favorable strength-to-weight ratios, tailored stiffness, fatigue resistance, and vibration damping. These properties provide new opportunities to enhance the functionality, flexibility, support, and strength capabilities of equipment used for fitness, training, and rehabilitation. This review examines recent advances and innovations in the application of composite materials for exercise, with a focus on how composites can provide benefits in terms of flexibility, joint support, strength training, and overall exercise performance. Composite materials offer lower weight, higher strength, and tailored stiffness that can improve performance in racquet sports, golf, footwear, and strength training equipment. They also provide flexible joint support through braces, casts, padding, and prosthetics. Successful implementation of composites in exercise equipment requires careful design analysis, material selection, and manufacturing methods. Future research directions include design optimization, multifunctional composites, improved manufacturing, and durability studies. Composites have the potential to revolutionize how we train, recover, and rehabilitate through optimized exercise equipment and assistive technologies.

1. Introduction

Composite materials are increasingly being used in sports and exercise equipment due to their favorable strength-to-weight ratios, corrosion resistance, and ability to be tailored to achieve specific performance characteristics [1,2]. The unique properties of composite materials provide new opportunities to enhance the functionality, flexibility, support, and strength capabilities of equipment used for fitness, training, and rehabilitation [3–6]. This review paper examines recent advances and innovations in the application of composite materials for exercise, with a focus on how composites can provide benefits in terms of flexibility, joint support, strength training, and overall exercise performance.

Composite materials are made by combining two or more constituent materials with different physical and chemical properties [7–12]. The resulting composite material exhibits a balanced combination of the properties of its constituents. Fiber-reinforced polymer composites are the most prevalent type of composite used in sports applications [13]. In these materials, strong load-bearing fibers like carbon fiber, glass fiber, or aramid fiber are embedded within a polymer resin matrix material [14]. The fibers provide strength and stiffness, while the matrix holds the fibers together and transfers loads between them [15]. By changing the type of fibers, their orientation and volume fraction, and the matrix material, engineers can tailor the properties of the composite to achieve specific requirements for strength, stiffness, fracture toughness, and weight [16]. Other types of composites used in sports include metal matrix composites, which incorporate ceramic or metallic fibers or particles within a metallic matrix, and sandwich composites, which have thick high-strength facesheets surrounding a lightweight core [17].

Composite materials offer several advantages over traditional metallic materials that make them well suited for sports and exercise uses [18]. The high strength-to-weight ratio of composites allows for lighter weight equipment, reducing fatigue and injury risks [19]. The stiffness and elasticity of composites can be tuned to meet the flexibility, vibration damping, and resilience needs of different applications.

Abbreviation: FRPs, Fiber-Reinforced Polymer Matrix Composites; MMCs, Metal Matrix Composites; CMCs, Ceramic Matrix Composites; HFRP, Hybrid Fiber-Reinforced Polymer; AFO, Ankle-Foot Orthosis; PLA, Polylactic Acid; TPU, Thermoplastic Polyurethane; SEM, Scanning Electron Microscopy; ISO, International Organization for Standardization; UV, Ultraviolet.

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Composites have high fatigue strengths for enduring repetitive cyclical loads [20]. Their fracture toughness and damage tolerance characteristics allow composites to withstand abuse [21]. Composite materials are also not susceptible to corrosion, an advantage over metals. The anisotropic properties of composites enable directional strength and stiffness to be achieved where needed [22]. Finally, composites allow for part integration and complex geometries, permitting customized designs and sizes for individual equipment [23].

Recent years have seen the increasing use of composite materials in place of traditional wood, steel, and aluminum alloys in exercise equipment [24]. Racquets for tennis, badminton, squash, and other sports have widely adopted composites, improving swing speeds, control, and feel compared to wood racquets. Composite materials comprise the majority of modern golf club heads and shafts, providing superior momentum transfer and directional ball striking over classic steel and persimmon wood clubs [25]. Athletic footwear heavily employs composites; the high strength and low weight contribute to energy return and running economy [26]. Weightlifting bars have transitioned from steel to composite designs to provide resilience, customized flex, and improved grip. The use of composites is also growing in other strength training equipment, like benches, platforms, and machine components [27].

Beyond high-performance equipment, composites also offer advantages for providing tailored flexibility and support in exercise gear [28]. The anisotropic properties allow directional bending stiffness to be designed into supportive braces, guards, and taping that provide protection and stability to joints like the knee, wrist, and elbow [29]. Composite orthoses and casts offer lighter weight alternatives to fiberglass, along with breathability and water resistance [30]. Smart composite materials are being developed that can sense joint motion and provide adjustable levels of flexibility and support. The vibration damping qualities of composites lend themselves to exercise equipment like yoga blocks that must provide stable, supportive surfaces for holding positions [31]. Advanced composites are even being integrated into prosthetic limbs for exercise and recreational use [32].

For strength training applications, composites allow the creation of high-capacity lifting equipment that exceeds the limits of traditional steel. By combining high strength fibers like carbon fiber with tough epoxy resins, composites can achieve strength-to-weight ratios up to 5 times higher than steel while maintaining stiffness [33]. This allows for lighter weight bars, plates, and machines that can lift extreme loads over 1000 pounds for advanced strength training, while avoiding permanent bending or failure. The use of composite materials also eliminates metal-on-metal contact in weightlifting, reducing noise and corrosion issues associated with steel equipment [34]. Manufacturing techniques like pultrusion and filament winding enable composites to be formed into the cylindrical bars and circular plates used in free weights [35]. The higher cost of composite materials is counterbalanced by their extended fatigue lifetime under maximum loading.

Realizing the full potential of composites in exercise equipment requires careful design considerations. The stiffness, strength, and fracture resistance must be adequate under expected loadings and environmental conditions. The complex stress states involved in exercise equipment require advanced modeling of the composite behavior. Special surface coatings or treatments may be necessary to provide wear resistance and grip. Designers must account for potential failure modes including delamination, cracking, and joint failures [36]. Manufacturing methods must achieve uniform high-quality lamina alignment and consolidation as well as consistent part geometries and tolerances. Components and systems must be designed for efficient manufacturability and assembly. Standards for testing and certification help ensure the safe performance and reliability of composite exercise equipment [37]. Fig. 1 illustrates the comprehensive overview of composite materials' use in sports and exercise equipment, highlighting their advantages, applications, and future research directions.

There remain numerous promising opportunities for future advancements in composites for exercise applications. Design optimization methods and multiscale modeling can further refine composite configurations tailored for exercise uses. Novel multifunctional composites capable of electrical conductivity, sensing, and self-healing would provide added functionality. Improved manufacturing techniques such as automated fiber placement could enhance composite part quality and consistency while reducing costs. Research into the long-term durability, fatigue damage progression, and environmental degradation



Fig. 1. Mindmap overview of composite materials in sports and exercise equipment.

mechanisms in exercise composites will support their continued adoption. As the understanding of composite performance continues to progress, they will play an integral role in powering human potentials.

2. Composite materials overview

Composite materials are formed by combining two or more constituent materials with distinct properties to create a new material with characteristics different from the individual components. The constituents are combined at a macroscopic level and retain their individual chemical identities. The constituent materials work synergistically to provide enhanced overall performance [38]. Fig. 2 shows the comparison between conventional monolithic materials and composite materials.

There are many types of composite materials, which can be categorized based on the nature of the constituent phases. The most widely used are fiber-reinforced FRPs, which consist of strong load-bearing fibers embedded within a polymer resin matrix[39]. The fibers typically provide strength and stiffness, while the matrix transfers stresses between the fibers and protects them from damage [40]. Common fiber reinforcement materials include carbon fiber, glass fiber, aramid fiber, boron fiber, and natural fibers like flax or hemp [41]. Thermosetting resins are most often used as the matrix, including epoxies, polyesters, vinylesters, and phenolics. The fibers may take the form of long continuous fibers or short dispersed fibers [42]. Composites can also incorporate woven, braided, or stitched fiber preforms.

Other types of composites include MMCs [44] and CMCs [45]. In MMCs, metallic matrices like aluminum, titanium, or magnesium are reinforced with particles, whiskers, or fibers of ceramics like silicon carbide or graphite [46]. Fig. 3 shows the application and type of MMCs with physical and mechanical properties. CMCs combine ceramic matrices with ceramic fiber fillers, providing extremely high temperature capabilities [47]. Fig. 4 shows the main CMCs matrices with typical reinforcements and the most popular industrial applications. Additional composite classes include carbon-carbon composites, which use carbon fiber reinforcement in a carbon matrix, and sandwich composites [48]. Sandwich composites are like a laminate but with thick, strong facesheets surrounding a lightweight core material [49].

Reinforcing fibers provide strength and stiffness in the direction of the fiber orientation. They carry most of the applied tensile and compressive loads in a composite [52]. The fibers suppress crack propagation in the brittle matrix and provide increased fracture toughness. Common reinforcing fibers and their properties are summarized below:

- Carbon fiber: extremely high strength (2500–5000 MPa) and stiffness (200–800 GPa); low density; high cost
- Glass fiber: high strength (1000–3500 MPa); low cost; prone to cracking
- Aramid fiber: high strength (3000–3150 MPa); high toughness and impact resistance

Polymer matrices in composites serve to transfer stresses between the reinforcing fibers, provide shear and transverse strength, and protect fibers from damage [53]. They also give composites environmental resistance and determine maximum service temperature limits. Key matrix materials include:

- Epoxy: superior strength and stiffness; temperature resistant; high adhesion; brittle
- Polyester: low cost; chemically resistant; lower strength/stiffness
- Vinyl ester: corrosion resistant; intermediate cost/performance

Various manufacturing techniques are employed to form composite components. Layup and curing of pre-impregnated fiber sheets is commonly used [54]. Resin transfer molding injects resin into a fiber preform. Filament winding wraps tows around a mandrel. Automated fiber placement and tape laying precisely deposit fibers. Pultrusion continuously pulls material through a die [55].

Composites offer several advantages that make them desirable materials for many structural applications:

- High strength-to-weight ratio: Composites are exceptionally strong yet lightweight materials. This allows for substantial weight reductions over metals.
- Anisotropic properties: The directional fiber orientation allows tailoring of properties like stiffness and strength.
- Fatigue and corrosion resistance: Composites exhibit excellent fatigue strength and do not corrode like metals.
- Part integration: Complex parts can be molded, reducing assembly compared to metals.
- Vibration damping: Composites provide excellent damping and isolation of vibrations.
- High fracture toughness: The fiber reinforcement impedes crack propagation in the matrix.
- Design flexibility: A wide range of properties can be achieved by varying constituents and configurations.
- Electrical insulation: Most polymer composites provide electrical non-conductivity.

Despite these advantages, composites also present some challenges and limitations:

- High raw material costs: Carbon fiber and some resins are very costly compared to metals.
- Complex failure modes: Composites can fail by cracking, delamination, buckling, and fiber breakage.
- Anisotropy: Properties vary with direction due to fiber orientation.
- Environmental degradation: Composites can degrade under moisture, UV exposure, and temperature.
- Lack of recycling: End-of-life composite recycling options remain limited.
- brittle materials with little plastic deformation capability.

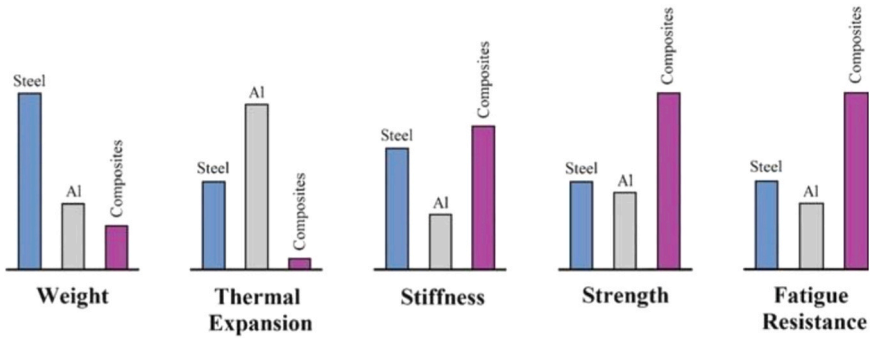


Fig. 2. Conventional monolithic materials and Composite materials, a comparison [43]. Copyright permission from Elsevier.

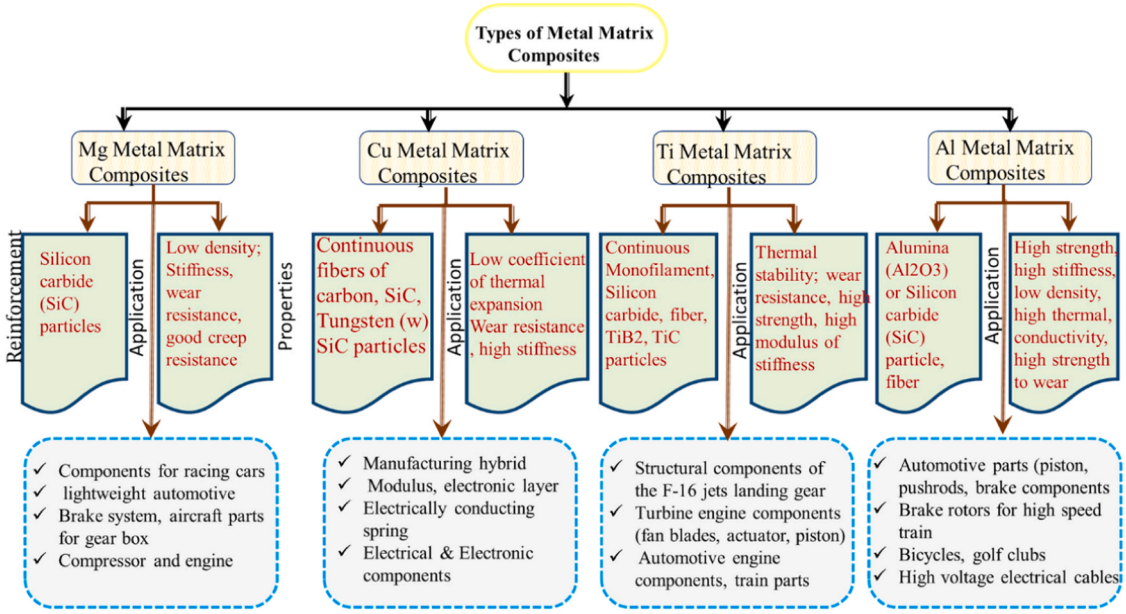


Fig. 3. Application and type of MMCs with physical and mechanical properties [50]. Copyright permission from Springer.

3. Composites in exercise equipment

The unique capabilities of composite materials have driven their adoption across a broad range of sports and exercise equipment over the past several decades. Composites provide exercise equipment with high strength, low weight, durability, and vibration damping that outperform traditional material choices like wood, steel, and aluminum. This section surveys the growing applications of composite materials in various types of exercise gear and accessories.

3.1. Racquet Sports

Racquet sports like tennis, squash, badminton, and racquetball have almost universally adopted composites in modern racquet designs. Early racquets used materials like wood, steel, and aluminum. While providing good stiffness, these materials had limitations in terms of weight, vibration damping, and durability. Composite racquets first emerged in the 1960 s, combining fiberglass and carbon fiber with polymer matrices like epoxy, vinyl ester, polyester, and Kevlar [56].

Modern racquets use advanced composites containing carbon fiber and other high stiffness, high strength reinforcements. The directional properties allow tailoring of stiffness and strength in different orientations to resist bending and torsional forces during play [57]. The excellent vibration damping provided by composites gives better shot control and reduces strain on player's elbows and shoulders. Lighter weights reduce swing effort and fatigue [58]. Resilient composite deflection combined with strength produces enhanced ball velocity, spin, and accuracy. The high durability and fracture toughness prevents breakage or splintering like wooden racquets.

Young and Liu [59] investigated the microstructure of a graphene-reinforced tennis racquet produced by HEAD. The researchers wanted to determine where graphene had been used in the racquet, what type of graphene material was employed, and for what purpose. They used a combination of optical microscopy and Raman spectroscopy to analyze samples from the racquet frame (Fig. 5). The results showed that the main structural components of the racquet were high-strength carbon fibers embedded in an epoxy resin matrix. The carbon fibers exhibited broad D and G bands in their Raman spectra, typical of polyacrylonitrile-based fibers. The epoxy resin matrix between the fiber plies gave a strong aromatic peak in its Raman spectrum. However, in resin-rich regions at the junction where the racquet handle meets the head, additional Raman bands were observed. This indicated the presence of a second phase in the resin in these regions. High-magnification optical microscopy revealed sub-micron white particles dispersed in the resin. The additional Raman bands in these areas matched those of graphitic carbon, with a narrow G band at 1580 cm^{-1} and a 2D band at 2680 cm^{-1}. By comparing the shape and position of the 2D band to those of different graphene materials, the researchers concluded that graphite nanoplatelets had likely been added to the resin-rich regions. The nanoplatelets, around 5 μm in diameter and 6–8 nm thick, would have improved the stiffness and toughness of the resin in these junction areas, which could otherwise be prone to failure during use. Thus, the graphene material was strategically employed where it was most needed to strengthen potential weak points in the racquet frame.

3.2. Golf

The searches for maximum driving distances and shot control have motivated extensive use of composites in both golf club heads and shafts. Golf club heads were traditionally made from woods like persimmon and laminated maple [25]. Beginning in the 1980 s, composite metal woods combining carbon fiber, Kevlar, and fiberglass with titanium and other metal alloys emerged [60]. These offered much higher strength and larger club head sizes for power driving.

Modern drivers have adopted pure composite heads made via resin transfer molding, compression molding, or filament winding processes [61]. The high strength and stiffness of carbon fiber composite heads maximizes energy transfer to the ball for distance. Their vibration damping provides improved feel and feedback. Larger club head sizes up to 460 cm^3 are enabled by composites. The ability to subtly alter fiber orientations allows tailoring of stiffness regions to place the club's center of gravity in an optimal location [62].

Slater et al. [63] tested how strain, strain rate, and geometry affect the damping properties of carbon fiber composites used for golf club shafts (Fig. 6). They created 11 composite panels with varying fiber orientations and geometries and subjected them to different levels of strain and strain rate through frequency testing. The results showed that the strains and strain rates experienced during a golf swing would not significantly change the damping characteristics of the composites. This means that simple quasi-static testing at low strain and strain rate is enough to determine how the shaft will perform dynamically during a swing, as long as the strains remain in the linear elastic region. However,

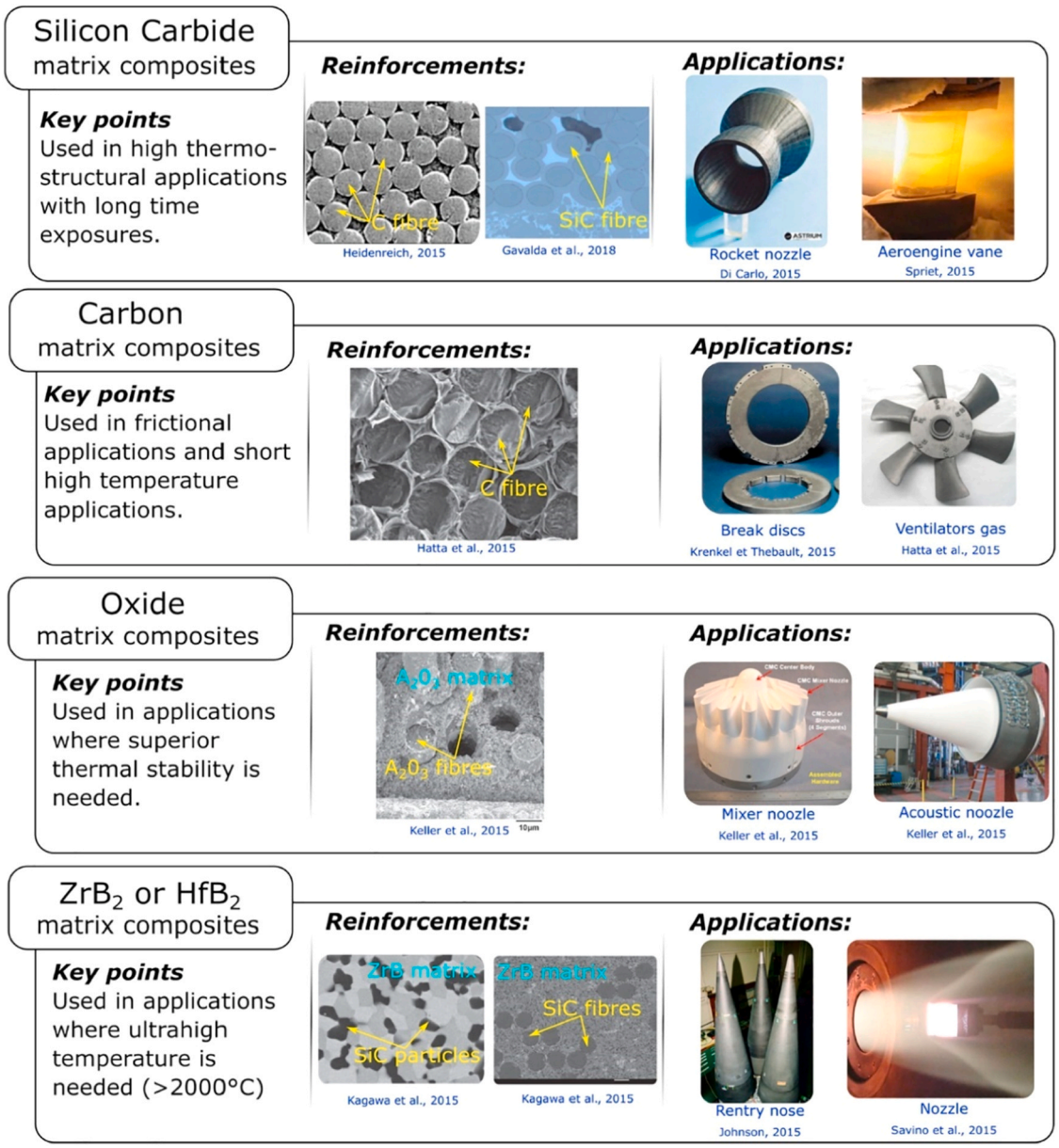


Fig. 4. Summary of the main CMCs matrices with typical reinforcements and the most popular industrial applications [51]. Copyright permission from Elsevier.

the panel geometry and fiber orientation did impact the damping, with lower aspect ratios and more off-axis fiber orientations resulting in lower damping. This shows that the panel geometry affects the shear properties and fiber-matrix interfacial slippage, which influence damping. To accurately characterize the damping of carbon fiber composites for golf shafts, both the panel geometry and fiber orientation must be considered, but strain rate testing is not necessary due to the insensitivity to strain and strain rate at golf swing levels.

Composite materials are also replacing steel in modern golf shafts [64]. Earlier generations used fiberglass or graphite composites. Current designs employ advanced carbon fiber reinforced epoxy shafts. Composite shafts offer very high strength and stiffness for efficient energy transfer during the swing while remaining exceptionally lightweight. Their tailored flex profiles aid precise club control and desired ball trajectories [65]. The fatigue life of composite shafts also far exceeds steel designs.

3.3. Footwear

Performance athletic footwear relies heavily on composite materials to reduce weight and provide energy return and efficiency. Many running shoe models now incorporate carbon fiber plates in the midsole to add stiffness and aid power generation like a spring [66]. Strategic placement of unidirectional carbon fiber bands affects flexion point positioning. Glass and aramid fiber composites feature in shoe uppers, where strength and tear resistance are priorities.

Irzmańska et al. [67]designed new bioactive composite materials with melt-blown nonwovens for use as insoles in protective footwear. The aim was to develop insoles that provide mechanical resistance, allow moisture transport, and inhibit microorganism growth. Several variants of melt-blown nonwovens were made using polypropylene, polycarbonate, and polyamide polymers (Fig. 7). A technique for ultrasonically bonding the composite layers was also developed. The composites were tested for mechanical properties like tear strength and abrasion resistance, hygienic properties like water vapor permeability, and microbiological properties. The results showed that the composites

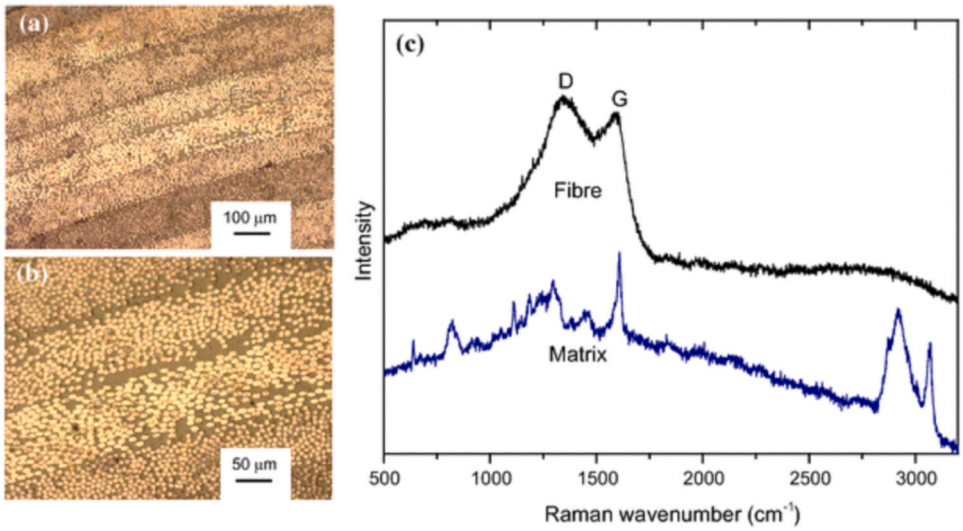


Fig. 5. The microstructure of the tip region of the racquet: (a) transverse section, (b) same section at higher magnification. (c) Raman spectra of the carbon fibres and the resin matrix [59]. Copyright permission from Springer.

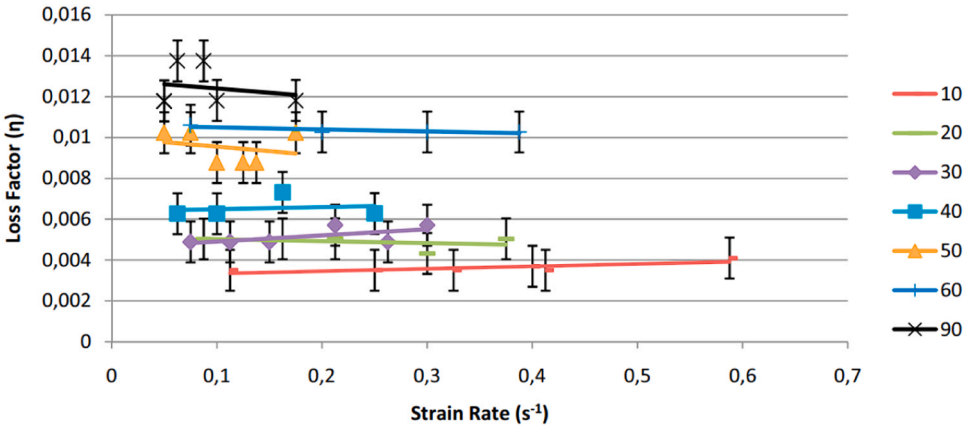


Fig. 6. The effect of strain rate on loss factor on different fiber orientations [63]. Copyright permission from Elsevier.

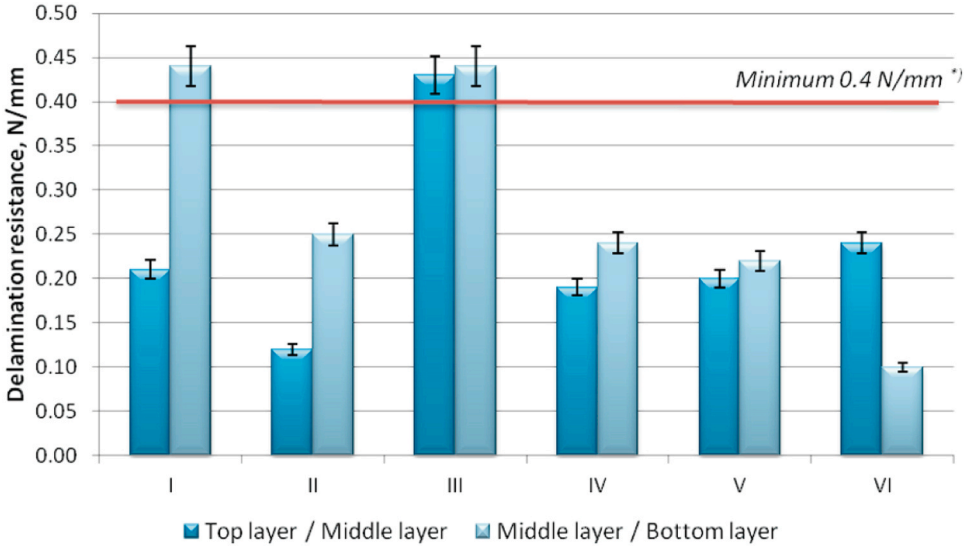


Fig. 7. Average values of delamination resistance for layers of different variants of bio- active composites used in protective footwear insoles [67]. Copyright permission from Sieć Badawcza Łukasiewicz - Łódzki Instytut Technologiczny.

containing polycarbonate melt-blown nonwovens with a bioactive agent performed the best overall. These composites were about 5–7 mm thick and withstood over 25,000 abrasion cycles, meeting the mechanical requirements. They also exhibited high water vapor permeability of 11–13 mg/(cm^2 h) and water vapor coefficients of 92–103, indicating good moisture transport properties. The polycarbonate nonwovens themselves provided good thermal insulation, translating to higher heat resistance of the composites. Most importantly, the composites containing the polycarbonate nonwovens effectively inhibited the growth of bacteria like Staphylococcus aureus and Escherichia coli as well as fungi like Candida albicans. The ultrasonic bonding method also ensured good bond strength between the composite layers. In summary, the bioactive composites with polycarbonate melt-blown nonwovens showed the best performance for use as insoles in protective footwear, offering mechanical resistance, moisture transport, and microbial inhibition.

The outsole tread in athletic shoes has transitioned from rubber to composite polymers like Pebax that contain rigid glass fibers for enhanced durability and grip [68]. TPU midsoles take advantage of composite technology, combining the shock absorption of foams with TPU fibers for rebound. TPU and nylon composite meshes increase ventilation and stability in shoe uppers. The embedding of antimicrobial copper fibers helps control odor in high performance shoes. Fahanwi et al. [67] aimed to develop novel nonwoven fibrous biocomposite materials as potential leather substitutes for footwear components using readily available renewable biomass sources of microbial cellulose and maple tree leaves mixed with biodegradable polymers. The biocomposite preparation was optimized using Design of Experiments to determine the optimal ratios of bacterial cellulose, maple leaf and polycaprolactone which had the most significant effect on the material properties. The optimized biocomposite showed a tensile strength of 2.13 MPa and elastic modulus of 76.93 MPa, indicating it was flexible with considerable mechanical strength. Scanning electron microscopy and pore volume analysis showed the biocomposite was porous and possibly breathable. The surface was hydrophilic with water contact angles between 60 and 85 degrees. The material also demonstrated good shape stability and adhesion properties. These results suggest the optimized biocomposite could potentially be suitable for use as components in footwear, though further improvements would be needed to match the performance of conventional synthetic leather.

3.4. Strength training

Human performance capabilities in strength sports like powerlifting, weightlifting, and bodybuilding have been transformed by the integration of composite materials into strength training equipment. Barbells and dumbbells previously made from steel or cast iron have been upgraded to composite designs that enable lifting extreme loads exceeding 1000 pounds. The ultimate tensile strength of high strength carbon fiber composites is 5–10 times higher than steel, opening new frontiers in heavy resistance training [69].

Pultruded carbon fiber lifting bars provide superior flex and spin characteristics. Their solid core construction eliminates steel bar flex and whip. Lai et al. [70] investigated the flexural creep behavior of large-diameter unidirectional pultruded carbon/glass HFRP bars under different conditions (Fig. 8). The HFRP bars had a 19 mm diameter with a glass fiber shell and carbon fiber core. The researchers conducted creep tests on unconditioned HFRP bars and bars that were preconditioned through 160 freeze-thaw cycles while soaked in water. They also tested bars under combined freeze-thaw cycling and mechanical loading. Creep tests were performed at stress levels from 50% to 70% of the ultimate stress for up to 5000 hours while monitoring strain and deflection. The results showed that the preconditioned bars had an 11% reduction in flexural strength and higher creep strain compared to unconditioned bars. Findley's power law model was used to analyze the creep behavior, and the model showed good agreement with experimental results. Based on the model, the researchers predicted that over 50 years, the unconditioned bars would have an 11% reduction in flexural modulus, while the preconditioned bars would have around a 20% reduction. The model also predicted that the preconditioned bars would have around a 27% increase in creep deflection over 50 years at 70% of the ultimate stress, close to failure. Scanning electron microscopy revealed microdamage and defects in the bars that likely contributed to their creep behavior under different conditions.

High strength composite dumbbells and plates from vinylester concrete allow incremental load increases up to 1000 pounds, avoiding large equipment jumps with steel plates [71]. Composite plyometric platforms and jump boxes offer strength, resilience, and light weight for explosive training. composites are even emerging in structural components of strength training machines to raise weight limits. A broad range of other exercise equipment has benefited from composite materials.

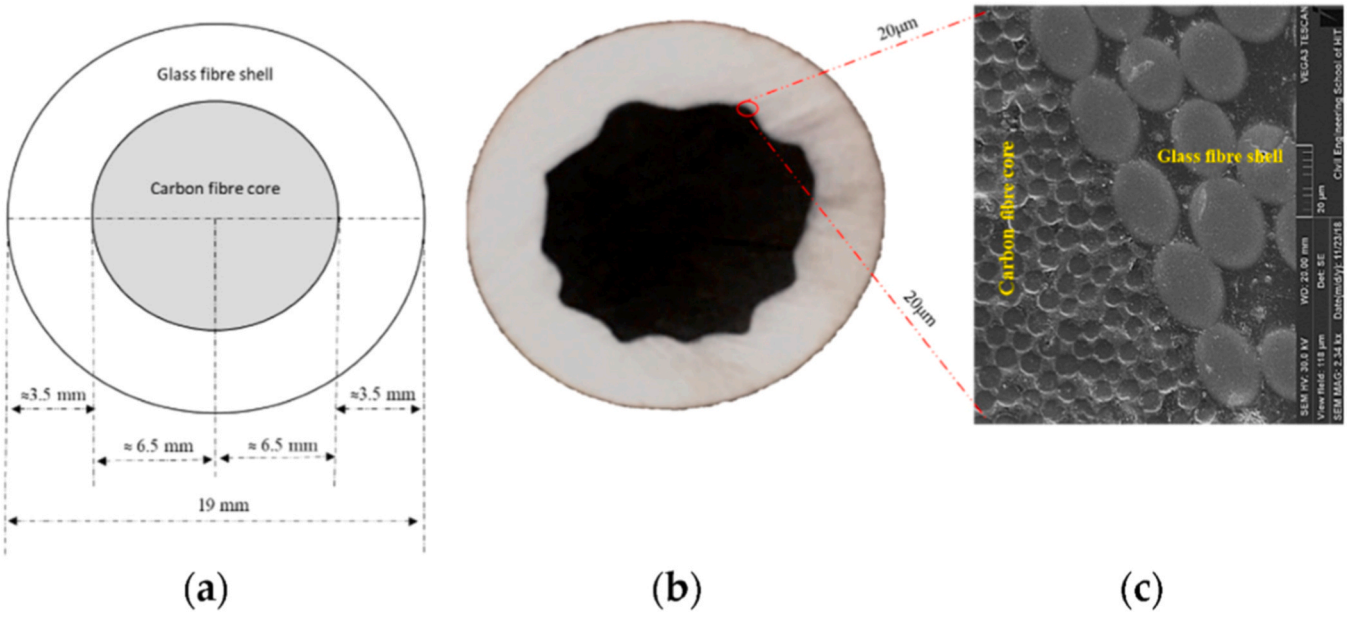


Fig. 8. (a) Diagram representing the cross-sectional dimensions of HFRP bars; (b) Cross section of hybrid HFRP bars; (c) Enlarged scanning electron microscopic image [70]. Copyright permission from MDPI.

Composite paddles and shafts for sports like canoeing, kayaking, and stand up paddleboarding provide water resistance without adding excessive weight [72]. Rehabilitation devices like pulleys and suspension straps apply high strength polyethylene and aramid composites [73, 74]. Batting helmets and catching masks use carbon fiber and other reinforced composites for ball impact protection [75].

Bicycle frames and components make extensive use of carbon fiber composites to reduce weight while adding stiffness [76]. Dvořák et al. [77] recently evaluated a composite bicycle frame made from carbon fiber reinforced polymer tubes joined using hand layup composite laminates. The researchers focused on analyzing the strength and strain behavior of the head tube joints connecting the top tube and down tube to the head tube. They tested the frame using standard ISO load cases and also on an ergometer to determine the operational strain envelope (Fig. 9). They found that the head tube joints experienced significantly higher strains than the frame tubes themselves, especially under pedaling and horizontal loading. To further analyze the head tube joints, they tested simplified frame specimens without seat stays or chain stays. They used strain gauges, digital image correlation, and acoustic emission monitoring to evaluate the deformation and failure of the joints. Finite element analysis of the composite layup showed that the positions of the sensors within the joints greatly impacted the measured strain values, indicating high sensitivity to sensor placement. The researchers then reinforced the composite layup of the head tube joints by adding additional carbon fabric layers. Testing showed that the reinforced joints exhibited higher load-bearing capacity, a more balanced stress distribution between the top tube and down tube joints, and detected damage at higher load levels compared to the original joints.

Motorsports like Formula 1 and NASCAR rely on carbon composites for stiff, lightweight chassis, body panels, and interior components that give rigidity and minimize vibration [78]. Boxing and MMA gloves utilize layered composites for wrist support, impact absorption, and lightweight feel. For example, Liu [79] aimed to design a boxing suit based on graphene composite fiber seamless knitted fabric to reduce injuries during boxing training. Nine types of fabrics were determined using an orthogonal matrix method varying the head yarn, inner yarn and knitting structure. A comprehensive fabric evaluation was conducted based on sequence entropy weight technology and the TOPSIS



Fig. 9. Bicycle frame (specimen 0) loading procedures: (a) Pedal forces; (b) Horizontal forces; (c) Vertical forces; (d) Bottom bracket stiffness; (e) Head tube torsion stiffness; (f) Ergometer test [77]. Copyright permission from MDPI.

method. Sample No. 7 with a veil of 70D/48 F graphene nylon, inner yarn of 30D graphene spandex/70D graphene nylon covered yarn, and 1+3 false rib knitted structure had the best performance with a relative proximity of 0.862. An actual wear test showed the anti-impact boxing suit had slightly better comfort than an ordinary suit, proving its good impact effect. In summary, the boxing suit with graphene composite fiber seamless knitted fabric had good protective performance and could be used for boxing training. The experimental results showed that Sample No.7 fabric had the highest infrared emissivity and shortest half-life, indicating better far-infrared and antistatic properties. It also had good UV resistance, wrinkle recovery, water permeability, air permeability and moisture absorption performance, making it suitable for the designed anti-impact boxing suit. Thus composites permeate the diverse universe of athletic equipment for enhancing human performance and protection.

3.5. Benefits over traditional materials

Composite exercise equipment provides several performance advantages over the traditional material choices:

- Lower weight: The fiber reinforcement carries loads at lower component weight. This reduces fatigue and injury risks.
- Tailored stiffness: Fiber orientation and layout allows directional stiffness optimization unmatched by metals. This aids swing control, energy return, and precision.
- High strength and toughness: Excellent specific strength and impact damage resistance permit high loads.
- Fatigue resistance: Composites withstand cyclic stresses far better than steel, especially under bending. Their elasticity reduces plastic deformation.
- Vibration damping: Composites damp uncomfortable vibrations and shock loads more effectively than metals.
- Consistency: Advanced composites avoid variability in properties between material lots.
- Environmental resistance: Composites avoid corrosion issues with long-term equipment use and exposure.
- Particle ejection prevention: Unlike wood, composites do not splinter or eject particles when fractured.
- Gripping: Composite surfaces can be textured to create grip, unlike smooth metals.
- Electrical insulation: Composites eliminate risks of current conduction from cables in metal-based equipment.
- Appearance: Composites offer styling flexibility over metals with options like tints, gloss finishes, and molded logos.

4. Composites for flexibility and support

Composite materials provide tailored flexibility and adjustable levels of support that can aid injury prevention and rehabilitation in exercise. Anisotropic composites allow directional bending stiffness to be designed into supportive devices. Compliant composites conform to anatomical shapes, while stiffer composites immobilize joints when needed. Smart composites are emerging that can sense and dynamically adapt joint support. This section examines flexible composite devices that provide joint stability, comfort, and protection during exercise.

4.1. Braces and supports

Braces, supports, and guards utilize composite materials like carbon fiber and fiberglass to protect vulnerable joints including knees, elbows, and wrists [80]. Ankle braces often combine rigid lateral composite struts that resist inversion/eversion strains with flexible medial padding for comfort [81]. They stabilize the ankle while permitting natural flexion mobility. Knee braces use composite components like hinges, frames, and straps to provide mediolateral support and reduce hyperextension risks without overly limiting motion [82].

Wrist braces apply four-way stretchable composite fabrics to compressively support tendons and ligaments during intense wrist motions in sports like tennis, golf, and weightlifting [83]. Guards like soccer shin guards couple hard composite shields with shock absorbing foam linings to protect bony prominence areas. Shoulder stabilization braces employ flexible composites allowing unrestricted arm motion but with increased proprioception feedback for better joint control [84]. Wan et al. [85] investigated the mechanical properties of 2.5-dimensional (2.5-D) woven glass fabric reinforced light-curable resin composites for potential use in orthotic applications. The researchers compared the properties of the 2.5-D composites to 2-dimensional (2-D) composites made with conventional woven glass fabrics. Both types of composites showed higher flexural strength and modulus than polypropylene, the material currently used to make orthotic devices. However, the 2-D composites exhibited higher static flexural properties than the 2.5-D composites due to less fiber undulation and curvature in the 2-D fabric. Despite the lower static flexural properties, the 2.5-D composites showed some advantages over the 2-D composites. They demonstrated higher delamination resistance as evidenced by the formation of smaller whitening areas under loading, indicating less crack propagation. The 2.5-D composites also avoided the wrinkling issues associated with 2-D composites when shaped around curved surfaces (Fig. 10). More importantly, the 2.5-D composites exhibited better impact and fatigue properties than the 2-D composites, likely due to their integrated structure and through-thickness reinforcement. These dynamic properties are critical for orthotic applications.

4.2. Splints and casts

Immobilizing splints and casts to protect injured limbs traditionally used plaster or fiberglass fabrics impregnated with polyurethane resins.

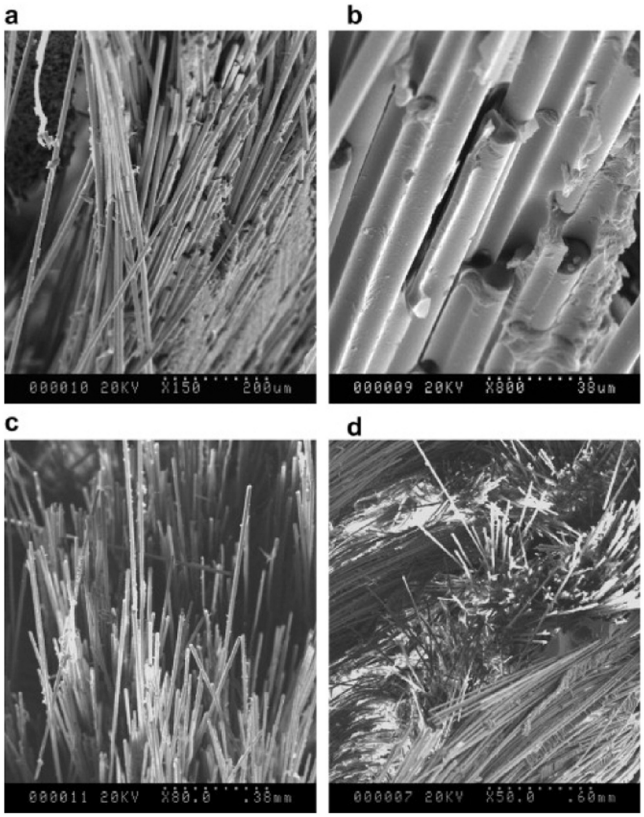


Fig. 10. SEM photos of tensile fracture surfaces of the 2.5-D composite specimens [85]. Copyright permission from Elsevier.

However, modern casting tapes increasingly rely on synthetic composites using polyester or polypropylene fabrics combined with water-activated polyurethane resins [30,86,87]. Schlégl et al. [86] aimed to compare the performance of traditional plaster and fiberglass casts with 3D printed PLA and PLA-calcium carbonate composite splints for fracture management (Fig. 11). The researchers characterized the materials through various mechanical tests including tensile, flexural, impact, hardness, fatigue and water absorption tests. They also manufactured actual casts from each material to compare practical aspects. The results showed that the 3D printed materials generally had better mechanical properties than the traditional casts. The PLA and PLA composites had higher tensile and flexural strength, which means they could potentially be made thinner while maintaining strength. This would make them lighter and more breathable. Fig. 10 shows the 3D models of the braces in Blender. The 3D printed materials also had significantly higher impact resistance, indicating they can better withstand dynamic forces if a patient bumps or falls on the cast. In the fatigue tests, only the 3D printed materials showed normal fatigue curves while the traditional casts did not, suggesting the 3D printed casts are more likely to retain their shape after repeated loading. The variable load tests also showed that the 3D printed casts were better able to reproduce their original support after higher loads compared to the traditional casts. The 3D printed materials also absorbed very little water, maintaining their rigidity, while the fiberglass cast absorbed over 5% water. Though manufacturing 3D printed casts was time consuming, the researchers believe the technology has the potential to be a good alternative to customized splints and casts in the future. These composite casts offer lighter weight, improved x-ray transparency, and breathability over older fiberglass models. They dry faster and do not overheat skin like plaster. Improved resin formulas provide stiffness and support equaling plaster and fiberglass [88].

Optional carbon fiber reinforcement layers can be added to create hybrid composite casts with slimmer profiles where complete immobilization is needed [89]. The unidirectional carbon fibers provide adjustable stiffness levels from flexible to completely rigid as needed. Some composites allow adjustable moisture curing rates from minutes to hours, providing time to set the injured extremity in an optimal healing position [90]. Antimicrobial coatings and perforations have been developed to reduce odor and itching issues with composite casts. Overall, composite materials provide improved alternatives to traditional plaster casting.

4.3. Padding and cushioning

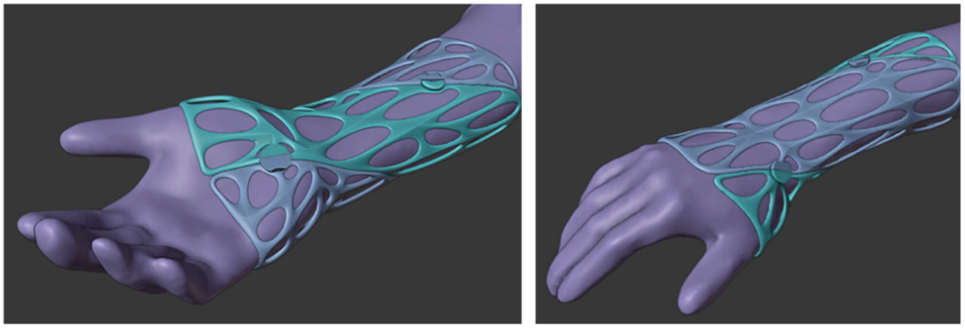
Flexible elastomeric composite foams play an important role providing padding and cushioning in exercises requiring contact with hard surfaces. Open cell polyurethane or latex foams reinforced with knitted textiles produce mats and flooring with desirable compression characteristics [91]. The high tear strength of glass and polypropylene fiber reinforcement prevents rips and adds durability. Such padding composites see use beneath yoga and Pilates poses performed on hard floors. They cushion and insulate against cold surfaces [92].

Sandwich composite mats surround polymer foam or air cores between protective fiber-reinforced skins [93]. These provide essential cushioning during activities like sit-ups, stretching, and floor calisthenics [94]. Thin composite liners are often incorporated into rigid wrist/hand supports used heavily in weight lifting to reduce chafing and distractions from pressure points [95]. Vibration damping composite liners also aid grip stability. The compliance and conformability of elastomeric composite padding improves comfort and reduces contact stresses during exercise.

4.4. Prosthetics and orthoses

For physiotherapy and adaptive exercise, composites enable high performance prosthetic limbs and orthotic devices. Carbon fiber lower limb prosthetics like blade sprinting legs match the strength, stiffness, and energy return of biological limbs while remaining lightweight [96]. Their fatigue resistance permits sustained training. Upper limb prosthetics utilize high strength composites for lifelike dexterity and appearance. Exoskeletal orthoses made from carbon fiber-reinforced polymers provide mobility assistance during rehabilitation exercise. Joint orthoses also apply composite materials for adjustable flexibility and support. Knee orthoses like Swedish and ACL braces use composite hinges to prevent hyperextension and instability while enabling free flexion [97]. Spinal orthoses composed of carbon fiber plates sandwiched between foam provide rigidity to limit risky motions. Shoulder and elbow orthosis designs employ flexible composite joints to limit joint travel while permitting exercise movements.

Shahar et al. [98] reviewed the history and development of AFOs, which are devices used to support and control the ankle and foot. AFOs have been made from materials like wood, metal, leather, plastics and carbon fiber composites (Fig. 12). The ideal AFO material should be lightweight, strong, stiff yet comfortable. While carbon fiber composites have the best strength-to-weight ratio and stiffness, they are expensive. Plastics are cheaper but have lower strength. They discusses that natural fiber composites like those made from kenaf plant fibers have the potential to replace current AFO materials. Kenaf composites are lightweight, renewable, biocompatible, recyclable and cheaper due to the abundance of raw kenaf. The mechanical properties of kenaf composites from previous studies show that they have tensile strength and stiffness values that are comparable to polypropylene plastics commonly used for AFOs. They compares the mechanical properties of AFOs made from polypropylene and carbon fiber composites from various research studies with the properties of kenaf composites. The results show that kenaf composites can achieve similar strength while being lighter in weight, cheaper and more sustainable than current AFO materials. They concludes that natural fiber composites like kenaf have great potential as alternative materials for fabricating AFOs that are cheaper, stronger,



(a) (b)

Fig. 11. Three-dimensional models of the braces in Blender (a) palmar view of the forearm and (b) dorsal view of the forearm [86]. Copyright permission from MDPI.

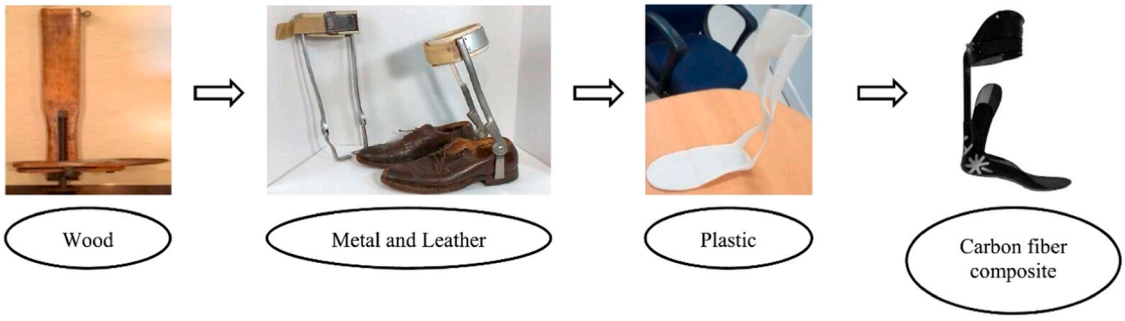


Fig. 12. The evolution of AFO materials [98]. Copyright permission from Elsevier.

eco-friendly and lighter. With the current trends in natural fiber composites and additive manufacturing using 3D printing, future AFOs made from natural fiber composites are likely to have reduced production time and costs.

5. Design and manufacturing considerations

The successful implementation of composite materials in exercise equipment requires careful engineering analysis and manufacturing. Composite behavior is complex, with directional properties and multiple failure modes. The design process must model expected mechanical loads and environmental exposures to specify appropriate composite constituents and configurations. Manufacturing methods must achieve robust consolidation and consistent geometries. This section reviews important considerations for the design and fabrication of composites for exercise uses.

5.1. Design analysis

Designing exercise equipment composites begins by determining the expected load ranges, directions, frequencies, and durations. Static and fatigue strengths can be calculated through laminate theory using the properties of the fiber reinforcement and matrix [99]. Stiffness and deflections under anticipated loads are modeled as well. Composite ply orientations are optimized to place fibers along principal stress directions. Potential failure modes like delamination, fatigue, and environmental degradation require analysis to specify damage prevention measures [100]. Interlaminar bonding enhancements, protective coatings, and isolation layers help improve durability. Generous fillet radii and chamfers reduce stress concentrations. Joint designs consider adhesive bonding, mechanical fastening, co-curing, and hybrid methods [101]. Inserts and anchors may be needed for attachments. Testing helps validate designs. Tensile, compression, flexure, and impact tests evaluate composite strengths and toughness [102]. Fatigue testing checks flaw growth models under cyclic loads [103]. Accelerated weathering examines moisture and UV degradation. Dynamic mechanical analysis evaluates damping properties. Any standards or regulations must be met with physical testing. Iteration and redesign adaptation is expected.

5.2. Material Selection

Material selection requires balancing strength, stiffness, toughness, durability, and cost needs. Thermosetting resins like epoxy and vinylester provide superior mechanical properties and environmental resistance over thermoplastics, at a cost premium [104]. Within thermosets, vinyl esters offer improved hydrolytic stability over epoxies. Thermoplastics can allow welding-based fabrication for speed.

Reinforcement selection depends on directional stiffness and strength requirements. High modulus carbon fibers provide maximum stiffness but lower strains-to-failure than glass fibers [105]. Hybrid composites can combine carbon and glass fibers to optimize cost and performance [106]. High strength polyethylene or Zylon fibers add toughness. Basalt fibers offer lower costs than carbon or glass.

Sandwich composites require choosing lightweight core materials. Foam and honeycomb cores provide high compressive properties and energy absorption for impacts [107]. Lattice truss and corrugated cores offer bending and shear stiffness. Wood and synthetic cores are options. The skin and core materials must be compatible for bonding [108]. Designing material combinations to meet performance requirements at acceptable costs is essential.

5.3. Fabrication methods

Common composite fabrication methods include hand layup, filament winding, pultrusion, compression molding, resin transfer molding, and automated fiber placement and tape laying:

- Hand layup stacks successive plies of fiber reinforcement preimpregnated with resin using rollers to compact layers. This allows complex shapes but depends on operator skill.
- Filament winding continuously wraps resin-wetted tows around a rotating mandrel to achieve cylindrical shapes like poles or golf shafts. Fiber angles are precisely controlled.
- Pultrusion pulls fiber tows through a resin bath and preforming guides before curing in a heated die to make constant profile parts like weight bars.
- Compression molding places reinforcement fabrics and resins into temperature/pressure molds to consolidate complex near-net-shaped parts.
- Resin transfer molding (RTM) injects liquid resin into a fiber preform contained within a mold cavity to fabricate intricately shaped composites.
- Automated fiber/tape placement and wrapping provides computer numerical control of layered fiber deposition for high precision and repeatability.

5.4. Manufacturing considerations

Achieving high quality exercise composites requires strict manufacturing standards and protocols. Composite constituents must meet specifications for purity, reactivity, viscosity, and tack. Reinforcement fibers require precision alignment and consistent volume fractions within narrow tolerances. Consolidation during curing should completely eliminate voids through positive pressure.

Tooling and processing parameters including temperatures, pressures, and cycle times require tight control to achieve repeatable results. Cured parts must undergo nondestructive evaluation like ultrasonic scanning to identify any manufacturing defects requiring rework. Finishing steps may involve machining, grinding, and edge trimming prior to joining, painting, or other secondary operations.

Consistent geometries and tolerances are critical in exercise components like shafts and tubes. Compliance with sporting regulations may

dictate allowable design dimensions. Statistical process control monitors key fabrication variables to stay within established limits. Manufacturing protocols aim to maximize composite part quality, consistency, and reliability.

6. Outlook

The future of composite materials in enhancing human performance through exercise is brimming with potential. Anticipated advancements in design optimization and modeling promise even more tailored composite configurations, specifically designed for unique exercise requirements. The horizon is further expanded by the prospect of multifunctional composites, which could incorporate capabilities like sensing, self-healing, and electrical conductivity. These innovations could add remarkable new functionalities to exercise equipment. Additionally, advancements in manufacturing techniques are expected to not only enhance the quality and consistency of these composites but also make them more cost-effective. Crucial to the sustained adoption of composites will be ongoing research into their long-term durability, understanding how they withstand fatigue and environmental degradation. As knowledge and technology in this domain evolve, composites are poised to become integral in developing optimized exercise equipment, protective gear, and assistive technologies. This evolution will fundamentally change the way we approach training, recovery, and rehabilitation, with far-reaching implications for human health, fitness, and wellbeing. The continued exploration and application of composite materials are set to redefine the landscape of physical fitness and rehabilitation, heralding a new era of innovation and human potential enhancement.

7. Conclusions

The integration of composite materials in fitness and rehabilitation equipment has marked a transformative phase in the industry. These materials, known for their high strength-to-weight ratios, have enabled the creation of lighter, yet more robust equipment, significantly reducing fatigue and injury risks for users. Their adaptability in stiffness and elasticity has been crucial in customizing equipment for specific needs, offering enhanced flex and vibration damping. This customization extends to various sports equipment, from racquet sports to strength training gear, where performance is noticeably enhanced. In rehabilitation, composites have shown immense value, allowing for the creation of braces and prosthetics that not only conform to the human body but also provide necessary support and immobilization. The success of composites in this field hinges on meticulous design, material selection, and manufacturing processes. These efforts ensure that the equipment meets the required performance standards consistently, underlining the composite materials' significance in revolutionizing fitness and rehabilitation equipment.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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