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Article

Transdisciplinary Innovations in Athlete Health: 3D Printable—Wearable Sensors for Health Monitoring and Sports Psychology

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Abstract: The integration of 3D printing technology into sensor development holds transformative potential for sports psychology, offering innovative solutions for monitoring athlete health and enhancing performance. Various theories have been established to explain how different levels and types of arousal impact athletic performance, providing valuable frameworks for optimizing athletes' well-being and performance. By incorporating wearable sensors into sports psychology, professionals can gain deeper insights into athletes' arousal and emotional states, enabling more precise assessments and interventions that lead to improved outcomes. This article explores the application of wearable sensors in sports, with a particular focus on 3D printable sensors that measure both physiological and psychological parameters in real time. These advanced sensors provide coaches and sports psychologists with critical data, allowing them to tailor interventions and strategies more effectively to each athlete's unique needs. The real-time data collection enabled by these sensors offers a dynamic approach to managing athlete performance and well-being. Furthermore, the article outlines future directions for sports psychology, emphasizing the importance of interdisciplinary collaboration and the integration of technological advancements, such as artificial intelligence. By harnessing these innovative tools, sports psychology can significantly enhance athlete resilience and performance, paving the way for a more comprehensive understanding of the complex relationship between mental states and athletic achievement. This approach not only advances the field but also contributes to the overall well-being and success of athletes in a highly competitive environment.

Keywords: sports psychology; wearable sensors; 3D printing; health monitoring; athlete performance

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1. Introduction

Health is defined as a state of complete physical, mental, and social well-being, essential for optimal human functioning [1]. This definition underscores an individual's capacity to adapt and manage challenges, a crucial aspect in sports where physical and psychological stresses are interconnected. Physical challenges in sports can lead to psychological consequences, manifesting as cognitive, emotional, and behavioral issues, while psychological challenges like relational problems, traumatic stress, anxiety, depression, aggression, disordered eating, and substance use can lead to serious physical consequences [2]. These interconnected stresses can impact an athlete's performance,

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training, career transitions, interpersonal functioning, and physical rehabilitation unless they are properly addressed.

Sports psychology, the study of how psychological factors influence athletic performance, physical activity, and sports participation, integrates psychology, kinesiology, and physiology to optimize athletes' mental well-being and performance. Understanding the complex relationship between the mind and body is crucial for developing effective training programs, enhancing performance, and promoting overall mental health in sports [1,3,4].

To further this understanding, wearable sensors play a pivotal role. These sophisticated instruments are worn on different body regions to monitor and analyze real-time physiological, biochemical, and electrophysiological outputs [61–70]. Sensors are positioned on areas such as the knees, feet, or hips to evaluate aspects of human motion like gait, and are equipped with a range of sensor types, including gyroscopes, force sensors, accelerometers, and electromyography, to collect precise data on physical activity. They also monitor biochemical and electrical impulses within the body, tracking physiological characteristics such as pulse rate (PR), heart period variability (HPV), resting pulse rate (RPR), and breathing frequency (BF) [5–7].

These devices provide uninterrupted, non-intrusive surveillance crucial for the prevention, treatment, and control of illnesses as well as for maintaining general health. Moreover, wearable sensor systems enable athletes to self-monitor and manage their psychological and physiological states, thereby enhancing their self-awareness and performance control [8]. As these sensors become increasingly important tools in sports psychology, they play a crucial role in maximizing athlete care and outcomes. The data collected by these sensors can be easily transmitted to the cloud through the Internet of Things (IoT) and 5G technologies, allowing sports professionals to analyze athletes' conditions and develop customized training or intervention programs. With ongoing advancements in data processing technologies such as cloud computing, machine learning, and artificial intelligence, raw sensor data can be transformed into actionable insights to identify potential issues before they impact performance [8].

As we have established a comprehensive framework on the intricate relationship between physical and psychological well-being in athletes, our discussion will now progress to more targeted applications of these insights. The following sections will delve into the sophisticated realm of wearable sensors, illuminating their critical role not merely as monitoring devices but as catalysts for enhanced athletic performance through real-time analytical capabilities. We will explore a variety of sports psychology theories that leverage this data to refine training and intervention strategies, thereby enhancing both mental resilience and physical performance. Additionally, we will detail the innovative 3D printing technologies that are pivotal in manufacturing these advanced sensors, underscoring the fusion of cutting-edge technology with sports science. This integration heralds a new era in sports psychology, where technological advancements and theoretical insights combine to foster a deeper understanding and improved support for athletes' health and performance.

2. Sports Psychology and Wearable Sensors

Sports psychology delves into the intricate relationship between arousal, emotion, and performance, significantly enriched by the advent of wearable sensor technologies. These devices capably monitor physiological indicators such as heart rate, skin conductance, and muscle activity in real time, providing precise data crucial for understanding an athlete's arousal and emotional states. This precise data facilitates the development of personalized training and intervention strategies, crucial for optimizing athletic performance [61–70].

Theoretical frameworks in sports psychology provide insights into how various levels and types of arousal impact performance. For instance, the Yerkes-Dodson Law proposes an optimal arousal level for peak performance that varies with the task's complexity [9]. Simple tasks may benefit from higher arousal, enhancing performance, whereas complex tasks typically require lower arousal levels. Drive Theory suggests a direct relationship between increased arousal and enhanced performance, especially in well-learned tasks [10]. Conversely, Reversal Theory, developed by

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Michael Apter, interprets arousal subjectively, suggesting that athletes can shift their arousal states to enhance performance through cognitive strategies [11]. Catastrophe Theory, proposed by J.G. Hardy, highlights a nonlinear relationship between arousal and performance, emphasizing the need to manage physiological arousal and cognitive anxiety to prevent performance drops [12]. The Individual Zones of Optimal Functioning (IZOF) model posits that each athlete has a unique optimal arousal level that maximizes their performance, underscoring the importance of personalized arousal management [13]. These theories are visualized in Table 1, which maps the theories to their potential applications in sports psychology using wearable sensors.

Table 1. Some theories and applications in sports psychology.

Theory	Proponent(s)	Key Concept	Main Implications	Application in Sports Psychology	Possible Type of Sensors
Yerkes-Dodson Law	Robert M. Yerkes, John D. Dodson	Optimal arousal level varies with task complexity.	Athletes need to find their optimal arousal level.	Helps determine the ideal arousal for different tasks.	Heart Rate Monitors
Drive Theory	Clark Hull	Increased arousal enhances performance for well-learned tasks.	A linear relationship between arousal and performance.	Useful for tasks where high arousal is beneficial.	Electrocardiogram (ECG) Sensors
Reversal Theory	Michael Apter	Arousal is subjectively interpreted as either pleasant or unpleasant.	Cognitive strategies can shift arousal perception.	Helps athletes manage and reinterpret their arousal.	Skin Conductance Sensors
Catastrophe Theory	J.G. Hardy	Performance drops when arousal and cognitive anxiety exceed optimal levels.	Manages both arousal and anxiety to avoid performance drops.	Monitors combined physiological and psychological states.	Multi-Sensor Systems
Multidimensional Anxiety Theory	Rainer Martens	Differentiates between cognitive and somatic anxiety.	Addresses both types of anxiety for optimal performance.	Helps tailor interventions for cognitive and somatic anxiety.	Wearable Electrodes
Processing Efficiency Theory	Michael Eysenck, Manuel Calvo	Anxiety affects cognitive processes and task performance.	Reduces cognitive load and stress to maintain performance.	Monitors cognitive and stress levels for performance optimization.	Brain-Computer Interfaces (BCI)
Individual Zones of Optimal Functioning (IZOF)	Yuri Hanin	Each athlete has a unique optimal arousal level.	Personalized arousal management approaches.	Helps identify and maintain individual optimal arousal zones.	Personalized Wearable Devices
James-Lange Theory	William James, Carl Lange	Physiological changes precede emotions.	Monitoring physiological changes can	Provides early indicators of emotional states.	Temperature Sensors

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			indicate emotional states.		
Cannon-Bard Theory	Walter Cannon, Philip Bard	Physiological and emotional responses occur simultaneously.	Monitors both physiological and emotional states concurrently.	Provides a comprehensive understanding of simultaneous responses.	Simultaneous Physiological Monitoring
Schachter-Singer Theory	Stanley Schachter, Jerome Singer	Emotions result from physiological arousal and cognitive interpretation.	Combines physiological data with contextual information.	Helps interpret and modulate emotional responses.	Multi-Modal Wearable Sensors

Advanced wearable sensor technologies, including smart materials, nanotechnology, and 3D printing, allow sports psychologists and coaches to monitor and manage an athlete's psychological status and arousal levels in real-time. This multidisciplinary approach facilitates personalized interventions and real-time feedback, significantly enhancing athletic performance and mental wellbeing.

The landscape of wearable devices and mobile applications for monitoring psychological stress, brain activity, and cognitive function is notably diverse and innovative. Notable applications include Opti Brain™, paired with the Muse™ headband for advanced EEG analysis, and the T2 Mood Tracker, which monitors emotional health [17]. Devices like the King-Devick Test and HitCheck are crucial for assessing cognitive function, particularly after concussions, while BrainCheck Sport focuses on attention and memory [17]. These examples illustrate the broad range of wearable technologies that are available for personal, medical, and research purposes as shown in Table 2, which lists wearable sensor applications in health monitoring and sports psychology.

Table 2. Some wearable sensor applications in health monitoring and sports psycholog [17].

Health monitoring with wearable sensors in sports psychology	Body Part	Brand	Application
EEG monitoring for improved focus and emotional control	Head	Muse™	Cognitive function, Emotional control
Advanced EEG analysis, paired with Muse™ headband	Head	Opti Brain™	Cognitive function
Monitors emotional health	Wrist	Sentio Solutions	Emotional health
Head impact sensor, measures and transmits data on head forces	Head	CSx	Concussion monitoring
Head impact sensor, measures and transmits data on head forces	Head	X2 Biosystems	Concussion monitoring
Integrates EEG monitoring	Eyes	Smith Optics	Focus and emotional control
Advanced oxygenation monitoring	Forehead	Artinis Medical Systems	Oxygenation monitoring
Combines EEG and near-infrared sensors for cognitive function	Head	Neuroelectrics	Cognitive function exploration
Monitors activity, sleep, HR, HRV, temperature, and stress levels	Wrist	FitBit	Commercial, personal health

Monitors ECG, HR, HRV, RR, SpO2, and body temperature	Chest/Torso	Zephyr	Medical, research
Monitors ECG, HR, HRV, RR, SpO2, and body temperature	Chest/Torso	Carré Technologies	Medical, research
Monitors ECG, HR, HRV, RR, SpO2, and body temperature	Chest/Torso	Polar H10	Fitness, health monitoring
Posture correction	Lower back	Lumo Bodytech	Health and wellness
Monitors HR and temperature	Finger	OURA	Sleep tracking, fitness
Assess cognitive function, especially after concussions	N/A	King-Devick	Cognitive assessment, sports
Assess cognitive function, especially after concussions	N/A	HitCheck	Cognitive assessment, sports
Focuses on attention and memory	N/A	BrainCheck	Cognitive assessment, sports
Monitors emotional health	N/A	T2	Emotional health

One of the most transformative advances in this field has been the integration of 3D printing. Initially pivotal for prototype design, 3D printing now facilitates the production of complex sensor structures that would be challenging with traditional manufacturing techniques. This technology enables the customization of sensors to precisely fit different body parts or meet individual users' specific needs, enhanced by the use of conductive polymers and nanomaterials that improve sensor sensitivity and performance. The development of multilayered structures allows for the integration of electronic components directly during the printing process, optimizing sensor performance and size.

The next sections will explore the specific 3D printing techniques that enable the creation of these sophisticated sensors, focusing on the adaptability and precision required by sports professionals. This discussion underscores the critical role of modern manufacturing processes in advancing sports psychology by integrating cutting-edge technology and theoretical insights.

3. 3D Printing Techniques for Wearable Sensors Used in Health Monitoring and Sports Psychology

3D printing, also known as additive manufacturing, is a versatile technology that encompasses a wide range of techniques, each suited to different materials including metals, polymers, and composites [18,19]. The procedures outlined in the ISO/ASTM 52900:2015 standards allow for layer-by-layer creation of products and offer the opportunity to select several types of materials during the printing process. In printing process, first, digital 3D model is created by 3D scanner or computer aided design (CAD) software. Then, the digital data are transferred to an STL file [19]. Afterwards, slicing software utilized converted the STL file into a G-code format [20]. The model is divided into a series of 2D levels, enabling the objects to be placed in a stacked manner, one layer at a time [21]. This digital process allows for the easy printing of various products, regardless of their geometry. 3D printing techniques can be utilised to explore multiple aspects of materials simultaneously, such as their electronic, fluidic, optical, acoustic, thermal, chemical, and electromagnetic properties, allowing for the creation of novel manufacturing procedures [18]. The primary methods used in 3D printing are as follows:

Wearable sensors fabricated using **vat photopolymerization (VP)** techniques have significantly broadened the scope of health monitoring applications. These sensors encompass a diverse range of functionalities, including glucose [29,30], lactate [29,30], sweat [31], and strain sensors [32–34], as well as tactile sensors and artificial skin [35], oximeters [36], smart bandages, and sensors designed for electroencephalography (EEG) and electrocardiography (ECG) [37]. The precision and customizability offered by VP allow for the creation of highly detailed and application-specific geometries, enhancing the functionality and effectiveness of these devices. Notably, while much of

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the current literature, including [37], focuses on the use of VP in wearable sensors, other studies have explored its application in broader contexts such as optical components [28,38] and medical devices [39]. This breadth underscores the versatility of VP techniques, demonstrating their efficacy in producing not only wearable sensors but also a wide range of intricate devices across various fields. In summary, vat photopolymerization has been instrumental in producing an extensive array of wearable sensors for diverse healthcare monitoring purposes. These sensors utilize the high resolution and design flexibility of VP to meet the exact needs of wearable healthcare applications, showcasing the significant impact of this technology on the advancement of wearable devices [37].

Material Extrusion (ME), notably through the popular techniques of fused deposition modeling (FDM) or fused filament fabrication (FFF), represents a cornerstone in 3D printing technology. In this method, thermoplastic filaments are heated and pushed through a nozzle to construct objects layer by layer [19]. This approach is extensively utilized across various domains such as prototyping, education, and the production of functional parts using a wide array of thermoplastics. The FDM process encompasses several variations like Precise Extrusion Deposition (PED), Precise Extrusion Manufacturing (PEM), and Multiphase Jet Solidification (MJS), which all involve melting materials during the printing process. Alternatively, there are non-melting processes such as solvent-based extrusion-free forming, Low-Temperature Deposition Manufacturing (LDM), Pressure-Assisted Microsringe (PAM), and Direct Ink Writing (DIW) [37]. Material extrusion (ME) has been instrumental in advancing the development of wearable sensors, enabling precise monitoring of diverse parameters such as strain [40,41], glucose [42], lactate [43], and deformation [37]. This technique has been enriched by the introduction of conductive inks composed of soft thermoplastic elastomers mixed with conductive additives like silver micro flakes, carbon black nanoparticles, or poly(3,4-ethylenedioxythiophene) (PEDOT). These innovative inks are crucial for sensors that monitor strain, temperature, and electrocardiogram signals, showcasing significant strides in sensor functionality. Further enhancements in this field include the development of core-shell filaments that merge a thermoplastic elastomer shell with an acrylonitrile butadiene styrene core, improving both the printability and flexibility of materials for cutting-edge wearable sensor applications [45,46]. Research has also been conducted on silicone elastomer sheets specifically designed for wearable biomedical devices, demonstrating the expansive application potential of ME even when its direct use is not explicitly detailed [47]. Additional innovations feature a multi-material micro-extrusion technique that facilitates direct deposition onto stretchable fabrics, significantly advancing the integration of functionality without compromising resolution [48]. The precision of filament-based techniques has been validated through the production of complex geometrical forms with high accuracy [46]. Furthermore, meticulous characterization of the mechanical properties of silicone elastomer sheets through biaxial tensile testing confirms the precise control attainable over material properties with ME [49]. These examples underscore the versatility of material extrusion in meeting various functional requirements and its capacity to drive innovation in wearable technology. Collectively, these advancements highlight the ongoing evolution of 3D printing techniques in enhancing both the design and functionality of wearable devices, paving the way for their seamless integration into daily health monitoring and medical diagnostics.

Powder Bed Fusion (PBF) is a sophisticated 3D printing technique that encompasses both Selective Laser Sintering (SLS) and Electron Beam Melting (EBM). SLS employs a laser to sinter powdered materials such as plastics or metals, building objects layer by layer [50]. In contrast, EBM utilizes an electron beam in a vacuum to melt metal powder precisely, making it particularly suitable for crafting durable and complex structures commonly used in aerospace and medical industries [51]. In the domain of wearable sensor technology, PBF is celebrated for its ability to fabricate components with exceptional strength and precision. An illustrative application of this technology includes the development of force sensors that incorporate a deformation element and a steel plate as a measuring element carrier. These sensors demonstrate PBF's capability to produce devices with minimal linearity and hysteresis errors, underscoring the technology's precision and reliability—essential qualities for sensors that must perform consistently under various conditions [52]. While specific

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applications of PBF in wearable sensors are well-documented, the broader literature often focuses more on the technology's capabilities than on detailed applications in wearable sensors. The materials typically used, featuring combinations such as a base body with a steel plate, exemplify PBF's versatility and adeptness in handling complex material compositions. These traits are crucial for achieving high resolution and accuracy in the final products [53]. However, the prevalence of wearable sensors utilizing PBF is noted to be limited, indicating a fertile area for further exploration and documentation within the industry. This observation points to the potential for expanded application of PBF in wearable technology, advocating for more extensive research and development to fully harness this technology's capabilities [54].

Material and Binder Jetting are innovative 3D printing techniques that closely resemble the process of inkjet printing. Material Jetting (MJ) involves the precise deposition of droplets of materials such as photopolymers or waxes, which are layered and then cured to form the final product [37]. Binder Jetting (BJ), conversely, employs a liquid binding agent that is sprayed onto a powder bed, effectively bonding the material layers together [37]. These methods are especially valuable for producing full-colour prototypes, intricate geometries, and multi-material components [51,52]. Extensive research in these technologies has led to the development of a variety of wearable (bio)sensors that monitor health-related metrics such as glucose, lactate, and sweat levels, in addition to strain, tactile feedback, and oxygen levels through wearable oximeters. These sensors, crafted with healthcare applications in mind, are distinguished by their exceptional stretchability, flexibility, cost-effectiveness, ultra-thinness, and lightweight properties. The materials used in these sensors, including composite filaments, elastomers, functional inks, and hydrogels, are particularly well-suited to the MJ and BJ processes, optimizing their functionality and application versatility [37]. While the specific details on the resolution and accuracy of these sensors are not elaborated upon in the sources, it is recognized that MJ and BJ can achieve high levels of precision. This precision is critical for wearable sensors, as it allows to produce devices with complex shapes and fine details essential for accurately capturing and monitoring physiological data [51,52]. In conclusion, the utilization of Material Jetting and Binder Jetting technologies has facilitated the development of a diverse range of wearable sensors designed to effectively monitor various physiological parameters. These technologies not only enable the creation of highly functional sensors but also ensure that the sensors are adaptable, comfortable, and precise, making them ideal for continuous health monitoring. This adaptability and precision ensure that these sensors meet the rigorous demands of modern healthcare applications, demonstrating the significant impact of these 3D printing techniques in the field of wearable technology [37,51,52].

Multi-Jet Fusion (MJF) is a sophisticated powder bed fusion technique developed by HP, which utilizes inkjet printheads to distribute a fusing agent across a powder layer. This agent is then sintered using a heat source, enabling the rapid construction of parts characterized by intricate details and robust mechanical properties. Renowned for its speed, precision, and versatility, MJF is particularly suited for fabricating parts with complex geometries and high dimensional accuracy. In wearable sensor technology, MJF has demonstrated its potential through the creation of sensors using conductive graphene nanoplate-carbon nanotube (GC) ink. These sensors, designed for healthcare applications, leverage MJF's layer-by-layer printing capability to enhance both mechanical properties and sensor sensitivity [53]. The technology's high-resolution capabilities are especially critical for producing sensors that demand precise dimensional accuracy, as evidenced in studies highlighting its effectiveness in achieving functional designs [54]. Further advancements include the development of voxelated conductive elastomers, showcasing MJF's ability to handle complex material compositions and adjust electrical conductivities within printed parts [55]. This adaptability plays a pivotal role in enabling functional diversity, allowing sensors to be tailored for varied healthcare monitoring scenarios. By combining detailed structural design with functional precision, MJF has emerged as a powerful tool for the development of advanced wearable sensors. These attributes underscore MJF's value not only in manufacturing intricate and reliable sensor components but also in pushing the boundaries of wearable technology. Its ability to seamlessly integrate mechanical and

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functional properties highlights its transformative impact on the field of healthcare monitoring and wearable devices.

Directed Energy Deposition (DED) is an advanced 3D printing technique that employs focused thermal energy—such as a laser, electron beam, or plasma arc—to melt materials, typically in powder or wire form. The melted material is deposited layer by layer, enabling the fabrication of new parts or the repair and enhancement of existing high-value components. Known for its precision and versatility, DED is particularly valuable in industries that demand complex, high-precision tasks, such as aerospace, automotive, and healthcare. A notable application of DED technology is the creation of piezoelectric sensors, such as Pyzoflex®, which transform mechanical stress into electrical charge—an essential feature for dynamic monitoring applications. These sensors are typically made from ceramics or polymers with piezoelectric properties, although their precise composition remains unspecified in available documentation [56]. This functionality makes Pyzoflex® sensors well-suited for applications requiring detailed and accurate monitoring of dynamic processes. Research has explored the role of these sensors in monitoring powder flow during laser-assisted Directed Energy Deposition (L-DED) processes [54,56]. These studies highlight the sensors' high resolution and accuracy, emphasizing their real-time precision in tracking powder flow. Such capabilities demonstrate the effectiveness of piezoelectric sensors in ensuring process reliability and precision. Furthermore, these findings underscore the adaptability of DED technology in integrating sensor functionality with high-tech manufacturing processes. In summary, DED's ability to combine precision, adaptability, and functionality makes it a powerful tool for developing advanced sensors and components. By enabling real-time monitoring and enhancing the accuracy of dynamic processes, DED showcases its potential as a transformative technology across multiple industries.

Hybrid Additive Manufacturing (HAM) combines the capabilities of 3D printing with the precision of subtractive techniques such as CNC machining. This innovative approach enhances the detail and surface finish of parts while enabling the creation of complex components with exceptional accuracy. By merging additive and subtractive methods, HAM addresses limitations in traditional manufacturing techniques, offering new possibilities for fabricating advanced materials and devices. One notable application of HAM involves the development of high-performance conductive polymer composites (CPCs) specifically tailored for wearable sensors. These materials, characterized by their flexibility and seamless integration potential, are particularly suitable for strain sensors embedded in clothing. This advancement highlights the versatility of HAM in producing functional components that align with the demands of modern wearable technology [57]. Further contributing to the field, new conductive photo-resins have been developed for additive manufacturing to create flexible conductive composites. These materials are ideal for wearable sensors requiring both adaptability and durability, offering a balance between functionality and resilience [58]. The integration of these innovations into HAM underscores its pivotal role in expanding the functionality and application range of wearable sensors, particularly in health monitoring within sports psychology. As illustrated in Table 3, Hybrid Additive Manufacturing demonstrates the widespread adoption and effectiveness of 3D printing techniques in creating advanced health monitoring devices. These sensors seamlessly integrate into everyday apparel and equipment, bridging the gap between cutting-edge technology and practical, user-friendly solutions. This multidisciplinary approach highlights the transformative potential of HAM in wearable sensor technology, paving the way for new possibilities in continuous health monitoring and sports psychology applications.

Table 3. 3D printing techniques for health monitoring with wearable sensors in sports psychology.

3D printing Techniques	Materials	Description	Applications	Resolution & Accuracy	Wearable Sensors	Benefits (Athlete Psychology Evaluation)
Vat Photopolymerization (SLA, DLP)	Acrylate-based resins, stimuli-responsive materials.	Involves curing liquid photopolymer resin using a light source, layer by layer, to create detailed parts.	High precision, smooth surface finishes, medical research, complex optical components.	High resolution, accuracy due to photocurable material selection.	Glucose sensors [28,29], lactate sensors [28,29], sweat sensors [30], strain sensors [31–33], artificial skin [34], tactile sensors [34], oximeters [35], smart bandages, tattoo type sensors, EEG & ECG sensors [36].	Enables detailed psychological evaluations by measuring stress and fatigue levels through various biomarkers, contributing to a comprehensive understanding of mental states during performance.
Material Extrusion (FDM, FFF)	Thermoplastic elastomers, conductive inks, silicone elastomers, core-shell filaments.	Uses heated thermoplastic filament extruded through a nozzle to build objects layer by layer.	Prototyping, functional parts from thermoplastics, flexible material extrusion.	Contingent on material properties and process parameters; some studies emphasize functional integration, others high-fidelity printing.	Strain sensors [39,40], glucose sensors [41], lactate sensors [42], temperature sensors [43], electrocardiogram sensors [44–46].	Useful for real-time psychological stress analysis through physiological responses, allowing adjustments in training regimens to optimize psychological resilience.
Powder Bed Fusion (SLS, EBM)	Steel, metal powders.	SLS uses a laser to sinter powdered material, EBM uses an electron beam to melt metal powder in a vacuum.	High-strength, complex metal parts, aerospace, and medical applications.	High resolution, accuracy, low error rates.	Force sensors [49].	Offers insights into the psychological impact of physical stress and fatigue during high-intensity activities, aiding in recovery and

						mental conditioning.
Material & Binder Jetting	Composite filaments, elastomers, functional inks, hydrogels.	Material jetting is similar to inkjet printing with photopolymer or wax; Binder jetting uses a liquid binding agent on a powder bed.	Full-color prototypes, complex geometries, multi-material parts.	High precision crucial for functionality; intricate geometries, detailed features.	Glucose sensors [28,29], lactate sensors [28,29], sweat sensors [30], strain sensors [31–33], artificial skin [34], tactile sensors [34], oximeters [35], smart bandages, tattoo type sensors, EEG & ECG sensors [36].	Facilitates multi-dimensional psychological evaluations, tracking emotional stability and stress response through sensor data integration, offering a more nuanced approach to mental health management.
Multi Jet Fusion (MJF)	Conductive graphene nanoplate-carbon nanotube (GC) ink, voxelated conductive elastomers.	Uses inkjet printheads to apply a fusing agent to powder, followed by heat to sinter material.	Functional parts with good mechanical properties.	High printing resolution, high dimensional accuracy.	Sensors with healthcare functionalities [52], components with varying electrical conductivities [53,54].	Enables complex psychological evaluations through advanced sensors capable of capturing minute physiological changes and emotional reactions under various performance and stress scenarios.
Directed Energy Deposition (DED)	Ceramics, polymers with piezoelectric properties (Pyzoflex® sensors).	Uses focused thermal energy (laser, electron beam, plasma arc) to fuse materials as	New part creation or repair of existing components, high-value industries.	High resolution and accuracy in powder flow monitoring for DED processes.	Pyzoflex® sensors [55].	Allows for the monitoring of psychological and physical responses in real-time, particularly useful in

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		they are deposited.				assessing how athletes cope with stress and pressure during competitions and training.
Hybrid Additive Manufacturing (HAM)	Conductive polymer composites, novel conductive photo-resins.	Combines 3D printing with subtractive processes like CNC machining.	Greater precision and surface finish in complex parts.	Improved precision and surface finish due to the integration of additive and subtractive techniques.	High-performance conductive polymer composites (CPCs), potentially wearable sensors [56,57].	Enhances athlete psychological evaluation by seamlessly integrating sensors into sportswear, allowing for the continuous assessment of mental states without disrupting the athlete's performance or comfort.

4. Future Directions and Innovations

The future of 3D printable sensors in sports psychology is promising, with significant technological advancements in the field. In sports, sensor fusion often involves integration of accelerometers, gyroscopes, and magnetometers. These technologies are applied in various sports, including athletics, swimming, cycling, and ball sports. Big data, paired with computer-based applications such as virtual reality (VR), augmented reality (AR), and neurotechnology, enhances the empirical and practical aspects of sports psychology, making it more appealing to athletes, multidisciplinary professionals, and investors. Sensor data collected pre- or post-3D printing can be utilized for digital twin applications, prototype development, and even mass production in remote areas. Artificial intelligence (AI) has the potential to transform sensor data analysis. Machine-learning algorithms can identify patterns that might elude human analysts, leading to more sophisticated models for predicting performance and mental states. Advancements in materials science will likely result in new materials that can further enhance the sensor capabilities. Innovations in biocompatible and smart materials that respond dynamically to stimuli will expand the use of 3D printable sensors in sports. The applications of 3D printable sensors in sports psychology extend beyond performance and mental health monitoring. These sensors can be adapted for rehabilitation, helping monitor recovery in injured athletes. Their flexibility and customization potential make them ideal for tracking individualized recovery metrics and providing psychological support during recovery. Future research should encourage collaboration among engineers, psychologists, and sports scientists to optimize sensor design and application. This interdisciplinary approach will yield innovative solutions that enhance both athletic performance and mental wellbeing.

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5. Conclusions

Three-dimensional (3D) printing is revolutionizing the design and production of wearable technology by enabling customized fits, self-sustaining wearables with built-in energy generation, and highly accurate sensors for health and environmental monitoring. Although it faces challenges, 3D printing remains essential for both prototyping and large-scale production of wearable devices. This technology allows for the creation of configurable, lightweight devices that meet the practical demands for flexibility and low weight. However, significant hurdles remain, particularly in enhancing the mechanical and electrochemical properties of components, such as batteries and supercapacitors [59]. Further research is required on the materials used in 3D printing, especially in developing printable organic, inorganic, and hybrid semiconductors for designing new sensors [60]. Additionally, challenges related to intellectual property and compliance with health regulations must be addressed, particularly in the creation of medical devices [22].

In conclusion, the integration of 3D printing technology with sports psychology offers a unique opportunity to advance our understanding of athletic performance and well-being. By harnessing 3D printable sensors, researchers and practitioners can collect real-time data on physiological and psychological metrics, leading to targeted interventions that significantly enhance athletic outcomes. As we move forward, it is crucial to address the challenges related to data security, sensor accuracy, and acceptance among athletes and coaches. Embracing advancements in AI and new materials can expand the applications of 3D printable sensors beyond performance monitoring to include health and wellness assessments.

By developing personalized interventions and employing cutting-edge technology, we can create a more supportive and effective environment for athletes, blending best sports psychology practices with innovative technological advancements. This calls for collaboration among all stakeholders in the field to explore the untapped potential of 3D printable sensors in sports psychology, ultimately fostering the generation of mentally resilient and physically adept athletes.

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References

1. Schinke, R.J., et al., international society of sport psychology position stand: Athletes' mental health, performance, and development. International journal of sport and exercise psychology, 2018. 16(6): p. 622-639.
2. Castonguay, L.G., T.F. Oltmanns, and A.P. Lott, Psychopathology: From science to clinical practice. 2021: Guilford Publications.
3. Gill, D.L., L. Williams, and E.J. Reifsteck, Psychological dynamics of sport and exercise. 2017: Human Kinetics.
4. Toros, T., et al., Investigation the Relationship between Mental Toughness and Courage Levels of Sports Sciences Faculty Students for Sustainable Performance. Sustainability, 2023. 15(12): p. 9406.
5. Schmidt, P., et al., Wearable-based affect recognition—A review. Sensors, 2019. 19(19): p. 4079.
6. Taskasaplidis, G., D.A. Fotiadis, and P. Bamidis, Review of Stress Detection Methods Using Wearable Sensors. IEEE Access, 2024.
7. Torku, A., Detecting and assessing older adults' stressful interactions with the built environment: an elderly-centric and wearable sensing-based approach. 2022.
8. Tao, Q., et al., Clinical applications of smart wearable sensors. Iscience, 2023. 26(9).
9. Scholcover, F., S.J. Cauffman, and D.J. Gillan. Timing and Physiological Arousal: Implications for Human Performance. in Proceedings of the Human Factors and Ergonomics Society Annual Meeting. 2018. SAGE Publications Sage CA: Los Angeles, CA.

 doi:10.20944/preprints202501.1611.v1

10. Murphy, S., The sport psych handbook. 2009: Human Kinetics.
11. Apter, M.J., D. Fontana, and S. Murgatroyd, Reversal theory: Applications and development. 2014: Psychology Press.
12. Tossici, G., V. Zurloni, and A. Nitri, Stress and sport performance: a PNEI multidisciplinary approach. Frontiers in Psychology, 2024. 15: p. 1358771.
13. Robazza, C., M. Pellizzari, and Y. Hanin, Emotion self-regulation and athletic performance: An application of the IZOF model. Psychology of Sport and Exercise, 2004. 5(4): p. 379-404.
14. James, W., THE JAMES-LANGE THEORY OF EMOTION. Visceral sensory neuroscience: interoception, 2002: p. 9.
15. McCarty, R., The fight-or-flight response: A cornerstone of stress research, in Stress: Concepts, cognition, emotion, and behavior. 2016, Elsevier. p. 33-37.
16. Dror, O.E., Deconstructing the "two factors": The historical origins of the Schachter–Singer theory of emotions. Emotion Review, 2017. 9(1): p. 7-16.
17. Peake, J.M., G. Kerr, and J.P. Sullivan, A critical review of consumer wearables, mobile applications, and equipment for providing biofeedback, monitoring stress, and sleep in physically active populations. Frontiers in physiology, 2018. 9: p. 743.
18. Pekgor, M., et al., Sensor-based filament fabrication with embedded RFID microchips for 3D printing. Materials Today: Proceedings, 2021. 46: p. 124-130.
19. Pekgor, M., et al., Design of a 3D-printable UHF RFID hybrid liquid antenna for biosensing applications. Materials Today: Proceedings, 2021. 46: p. 4619-4624.
20. Osman, A. and J. Lu, 3D printing of polymer composites to fabricate wearable sensors: A comprehensive review. Materials Science and Engineering: R: Reports, 2023. 154: p. 100734.
21. Gross, B.C., et al., Evaluation of 3D printing and its potential impact on biotechnology and the chemical sciences. 2014, ACS Publications.
22. Bongiovanni, R. and A. Vitale, Vat Photopolymerization. High Resolution Manufacturing from 2D to 3D/4D Printing: Applications in Engineering and Medicine, 2022: p. 17-46.
23. Pagac, M., et al., A review of vat photopolymerization technology: materials, applications, challenges, and future trends of 3D printing. Polymers, 2021. 13(4): p. 598.
24. Andreu, A., et al., 4D printing materials for vat photopolymerization. Additive Manufacturing, 2021. 44: p. 102024.
25. Pongwisuthiruchte, A., et al., Mechanically tunable resins based on acrylate-based resin for digital light processing (DLP) 3D printing. Scientific Reports, 2022. 12(1): p. 20025.
26. Bahati, D., M. Bricha, and K. El Mabrouk, Vat photopolymerization additive manufacturing technology for bone tissue engineering applications. Advanced Engineering Materials, 2023. 25(1): p. 2200859.
27. Li, W., et al., Stereolithography apparatus and digital light processing-based 3D bioprinting for tissue fabrication. Iscience, 2023. 26(2).
28. Tarancón, A., et al., 2022 roadmap on 3D printing for energy. Journal of Physics: Energy, 2022. 4(1): p. 011501.
29. Gowers, S.A.N., et al., 3D Printed Microfluidic Device with Integrated Biosensors for Online Analysis of Subcutaneous Human Microdialysate. Analytical Chemistry, 2015. 87(15): p. 7763-7770.
30. Samper, I.C., et al., 3D printed microfluidic device for online detection of neurochemical changes with high temporal resolution in human brain microdialysate. Lab on a Chip, 2019. 19(11): p. 2038-2048.
31. Nah, J.S., et al., A wearable microfluidics-integrated impedimetric immunosensor based on Ti3C2Tx MXene incorporated laser-burned graphene for noninvasive sweat cortisol detection. Sensors and Actuators B: Chemical, 2021. 329: p. 129206.
32. Muth, J.T., et al., Embedded 3D printing of strain sensors within highly stretchable elastomers. Advanced materials, 2014. 26(36): p. 6307-6312.
33. Xiao, T., et al., 3D printing of flexible strain sensor array based on UV-curable multiwalled carbon nanotube/elastomer composite. Advanced Materials Technologies, 2021. 6(1): p. 2000745.
34. Abshirini, M., et al., Functional nanocomposites for 3D printing of stretchable and wearable sensors. Applied Nanoscience, 2019. 9: p. 2071-2083.

doi:10.20944/preprints202501.1611.v1

35. Yin, F., et al., Advanced polymer materials-based electronic skins for tactile and non-contact sensing applications. InfoMat, 2023. 5(7): p. e12424.
36. Mostafalu, P., et al., Wireless flexible smart bandage for continuous monitoring of wound oxygenation. IEEE Transactions on biomedical circuits and systems, 2015. 9(5): p. 670-677.
37. Kalkal, A., et al., Recent advances in 3D printing technologies for wearable (bio) sensors. Additive Manufacturing, 2021. 46: p. 102088.
38. Dileep, C., et al., Review of Vat photopolymerization 3D Printing of Photonic Devices. Additive Manufacturing, 2024: p. 104189.
39. Ding, X., et al., Wearable sensing and telehealth technology with potential applications in the coronavirus pandemic. IEEE reviews in biomedical engineering, 2020. 14: p. 48-70.
40. Le, T., et al. A novel strain sensor based on 3D printing technology and 3D antenna design. in 2015 IEEE 65th Electronic Components and Technology Conference (ECTC). 2015. IEEE.
41. Votzke, C., et al. Highly-stretchable biomechanical strain sensor using printed liquid metal paste. in 2018 IEEE Biomedical Circuits and Systems Conference (BioCAS). 2018. IEEE.
42. Nguyen, T.N., et al., Facile fabrication of flexible glutamate biosensor using direct writing of platinum nanoparticle-based nanocomposite ink. Biosensors and Bioelectronics, 2019. 131: p. 257-266.
43. Nesaei, S., et al., Micro additive manufacturing of glucose biosensors: A feasibility study. Analytica Chimica Acta, 2018. 1043: p. 142-149.
44. Zou, Q., et al., Tunable ionic pressure sensor based on 3D printed ordered hierarchical mesh structure. Sensors and Actuators A: Physical, 2020. 308: p. 112012.
45. Pless, C.J., et al., Emerging strategies in 3D printed tissue models for in vitro biomedical research, in Bioprinting. 2022, Elsevier. p. 207-246.
46. Patil, N.A., et al., Additive manufacturing of thermoplastic elastomer structures using dual material core-shell filaments. Additive Manufacturing, 2024. 82: p. 104044.
47. Putra, D.I., D. Suarmin, and S. Ekariani. Fatigue Warning System During Physical Exercise Based on Heart Rate and Oxygen Saturation Using Non-invasive Wearable Sensor. in 2022 International Symposium on Information Technology and Digital Innovation (ISITDI). 2022. IEEE.
48. Pless, C.J., et al., Soft Electronic Block Copolymer Elastomer Composites for Multi-Material Printing of Stretchable Physiological Sensors on Textiles. Advanced Electronic Materials, 2023. 9(5): p. 2201173.
49. Putra, K.B., et al., Biaxial test and hyperelastic material models of silicone elastomer fabricated by extrusion-based additive manufacturing for wearable biomedical devices. Journal of the mechanical behavior of biomedical materials, 2020. 107: p. 103733.
50. Chadda, R., et al. Disruptive force sensor based on laser-based powder-bed-fusion. in 2020 IEEE SENSORS. 2020. IEEE.
51. Li, M., et al., Metal binder jetting additive manufacturing: a literature review. Journal of Manufacturing Science and Engineering, 2020. 142(9): p. 090801.
52. Venukumar, S., et al. A Review on Metal Binder Jetting 3D Printing. in E3S Web of Conferences. 2023. EDP Sciences.
53. Hou, Y., et al., 3D printed conformal strain and humidity sensors for human motion prediction and health monitoring via machine learning. Advanced Science, 2023. 10(36): p. 2304132.
54. Adach, M., et al., Study on geometry, dimensional accuracy and structure of parts produced by multi jet fusion. Materials, 2021. 14(16): p. 4510.
55. Chen, J., L. Zhao, and K. Zhou, Multi-jet fusion 3D voxel printing of conductive elastomers. Advanced Materials, 2022. 34(47): p. 2205909.
56. Petrovic-Filipovic, V., et al., Monitoring concept for powder flow monitoring in Laser-Directed Energy Deposition (L-DED) process based on flexible piezoelectric sensors. Materials Open Research, 2023. 1(1): p. 1.
57. Liu, G., et al., 0D to 2D carbon-based materials in flexible strain sensors: recent advances and perspectives. 2D Materials, 2023. 10(2): p. 022002.

 doi:10.20944/preprints202501.1611.v1

58. Engel, K., P.A. Kilmartin, and O. Diegel, Flexible and multi-material intrinsically conductive polymer devices fabricated via DLP and DIW additive manufacturing techniques. Rapid Prototyping Journal, 2023. 29(10): p. 2164-2175.
59. Egorov, V., et al., Evolution of 3D printing methods and materials for electrochemical energy storage. Advanced Materials, 2020. 32(29): p. 2000556.
60. Garlapati, S.K., et al., Printed electronics based on inorganic semiconductors: From processes and materials to devices. Advanced Materials, 2018. 30(40): p. 1707600.
61. Yin, J.; Li, J.; Reddy, V.S.; Ji, D.; Ramakrishna, S.; Xu, L. Flexible Textile-Based Sweat Sensors for Wearable Applications. Biosensors 2023, 13, 127. doi: 10.3390/bios13010127
62. Zhang, S.; He, Z.; Zhao, W.; Liu, C.; Zhou, S.; Ibrahim, O.O.; Wang, C.; Wang, Q. Innovative Material-Based Wearable Non-Invasive Electrochemical Sweat Sensors towards Biomedical Applications. Nanomaterials 2024, 14, 857. doi: 10.3390/nano14100857
63. De Fazio, R.; Mastronardi, V.M.; De Vittorio, M.; Visconti, P. Wearable Sensors and Smart Devices to Monitor Rehabilitation Parameters and Sports Performance: An Overview. Sensors 2023, 23, 1856. doi: 10.3390/s23041856
64. Migliaccio, G.M.; Padulo, J.; Russo, L. The Impact of Wearable Technologies on Marginal Gains in Sports Performance: An Integrative Overview on Advances in Sports, Exercise, and Health. Appl. Sci. 2024, 14, 6649. doi: 10.3390/app14156649
65. Ju, F.; Wang, Y.; Yin, B.; Zhao, M.; Zhang, Y.; Gong, Y.; Jiao, C. Microfluidic Wearable Devices for Sports Applications. Micromachines 2023, 14, 1792. doi: 10.3390/mi14091792
66. Seçkin, A.Ç.; Ateş, B.; Seçkin, M. Review on Wearable Technology in Sports: Concepts, Challenges and Opportunities. Appl. Sci. 2023, 13, 10399. doi: 10.3390/app131810399
67. Steins, R.; Breitbach, A.P.; Ross, M.; Ciarlo, E.; Melillo, E.; Brant, O. It Takes a Team—Enhancing Student-Athlete Health and Well-Being through an Interprofessional Approach. Sports 2024, 12, 209. doi: 10.3390/sports12080209
68. Ba, N.; Yue, W.; Cao, C.; Wu, W.; Cheng, P. Advances in Wearable Smart Chemical Sensors for Health Monitoring. Appl. Sci. 2024, 14, 11199. doi: 10.3390/app142311199
69. Migliaccio, G.M.; Padulo, J.; Russo, L. The Impact of Wearable Technologies on Marginal Gains in Sports Performance: An Integrative Overview on Advances in Sports, Exercise, and Health. Appl. Sci. 2024, 14, 6649. doi: 10.3390/app14156649
70. De Fazio, R.; Mastronardi, V.M.; De Vittorio, M.; Visconti, P. Wearable Sensors and Smart Devices to Monitor Rehabilitation Parameters and Sports Performance: An Overview. Sensors 2023, 23, 1856. doi: 10.3390/s23041856