

## Review Article

# The role of emerging technologies in advancing athlete performance: A narrative review

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## Abstract

The pursuit of peak athletic performance is increasingly driven by technological innovation. This narrative review explores the role of emerging technologies in monitoring, analyzing, and enhancing the capabilities of athletes. We focus on the crosstalk between specific organ systems—the brain, the musculoskeletal system, and the cardiovascular system—and the technologies designed to interface with them. Key areas discussed include neurotechnology for cognitive training and recovery, wearable sensors and imaging for musculoskeletal assessment, and advanced biomonitoring for cardiovascular and metabolic optimization. A summary table synthesizes the technologies, their target organs, and primary applications. While these tools offer unprecedented insights, we also discuss challenges related to data interpretation, integration, and accessibility. The future of athletic performance lies in a holistic, technology-enabled understanding of the athlete as a complete, interconnected system.

*Key Words:* Performance, Technologies, Athlete, Sport

## Introduction

Elite sport has evolved into a domain where marginal gains determine victory. Traditional training methods, while foundational, are now being supplemented and revolutionized by a suite of emerging technologies. These tools provide objective, high-frequency data on an athlete's physiological and psychological state, moving beyond subjective feedback and infrequent testing (Halsen et al., 2016). This review will explore how modern technologies are creating a new paradigm in sports science by focusing on the critical "crosstalk" between technology and the primary organ systems responsible for performance. We define this crosstalk as the bidirectional flow of information: the technology probes and stimulates the organ system, and the organ system's response informs subsequent training, recovery, and strategic interventions. By examining the brain, muscles, bones, and cardiovascular system individually, we can appreciate the targeted advances before considering the need for a unified, systemic approach.

### Neurotechnology: Interfacing with the athlete's brain

The brain, as the central command organ, is a new frontier in athletic optimization. Technologies are emerging to enhance cognitive function, accelerate skill acquisition, and improve mental recovery.

- **Electroencephalography (EEG) for cognitive assessment and training:** Portable EEG systems allow researchers and practitioners to measure brain activity in real-world training environments. This provides insights into an athlete's cognitive state, such as focus, fatigue, and "flow state." Studies have used EEG to identify neural markers of expert performance in marksmen and golfers, demonstrating distinct brainwave patterns associated with optimal performance (Cheron et al., 2016). The crosstalk here is direct: the technology reads cortical activity, and this feedback can be used for neurofeedback training, where athletes learn to self-regulate their brainwaves to enhance concentration and reduce performance-anxiety.

- **Transcranial direct current stimulation (tDCS):** tDCS is a

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non-invasive technique that uses a weak electrical current to modulate cortical excitability. Preliminary research suggests that tDCS can enhance motor learning, muscular endurance, and even perceived effort. For instance, a study by Angius et al. (2018) showed that tDCS applied to the motor cortex delayed time to task failure in a cycling test, indicating a potential central governor effect. The crosstalk involves the technology directly stimulating neural tissue, altering its firing thresholds, which in turn influences peripheral performance and perception. While promising, the ethical and practical applications in sport require further rigorous investigation.

### Musculoskeletal technologies: Engineering strength and resilience

The musculoskeletal system is the primary engine of athletic movement. Technologies here aim to quantify load, optimize movement patterns, and prevent injury.

- **Wearable inertial measurement units (IMUs):** IMUs, containing accelerometers, gyroscopes, and magnetometers, are ubiquitous in elite sport. Embedded in GPS pods, smart clothing, or patches, they provide detailed kinematic data on an athlete's movement. The crosstalk between IMUs and the musculoskeletal system is one of quantification. The sensors capture the external manifestation of muscle contractions and skeletal leverage—measuring sprint acceleration, jump height, and change-of-direction loads. This allows for precise monitoring of training load and the identification of asymmetries that may predispose an athlete to injury (Gleadhill et al., 2022).

- **Markerless motion capture and computer vision:** Traditional motion capture requires a lab environment with reflective markers. Emerging computer vision algorithms can now extract sophisticated biomechanical data from standard video footage, including from smartphones (Kanko et al., 2021). This technology "sees" and models the skeleton, providing insights into joint angles, velocities, and forces during sport-specific movements. The crosstalk is visual: the system interprets the complex biomechanical output of the musculoskeletal system, enabling large-scale, in-the-field gait and technique analysis without encumbering the athlete.

- **Advanced imaging: Diffusion tensor imaging (DTI):** While MRI is standard for diagnosing structural injuries, advanced techniques like DTI can visualize the health of muscle tissue at a microstructural level. DTI can track the movement of water molecules along muscle fibers, providing biomarkers for muscle damage and recovery (Zhou et al., 2022). This represents a deep level of crosstalk, where the technology probes the internal architecture of the muscle itself, offering an objective measure of tissue status long before it manifests as pain or performance decrement.

### Cardiovascular and metabolic monitoring: Optimizing the engine and fuel

Sustained performance depends on the efficient delivery of oxygen and nutrients. Technologies in this sphere provide a continuous window into the body's metabolic engine.

- **Continuous glucose monitors (CGMs):** Originally developed for diabetes management, CGMs are being adopted by athletes to understand their personal glycemic responses to training and nutrition. By measuring interstitial glucose levels every few minutes, athletes and dietitians can see how different foods, meal timings, and exercise intensities affect fuel availability. The crosstalk is biochemical: the sensor reads a key metabolic variable from the interstitial fluid, informing nutritional strategies to optimize energy levels and recovery (Thomas et al., 2023).

- **Next-generation heart rate variability (HRV):** HRV, the variation in time between heartbeats, is a well-established proxy for autonomic nervous system balance. Newer, consumer-friendly devices and algorithms have made daily HRV tracking accessible. The crosstalk is autonomic: the technology interprets the heart's rhythmic pattern, which is controlled by the sympathetic and parasympathetic nervous systems, to provide a quantifiable measure of stress, recovery, and readiness to perform (Plews et al., 2017).

### Discussion

The technologies reviewed provide an unprecedented, granular view of the athlete. However, several challenges remain. The sheer volume of data risks creating "paralysis by analysis." The key is not just collecting data, but integrating it into a coherent model of the athlete. This requires sophisticated data fusion platforms and machine learning algorithms to find meaningful patterns across different biological systems (Ruddy et al., 2021).

The concept of crosstalk must be expanded from a single-organ focus to a systemic one. For example, how does cognitive fatigue (measured by EEG) impact running biomechanics (measured by IMUs) and cardiovascular efficiency (measured by HRV)? The future lies in multi-modal sensing that can capture this complex interplay in real-time.

Furthermore, ethical considerations regarding data ownership, athlete privacy, and the potential for technological coercion must be addressed. The goal of these technologies should be to empower the athlete, not to replace coaching intuition or the innate human experience of sport.

### Conclusion

Emerging technologies are fundamentally changing the landscape of athlete development. By enabling a detailed, object-

**Table 1.** Emerging technologies and their role in athlete performance.

Technology Category	Specific Technology	Target Organ System	Primary Application	Example Source
Neurotechnology	Portable Electroencephalography (EEG)	Brain / Central Nervous System	Cognitive state assessment, neurofeedback, focus training	<a href="#">Cheron et al., 2016</a>
	Transcranial Direct Current Stimulation (tDCS)	Brain / Motor Cortex	Enhancing motor learning, increasing perceived endurance	<a href="#">Angius et al., 2018</a>
Musculoskeletal	Inertial Measurement Units (IMUs)	Musculoskeletal System	Load monitoring, movement analysis, injury risk screening	<a href="#">Gleadhill et al., 2022</a>
	Markerless Motion Capture	Musculoskeletal System	Biomechanical analysis in ecological settings, technique feedback	<a href="#">Kanko et al., 2021</a>
	Diffusion Tensor Imaging (DTI)	Skeletal Muscle Microstructure	Assessing muscle damage and recovery at a cellular level	<a href="#">Zhou et al., 2022</a>
Cardiovascular/Metabolic	Continuous Glucose Monitors (CGMs)	Metabolic System / Pancreas	Personalized nutrition, fueling strategies, metabolic health	<a href="#">Thomas et al., 2023</a>
	Heart Rate Variability (HRV)	Cardiovascular / Autonomic Nervous System	Readiness monitoring, recovery tracking, training load management	<a href="#">Plews et al., 2017</a>

-ive, and continuous dialogue with the brain, musculoskeletal, and cardiovascular systems, these tools are moving sports science from a reactive to a proactive discipline. The critical crosstalk between organ and technology provides the data necessary for truly personalized training, nutrition, and recovery protocols. As these technologies become more integrated, accessible, and intelligent, they will continue to push the boundaries of human performance, provided they are applied within an ethical framework that prioritizes the well-being of the athlete.

### What is already known on this subject?

Elite sport has evolved into a domain where marginal gains determine victory. Traditional training methods, while foundational, are now being supplemented and revolutionized by a suite of emerging technologies.

### What this study adds?

As these technologies become more integrated, accessible, and intelligent, they will continue to push the boundaries of human performance, provided they are applied within an ethical framework that prioritizes the well-being of the athlete.

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### Data availability

Review article.

### Compliance with ethical standards

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**Ethical approval** Not applicable.

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### Author contributions

Conceptualization: B.D., Methodology: F.R.; Software: None.; Validation: N.G.M., Formal analysis: None.; Investigation: B.D.; Resources: F.R.; Data curation: None.; Writing - original draft: B.D., Writing–review & editing: N.G.M.; Visualization: F.R.; Supervision: B.D.; Project administration: F.R.; Funding acquisition: F.R.

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