







REVIEW

Youth athletes and wearable technology

[version 1; peer review: 2 not approved]

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Abstract


Wearable sensors have become integral tools for monitoring biomechanical and physiologic aspects of athletic training and performance. A prominent trend in fitness technology, wearable devices now measure a variety of health characteristics, including movement and posture, physiologic measures (eg, heart rate and energy expenditure), and fluid and electrolyte losses, to understand an athlete's physiologic responses during activity. Sleep has proven integral to athletic performance, and sleep monitoring wearable devices (eg, watches, rings, and headbands) use various measures, such as actigraphy and pulse oximetry, to analyze sleep quality. Young athletes benefit from wearable devices during training sessions, where multimodal data are collected and analyzed to assess performance. Wearable devices are also useful for resistance training, biofeedback, and electrical muscle stimulation, providing athletes with tools to optimize their training regimens. Moreover, these devices play a crucial role in athlete safety by monitoring cardiac physiology, head impacts, and muscle rehabilitation after injury. We provide a comprehensive review of current wearable technology and its application in youth athletics, describe where and how these sensors are used to help enhance physiologic, biomechanical, and performance parameters, and discuss future directions for wearable devices to advance sports science and athlete management.

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What wearable technology can do

Wearable devices are typically small, sensor-based, and worn on the skin to enable monitoring of biomechanical and physiologic characteristics, which benefits athletes by informing training and performance and reducing injury. These devices include a wide range of technology, including electrocardiography (ECG), electromyography (EMG), electroencephalography-based brain sensing platforms, and microelectromechanical systems (MEMSs). The American College of Sports Medicine has identified wearable technology as the top trending fitness technology for 4 of the past 5 years.¹⁻⁴ The rapid growth of wearable devices can be attributed to their use as both wellness and medical devices, monitoring parameters that describe general well-being and detect medical abnormalities.⁵ This dual use in fitness and health has presented potential for wearable devices in the young athlete population, where they have been used to track activity,⁶ monitor cardiovascular health,^{7,8} and identify sleep trends⁹ and as a tool for training^{10,11} and real-time performance feedback¹² (Figure 1). Here, we explore the current applications of wearable devices in the training of young athletes.

Assessment of activity and health

Movement and physical activity tracking

The most common use for wearable devices in sports is to monitor movement and physical activity. Some of the earliest activity monitors were movement sensors for detecting step count, including pedometers, accelerometers, and global positioning system (GPS) devices.^{8,13} With pedometers, steps are counted when the vertical acceleration of a spring-loaded lever arm passes a designated force sensitivity threshold.¹⁴ Similarly, accelerometers and gyrometers are MEMSs that detect changes in capacitance based on the vibration and rotation of a mass between 2 electrodes to calculate step counts.¹⁵ Step count can then be used to derive other measures of importance to young athlete across a variety of sports, from tracking gait velocity in runners,^{16,17} to monitoring stair running in resistance trainers,¹⁸ to recording calories expended in endurance athletes.^{19,20} GPS and ultrawideband devices function differently in that they transmit signals from satellites to determine speed and position.²¹ By using anchor-based techniques for tracking, GPS is more appropriate for athlete tracking than MEMS devices, which rely on abrupt motion for tracking.²² Some sports applications of GPS devices include monitoring sprint running performance²³ and determining the distance covered by golfers.²⁴

Heart rate and heart rate variability monitoring

Monitoring heart rate (HR) is important for determining the intensity of training for athletes and detecting overtraining to prevent injury.²⁵⁻²⁷ Wearable HR monitors primarily consist of chest-worn straps with sensors placed on the sternum or wrist-worn devices. While wrist-worn devices have become popular with endurance athletes, a recent study showed that chest-worn devices are more accurate than wrist-worn when compared to ECG, the criterion standard in medical settings. Wrist-worn devices use optical plethysmography, which shines light onto the skin and determines HR by visualizing oscillating blood volume.²⁷ Movement causes HR to rise due to increased demand for oxygen transport and carbon dioxide removal; as athletes exert themselves, their HR continues to rise until it reaches an individual-specific maximum HR.²⁸ Over time, this causes changes in the heart structure, leading to *athlete's heart*, which is characterized by hypertrophied left ventricular walls and reduced resting HR. HR monitors can be used to assess these changes to determine if evaluation by a medical professional is required.²⁹ Additionally, HR monitors can be used to estimate energy expenditure (EE) to a relatively high degree of accuracy.³⁰

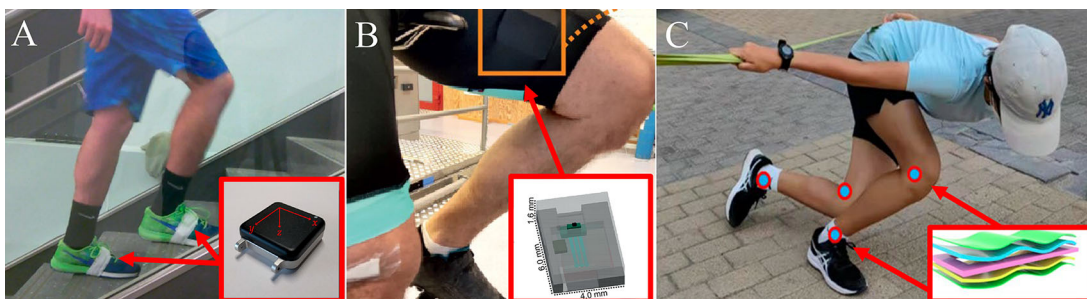


Figure 1. A, Inertial measurement units (IMUs) mounted on shoes to assess stair climbing performance.¹⁸ B, Sweat lactate monitoring using a wearable sensor.⁴⁵ C, Triboelectric nanogenerator for speed skating land training monitoring.⁵⁵

Wearable devices can also be used to monitor HR variability (HRV), which is especially useful for endurance athletes who have greater HRV than the general population.³¹ While the criterion standard for HRV monitoring is ECG, wearable devices incorporating photoplethysmography sensors have also been used for this purpose.³² Because HRV is a marker of the autonomic nervous system and its responses to both external and internal stimuli, it is an important tool for evaluating training load. HRV can also determine the presence of respiratory sinus arrhythmia, a cardiopulmonary condition to which athletes are particularly susceptible and during which respiration interferes with variations between R waves on ECG.³³

Other advances in HR monitors involve the incorporation of wearable devices into common personal items. This includes the development of smart clothing, which integrates electrodes and sensors into wearable clothing material,³⁴ devices worn on the ear in the form of headphones,³⁵ and epidermal patches placed directly on the skin.³⁶ These devices demonstrate the potential for engineering advances in health monitoring as they become less invasive, more common, and more innovative.

Energy expenditure

EE consists of 3 parts: 1) basal EE, the energy required to maintain body functioning at rest; 2) diet-induced thermogenesis, the energy from breaking down food products; and 3) activity EE, the energy required for physical activity. Tracking activity EE in athletes is important in evaluating sufficient caloric intake levels and determining training load and seasonal planning.^{37,38} The criterion standard for monitoring EE is indirect calorimetry, which works by recording oxygen consumption and carbon dioxide release at regular intervals, typically breath-by-breath.³⁹ Wearable devices to estimate EE often use a combination of measures, including movement trackers (eg, accelerometers), physiologic monitors (e.g., HR monitors), galvanic skin response, heat flux, and ambient temperature.^{38,40} However, EE trackers are limited as they are based on algorithms validated on resting adults, and as such, have been shown to underestimate EE during physical exertion by athletes, particularly youth athletes.³⁸

Sweat sensing

Most wearable devices that focus on monitoring sweat use microfluidic biosensors and chemical assays to provide visual feedback to the user. A range of parameters are commonly monitored in sweat devices, including sweat rate, concentrations of compounds (eg, chloride, calcium, ammonium, and lactate), and pH levels. Sweat patches monitor sweat rate and chloride concentration to inform athletes about appropriate hydration based on their level of water loss.^{41,42} Other devices monitor calcium and ammonium levels in sweat to assess bone and liver function and inform trainers and coaches about the use of potential nutritional supplements or vitamins.⁴³ Another variable commonly measured by sweat monitoring is lactate concentration using enzyme biosensors.^{44,45} As a product of metabolism during exercise, lactate is linearly related to sweat rate and can determine lactate anaerobic threshold, an abrupt increase in lactate concentrations due to an inability to clear lactate as fast as it is being produced. This threshold is of particular importance for endurance athletes as a predictor of their running performance and velocity.⁴⁶

Sleep monitoring

Wearable sleep monitors come in many forms, including watches, rings, and headbands,⁴⁷ most of which use measures such as actigraphy, pulse oximetry, HRV monitoring, and skin temperature.⁹ Actigraphy is the integration of sleep diaries with accelerometers; however, they have been shown to significantly overestimate sleep variables due to low specificity when compared to the criterion standard of polysomnography.⁴⁸ Pulse oximetry, a measurement of oxygen concentration in the blood, adds a layer of improvement in monitoring sleep efficiency and estimating stages of sleep. The most accurate wearable sleep monitors use a combination of actigraphy, pulse oximetry, and electroencephalographic sensors.^{49,50}

Maintaining healthy sleep cycles is critical for young athletes, as sleep-related metabolic, hormonal, and immunologic functions allow for exercise recovery, improved performance, better mental health, muscle repair, bone growth, and production of cytokines to promote immune function.^{51,52} Additionally, monitoring sleep parameters, such as total sleep time, sleep efficiency, and wakefulness after sleep onset, can reveal poor sleep hygiene and sleep disturbances, including sleep apnea and insomnia, found to be more common in young athletes.⁵³ However, these devices have considerable room for improvement, as evidenced by consistently high sensitivity and low specificity, resulting in overestimation of total sleep time and sleep efficiency and underestimation of wakefulness after sleep onset by most commercial sleep monitors.⁴⁸

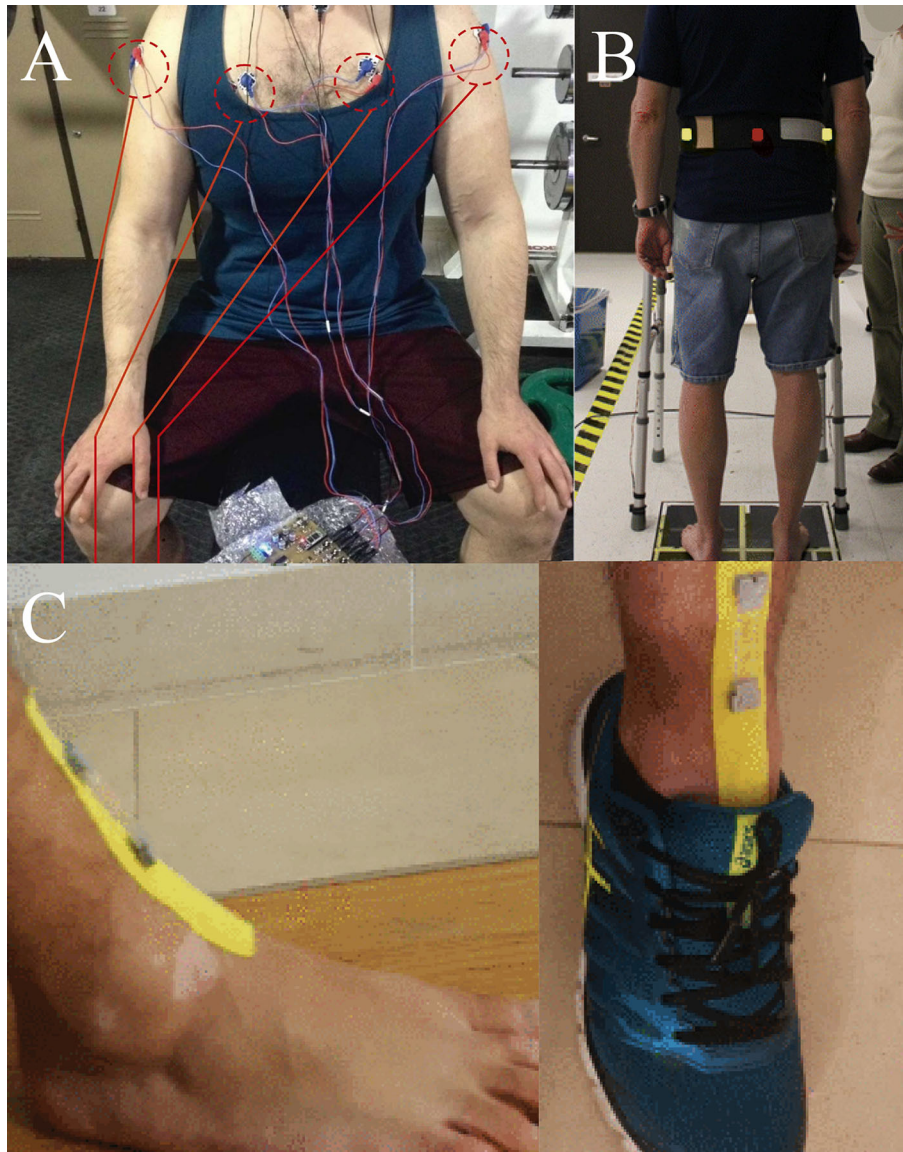


Figure 2. A, Multichannel wireless wearable surface electromyography system for real-time training performance monitoring.⁶³ B, Wearable sensing and vibrotactile feedback system for postural balance and gait training.⁷³ C, Wearable optical fiber sensor for gait rehabilitation.⁹⁹

Performance feedback for training

Wearable devices have been widely used to enhance the performance of young athletes during routine training (Figure 2). The purpose of performance-enhancing wearable devices for athletes is categorized as training monitoring and assessment, resistance training, biofeedback, muscle stimulation, and athletic motivation.

Training monitoring and assessment

Training monitoring and assessment systems within wearable devices use the wearable sensor to collect dynamic and biologic data from athletes during training.^{40,54} Most existing technology uses wearable inertial measurement unit (IMU) or force sensors to measure the joint angles, accelerations, and interaction forces of young athletes. These devices then use data analysis methods and classification-based machine learning (ML) algorithms to assess performance during the training session.^{55–60} This information can be used to improve efficiency and output and correct biomechanics to reduce risk of injury. For example, Wang et al⁵⁸ used a wearable IMU sensor and a classifier-based ML algorithm to track and measure human motor skills in hammer-throw training to help coaches assess athletes' mechanics, strengths, and areas of

improvement. Yi and Yu⁵⁹ implemented a similar approach to track biomechanics in motion during Wushu training (a martial art originating in China). In their study, measurements from the wearable IMU sensor were processed by a Kalman filter to estimate the acceleration of athletes, then principal component analysis and linear discriminant analysis algorithms classified the measured data into specific Wushu motion.⁵⁹ McGrath et al⁵⁶ compared various types of ML algorithms to identify overtraining in fast bowling by using dynamic data collected from a wearable IMU sensor. Four types of ML algorithms—random forest, support vector machine, gradient boosting, and neural networks—were used to detect overtraining, and the accuracy of each algorithm was determined based on the classification performance. When the algorithms were compared, the support vector machine had the best accuracy in the detection of overtraining.⁵⁶

The above-mentioned research used laboratory wearable sensory systems to track the kinematics of athletes using equipment that is not designed to be worn for prolonged periods of time. To improve the ergonomics of wearable sensors for tracking performance, Lu et al⁵⁵ developed a stable and durable triboelectric nanogenerator to track the loading level of athletes during training. Their sensor uses MEMS technology, allowing it to be smaller and more ergonomic than other similar sensors.⁵⁵

Skazalski et al⁵⁷ demonstrated the validity and reliability of a commercially-used wearable sensor, VERT (Mayfonk Athletic, LLC), to track jump-specific training and competition load in elite volleyball players. VERT tracked the training jump height of volleyball players, then evaluated competition load with respect to the measured jump height. To validate VERT, the competition load measured by the sensor was compared to the load measured by a laboratory wearable sensor. Their results demonstrated the accuracy and validity of the sensor in the training of professional volleyball athletes.⁵⁷

Instead of wearable IMU and force sensors, Tahla⁶¹ used a wearable graphical motion tracking system. Athletes were required to wear a motion tracker while an image-capturing system collected images and incorporated image processing methods, such as computer vision and deep neural network, to detect the motion of athletes. Unlike wearable IMU and force sensors, the wearable graphical motion tracking system requires simultaneous use of an external image-capturing system, which makes it only available in a laboratory environment.⁶¹

In addition to dynamic data, such as angular acceleration of an athlete's joint, physiologic parameters, such as HR and EMG, can also be used to monitor and assess the performance of young athletes.^{62–67} Compared to performance monitoring and assessment systems that collect dynamic data, devices that collect biologic data focus on interpreting the intensity and effect of an athlete's exercise session. For example, Zhu et al⁶⁷ used a wearable ECG sensor to monitor HR of athletes and quantified training intensity during different physical activities. The detected training intensity can optimize coaching of athletes by targeting HR range.⁶⁷ Training intensity can also be monitored by other types of biologic signals.^{63,66} For example, Orucu and Sele⁶³ used surface EMG sensors to measure the level of muscle activation from agonistic muscles of athletes. The measured EMG signal was compared to the maximum voluntary contraction to determine the ideal level of training intensity for individual athletes.⁶³ Yogev et al⁶⁶ used a wearable muscle oxygenation sensor to measure the exercise intensity of cyclists.

Resistance training

Wearable devices can also improve the performance of young athletes during resistance training. In contrast to wearable devices designed for evaluation of cardiovascular training, wearable resistance training devices involve attaching an external load onto the lower or upper limb of athletes, depending on the type of sport. However, few researchers have investigated wearable resistance training devices for improving the performance of athletes.^{10,68,69} Feser et al¹⁰ and Bustos et al⁶⁸ investigated the effects of lower limb wearable resistance devices on the training performance of soccer and rugby athletes, respectively, and demonstrated the efficacy of the devices to improve training performance. Kadhim et al⁶⁹ developed a variable resistance suit for both upper- and lower-limb resistance training, designed to modulate tunable, bidirectional, and speed-dependent resistance at the elbow and knee joints.

Biofeedback

Wearable devices can also be used to provide biofeedback to the young athlete. Traditionally, feedback from coaches and trainers occurred via subjective observation; however, wearable devices allow cost-effective quantification of biomechanical variables to enhance performance and aid training.^{70,71} Wearable devices can provide biofeedback by collecting and storing data or providing real-time feedback on variables such as joint load and balance performance.^{72,73} In collecting biometric data, these devices can inform users about the chance of injury when load or balance exceeds specific thresholds or when improper biomechanics threaten joint stability. Additionally, wearable devices can integrate haptic components, which provide vibrotactile feedback to athletes to change training intensity or correct movement patterns or

timing. For example, sensorized insoles with haptic feedback are used to aid soccer players in improving sprint performance.⁷⁴ Other biofeedback sensors use real-time ultrasonography to improve muscle contraction training in bodyweight and weight training by sending images to an external device (eg, smartphone) through an app to help athletes visualize the activation of their muscles.⁷⁵ In addition to biomechanical improvements, wearable devices can be used to provide biofeedback to improve stress management, maintain hydration status, and regulate sedentary activity.^{76–78}

Muscle stimulation

Electrical muscle stimulation, which uses electrical impulses to contract targeted muscles, is another application of wearable devices to modulate the behavior of young athletes. Electrical muscle stimulation is used for training purposes to aid coaches in guiding athletes to learn correct muscles to engage at the right time, thereby enhancing muscle coordination and mitigating injuries.^{79,80} The wearable devices used for electrical muscle stimulation include IMUs, EMG sensors, microprocessors, motors, and actuators.^{81–83} IMUs are used to monitor sports activity and exertion by stimulating vibrotactile or electrotactile bands and informing the athlete of abnormal movement or overexertion.⁸¹ EMGs are similarly used to monitor muscle contraction and activation while also monitoring for fatigue, both of which can guide an athlete's training.⁷⁹ Microprocessors are used to communicate with software involving vibrating motors and actuators that provide vibrotactile and electrotactile feedback, respectively.^{84,85} While most of these devices are wrist-worn smart bands, some apply transcranial direct current stimulation, where a small current (2-3 A) is delivered over the head to target the motor cortex.⁸⁶ A study using this method with wearable technology headphones found that the feedback improved power output and accuracy during spring cycling.⁸⁷

Athletic motivation

Another aspect of wearable devices is the functionality of social motivation through the shared use of these devices in team sports. Applications that encourage sharing of workout session data with others have been shown to promote social networks to improve adherence to training.^{88,89} This is especially beneficial for adolescent athletes, who are forming their identity in sports. High school athletes with wearable devices were found to be more likely to indicate a desire to pursue professional sports in the future.⁹⁰ Wearable devices can also provide motivation through reminders to maintain the frequency of training and provide statistics on training intensity and chance of injury.⁹¹

Rehabilitation of athletes

Approximately 30 million children and teenagers engage in organized sports, resulting in over 3.5 million sports-related injuries each year among young athletes.^{92,93} To successfully return to competition, the guidance of a therapist-led rehabilitation program is imperative. This rehabilitation process involves various stages, including diagnosis, inflammation management, promotion of healing, fitness enhancement, and injury prevention.⁹⁴ Consequently, recovery from sports-related injuries demands a considerable amount of time and effort. Because of the increasing number of sports-related injuries and the extended amount of effort required for rehabilitation, the US is experiencing a shortage of rehabilitation therapists.

An alternative to traditional rehabilitation with a professional therapist, exoskeletons and exosuits are a subcategory of wearable devices designed to provide controlled force or motion to help in physical rehabilitation of various conditions, including recovery and rehabilitation from injuries in athletes.^{95,96} Compared to conventional rehabilitation therapy that relies on the instruction and assistance of a therapist, rehabilitation with wearable exoskeletons or exosuits alleviates the human workload, allowing repeatable and longer rehabilitation sessions for the patient while providing a means to assess the progression of rehabilitation outcomes through integrated sensors.⁹⁷ A few studies have demonstrated the applicability and effectiveness of using wearable devices in athlete rehabilitation^{98–101}; however, due to high cost and inaccessibility, the use of these devices for rehabilitation of sports-related injuries in young athletes is limited.

Training and performance enhancement

Wearable technology can monitor athletes' performance and inform their training regimens. These devices provide feedback on physical stress, which can be used to balance resistance training and endurance programs.¹⁰² Information such as HR, HRV, distance, and sweat can help athletes optimize training. These measures are tracked using a combination of position sensors such as GPS, global navigation satellite system, ultrawideband, inertial sensors, and accelerometers.¹⁰²

Global positioning system

GPS can track the pace and location of competitors in numerous sports, including football, orienteering, cross-country skiing, and field hockey. Using GPS, athletes gain information about speed and position parameters.¹⁰³ In rugby, a

high-intensity sport characterized by rucking, sprinting, scrummaging, and tackling, GPS has been used to investigate collisions (changes in a player's momentum brought on by contact with another player), impact forces, and physiologic demand.^{15,104} Some players are more prone to collisions due to their position on the field. GPS can quantify the number of collisions and intensity of contacts by position and player to inform tackling profiles and relative risk of injury.¹⁰⁴ For example, in rugby, different positions demand different skills and strengths; hence, data such as distance traveled, pace, calorie expenditure, HR, locomotor activity, load, and speed can assist players and coaches in developing position-based training.^{104,105} Athletes can receive maximum training benefits when the training stimulus aligns with the physical demands of the sport.¹⁰⁵

IMU sensors

While GPS visualizes the field of play and provides feedback on speed and distance, it does not measure biomechanics. However, biomechanical parameters can be measured by IMU sensors.¹⁰⁶ These sensors measure impact accelerations and multiple angles of movement with a mechanical movement-sensing device that can track movement patterns and mechanics in multiple dimensions.^{15,107–109} Major components of IMUs include accelerometers, gyroscopes, and magnetometers.¹¹⁰ IMU-based devices measure movements such as jump height, impact force, trunk rotation, and joint position.¹¹¹ For example, IMUs can be used in sprinters to measure stance durations that contribute to running speed.¹⁵ In swimmers, triaxial accelerometers and gyroscopes provide data related to stroke technique, racing performance, and energy consumption. By examining the signals from IMU devices and comparing them to video recordings, biomechanical and training changes can be made that may lead to reduced risk of injury and improved athletic performance. Accelerometers can also be used to assess energy consumption using vertical integration, an essential factor in determining a training regimen's intensity.¹⁵

IMU devices with gyroscopes can measure velocity around a fixed axis.¹¹⁰ These devices have been used to optimize velocity-based resistance training in overhead movements to improve mean power propulsion among volleyball athletes.¹¹² Optimizing velocity-based strength training while minimizing injury is critical to elite-level volleyball and general sports performance.

Magnetometers are typically used with accelerometers and gyroscopes to filter the orientation of movements.^{110,113} In individual sports, such as sprinting and skiing, athletes' speed and timing influence their success. Magnetometers can help determine these minute changes by using anisotropic magnetoresistive technology, which uses gravitational forces to measure movements in athletes along all 3 axes (x, y, and z).^{110,114}

Using wearable IMU devices, including accelerometers, gyroscopes, and magnetometers, swimmers gain information on acceleration, angular velocity, magnetic field, and attitude angle.¹¹⁵ This information can be used at the macro level to identify the total quantity of swimming (eg, number of laps) and at a micro level to identify the swimming phases in each lap that can aid in development of a swimmer's training strategy.

IMUs can overcome the limitations of GPS-based measurements as they offer an external load estimate of physical activity. This measurement represents all stress placed on the body due to acceleration, deceleration, direction changes, collisions, and foot strikes. These load measurements can be taken indoors or in locations with low signal quality, unlike GPS measurements, which depend on satellite signal strength.¹¹⁶ A combination of GPS and IMUs in wearable technology can track the position and orientation of players.¹¹⁰ For example, a swimmer's speed at the midway point and the number of strokes for each trial can be calculated using GPS and IMU data. This combination has been shown to accurately record swimmers' velocity with freestyle, breast, and butterfly strokes, helping them precisely measure strokes to enhance their performance.^{117,118}

Athletic injury reduction and prevention

Athletic groups are constantly looking to reduce injuries while advancing player development. Wearable technology can help reduce injuries by informing a balanced training and recovery regimen.¹¹⁹ Data such as HR provided by wearable technology is a good indicator of athletes' training and rest capacity.¹²⁰ Information such as hydration status, sleep, and cardiac health can inform training and return-to-play protocols after injury.¹²¹

Managing workload

Data from wearable devices can inform injury prevention by optimizing athlete workloads.¹⁰⁹ It is possible to determine an athlete's internal and external workload during a training session using parameters captured by wearable sensors. External workload is an objective indicator of the external stress placed on the body, which is essential to evaluate the efficacy of a training program and reduce risk of injury. Accelerometers and GPS measure distance, velocity, duration, and training frequency; this information informs external workload.^{116,122} A study determining the impact detection rate

in American football found 96% validity for 2 wearable sensors: a helmet system with 6 linear accelerometers and a mouthguard system with a 3-axis linear accelerometer and a 3-axis angular rate sensor to track concussions by detecting linear and angular head accelerations (external workloads) at impact.¹²³

Internal workload includes physiologic and mental stress experienced by athletes during training and competitions.¹¹⁶ Managing internal workload enables tailoring of training exercises and detection of potential health hazards, burnout, and dysfunction. Wearable technology, including chest belts and photoplethysmography, can monitor internal workload indicators (eg, HR, HRV, and temperature monitoring) to measure changes in the body in reaction to external workload.^{122,124} Abnormal HR or rise in body temperature can indicate an athlete's inability to cope with training intensity; this information can be used to modify the workout with adequate recovery.¹²⁵ The acute-to-chronic workload ratio, a measure of how hard an athlete is training and their willingness to take on greater athletic demands, can be determined by developing the athlete's workload profile using both external and internal workloads.¹²¹ A study determining the relationship between workload and risk of injury in young football players using GPS and accelerometer sensors suggested that noncontact injury was linked to higher acute workload. Gradual increases in chronic activity may help athletes improve their physical stamina for greater acute workload and injury resistance.¹²⁶

Adequate sleep and recovery

Sleep is vital for athletic recovery, muscle repair, and adaptation following training. It also improves performance and mitigates injury.¹²⁷ Wearable sleep sensors use actigraphy to track movement, HR, and HRV as indications of sleep-wake cycles.^{120,127} Athletes in high-intensity aerobic sports, such as cycling and swimming, who endure large amounts of psychological and physical stress, can use these devices to balance resistance-training programs with sleep hygiene, allowing for adequate rest and recovery.¹²²

Hydration

Hydration levels can provide insight into athletes' physiologic state. Increased feeling of exertion, lower aerobic capacity, impaired cognitive function, and poor physical performance are associated with fluid losses above 2% of body weight in athletes.¹²⁸ One study developed dehydration self-monitoring technology that can instantaneously determine the hydration status of human skin with wearable electrodermal activity sensors combined with signal processing and ML methods.¹²⁹ This wearable technology can track hydration levels with 84.5% accuracy, send signals to a smart device in real-time, and immediately notice when a dangerous threshold is crossed.¹²⁹ Another study used cardiovascular response to orthostatic postural shifts to develop a noninvasive wearable technology implanted with ECG leads and IMUs for measuring dehydration in athletes.¹²⁸ The study suggested that wearable technology can detect at least 2% body weight loss from dehydration by using the connection between hydration and cardiovascular reactions to orthostatic changes.¹²⁸

Change of direction

In athletes, frequent sharp change-of-direction occurrences may cause neuromuscular and musculoskeletal fatigue, increasing the risk of musculoskeletal injury.¹⁰⁹ IMU data have demonstrated a relationship between acceleration load and frequency of overexertion injuries in athletes in contact sports such as American football, Australian football, and rugby.¹²⁰ IMUs are placed on the body to track the players' movements on the field surface. These movement patterns can assess risk factors, such as position, load, and level of play, that can help athletes correct improper biomechanics to better tolerate external stress from impacts that may otherwise result in injuries.¹²⁰ While motion-capture camera systems can also be used to detect change of direction, with numerous businesses now providing comparable solutions, wearable technology is emerging as a preferable alternative to camera-based athlete tracking systems due to their versatility, ease of use, and unrestricted data collection space.¹⁰⁹

Cardiac health

Wearable technology can assist both recreational and elite athletes in improving their performance and ensuring their safety by monitoring cardiac physiology and pathology. A combination of ML and photoplethysmography in wearable technology can be used to identify patients with obstructive hypertrophic cardiomyopathy.¹³⁰ The optical sensor in these devices records pulse wave traces, detecting changes in blood volume at the skin surface. Additionally, wearable technology can track cardiac rhythms, which can help detect atrial fibrillation.^{131,132} Wearable technology with ECG capability has been shown to detect atrial fibrillation with the same accuracy as 12-lead ECG machines.¹³³

Rehabilitation

Wearable technology can provide feedback to monitor biochemical indicators of muscle metabolism, oxygenation, and blood flow to provide insight into muscle rehabilitation. Near-infrared spectroscopy is used to gauge the oxygenation of living muscles.¹¹⁶ Wearable sensors with near-infrared spectroscopy can measure athletes' muscle oxygen saturation levels and provide feedback on muscle recovery. These sensors can also continuously measure change in oxygen

saturation of muscle tissue to assess a player's capacity to maintain performance while avoiding fatigue during workouts.¹³⁴ A study compared changes in muscle oxygenation levels in club-level swimmers and triathletes during a 200-m swim using wearable near-infrared spectroscopy sensors,¹³⁵ and found that the swimmers displayed no significant change in tissue saturation index in the upper and lower body ($P=.686$). In contrast, the triathletes experienced a significant reduction in tissue saturation index in the upper body compared to the lower ($P=.043$), suggesting that triathletes predominantly use the upper body for propulsion during the same exercise.¹³⁵ Another study used wearable near-infrared spectroscopy sensors to determine muscle tissue oxidative capacity and recovery time in intermediate, advanced, and elite rock climbers.¹³⁶ The study indicated that oxygen recovery per second in the elite group was significantly higher than that in the intermediate and advanced groups (flexor digitorum profundus: 4.2 vs 0.7 and 0.3; flexor carpi radialis: 4.8 vs 0.1 and 0.2, respectively); therefore, the elite group required less time to half recovery than the control and intermediate groups.¹³⁶

Future directions of wearable technology in sports

Implementation of ML for accurate detection and prediction

Many recent studies of wearable technology use ML and deep learning (DL) models to detect unsafe movement patterns, changes in balance, and abnormal heart rhythms to decrease the risk of injury.^{137–140} These studies demonstrate the potential of advanced computational algorithms, such as convolutional neural networks, recurrent neural networks, and long short-term networks, in assessing physical performance and preventing injury. However, studies of this nature are scarce as most wearable devices have limited computational power to run ML/DL models. A benefit of using ML/DL is the ability to identify patterns that are difficult for coaches, athletic trainers, and personal trainers to monitor, including sleep and movement patterns. For example, Zhang et al¹⁴¹ described the use of multilevel feature learning and recurrent neural networks on data collected from a wrist-worn wearable device to classify stages of sleep. Jacobson et al¹⁴² also demonstrated the application of a multilayered ensemble DL model in adolescents to predict anxiety based on sleep pattern data from wearable devices. However, despite proven uses in monitoring sleep patterns, this methodology has not been investigated in improving health outcomes for young athletes.

Movement pattern data may also benefit from the application of ML/DL tools, but more research related to use in athletic training is needed. While Arciniega-Rocha et al¹⁴³ and Jiang and Zhang¹⁴⁴ have shown the use of DL to identify correct stances in the training of athletes, research on the application of ML/DL to develop training plans that optimize learning is limited. Tracking athletic progress with a more detailed perspective can help construct individualized training plans that reduce the risk of injury and maximize learning speed.

Sport-specific wearable devices for young athletes

Many recent wearable devices have integrated multiple sensors to increase the number of measurable variables. This design improvement provides more comprehensive information regarding an athlete's physiologic, biomechanical, and performance parameters for use by athletes, coaches, trainers, and health care personnel. For example, Fuss et al¹⁴⁵ investigated pressure-sensitive boots to monitor the training load of kicking in soccer players. The researchers identified an optimal type of foot support to maximize the chances of scoring a goal. Similarly, accelerometers can be placed at particular parts of the body to monitor movement speed, direction, and explosive effort, as well as assess injury risk in sports such as volleyball.¹¹³ However, there is a lack of research comparing these parameters and their relevance and implications for young athletes in a variety of sports environments. Some wearable devices may be particularly helpful for all young athletes, such as HRV monitors which may assist in the detection of cardiac malformations and arrhythmogenic conditions and may alert coaches and parents when young athletes need to seek medical care.³² Particularly for young athletes participating in endurance sports, HRV monitoring may be of critical importance to early diagnosis of cardiopulmonary conditions such as respiratory sinus arrhythmia. Further interdisciplinary collaborative research is needed to determine the parameters and viable wearable sensor options necessary to improve youth athlete performance and safety.

Expand the utility of wearable technology in training and rehabilitation of young athletes

Wearable exoskeletons and exosuits have been used for rehabilitation and training. As highlighted above, these wearable technologies have proven valuable in reducing human labor while improving repeatability and effectiveness of physical therapy. Swank et al¹⁴⁶ demonstrated the benefits of wearable exoskeletons in the rehabilitation of patients with spinal cord injuries, while Longatelli et al¹⁴⁷ and Shapkova et al¹⁴⁸ used exoskeletons to aid patients with stroke or paralysis in regaining their motor capabilities. Additionally, Schnieders et al¹⁴⁹ and Proud et al¹⁵⁰ successfully implemented exoskeletons in military personnel training for manual handling and operation of firearms. Further research is needed to explore and understand the potential implementation of exoskeleton and exosuit technologies in athletic training.

In the multifaceted realm of training and rehabilitation, an intriguing parallel emerges when comparing the application of exoskeletons for athletes and nonathletes. Exoskeletons, primarily conceived for regimented applications, exhibit an

adaptability that traverses diverse user groups. Exoskeletons have a control system that relies on wearable sensors, such as IMU¹⁵⁰ or EMG sensors,¹⁵¹ that detect the user's body joint angular displacement or velocity, or the force produced by muscles. This meticulously designed assistive mechanism helps the user along a trajectory of predefined motions or compensates for the gravitational forces experienced by the user. For patients with limited motor functions, exoskeletons can discern their motion intentions through a number of sensors,^{95,152,153} gently guiding their movements toward a goal and improving the dexterity of their impaired limbs. Likewise, athletes may be able use exoskeletons to improve agility, power, and endurance, while avoiding movement patterns that risk injury. The applications of exoskeletons in athletic training should embrace a holistic and nuanced evaluation of the performance of athletes, leveraging several state-of-the-art wearable sensors, including IMUs,¹⁵⁴ EMG,⁶³ and ECG.¹⁵⁵ Data collected by the wearable sensors will quantify athletic performance, allowing the exoskeleton's training strategies to be adjusted to improve training outcomes. Rehabilitative exoskeletons, therefore, may be viewed as both movement facilitators and ambitious trainers. The process of helping athletes recover to preinjury ability is collaborative work, with the exoskeleton and an ensemble of wearable sensors playing pivotal roles, echoing the data collected from wearable sensors.⁶ The application of exoskeletons for athletes for training and rehabilitation, therefore, is an extension of the application of wearable sensors.

Conclusion

We reviewed wearable technology and its potential for enhancing training, performance, and injury prevention in young athletes. Wearable devices serve versatile roles as training monitors, aids, and biofeedback tools in athletic training. GPS devices play a crucial role in monitoring diverse sports activities, from sprinting to golf distances, while HR monitors are used to track HR and estimate EE. Ongoing innovations focusing on more accessible, less expensive, and less invasive designs demonstrate notable progress in health monitoring. ML, particularly the support vector machine, shows promise in detecting overtraining. Biologic signals, such as surface EMG and muscle oxygenation monitor training intensity and effectively enhance athletic performance. These wearable devices also contribute to stress management, sleep, cardiac health, and hydration regulation to provide comprehensive information aligning training stimuli with sports demands. Also, biomechanics during changes in direction can be analyzed using wearable sensors for injury prevention, track cardiac rhythms, and identify conditions like atrial fibrillation. Challenges exist, such as the underestimation of EE during physical exertion in young athletes. At present, some forms of wearable technology are limited to investigational laboratory settings. Collaboration among coaches, trainers, athletes, and medical personnel is crucial for refining parameters and selecting viable wearable sensor options. The evolving landscape of wearable technology holds promising opportunities for personalized training plans and improved outcomes for young athletes.

Ethics and consent

Ethical approval and consent were not required.

Data availability statement

No data are associated with this article.

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Version 1

Reviewer Report 11 January 2025

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× **Fergus Guppy** 

Heriot-Watt University, Edinburgh, Scotland, UK

The authors are to be commended for conducting a thorough review of the literature around wearable technology, however it feels that the focus of the review could be rethought, with the link back to the practitioner and why they should consider measuring these things using wearable technology allowing them to compare to the laboratory measures of the same outcomes.

There is also limited linking back to youth athletes, with the focus very much on the technology. This is therefore, not reflected in the title of the work.

There is also detail here on devices work (e.g. accelerometers and MEMSs). Is that vital information for the understanding of the data collected? This links back to the question about what is the aim of this piece. Currently does not feel that it is achieving the aim.

See below some specific comments on various sections
What wearable technology can do:

L1 – wearable tech does not need to be worn on the skin, could be worn close to it so would suggest amending this.

L9 list with lots of ands in. This could do with revision.

Ref 24 - This is an undergraduate thesis. Is this the most appropriate source for this information? Also would suggest that this part needs clarification due to the use of distance covered. Does this mean the distance covered by the ball or by the golfer walking the course? I would suggest clarifying this and providing a more appropriate (preferably peer reviewed) source for this information.

HR/HRV – Not sure of the relevance of the athlete heart here. How does this relate to sensor wearing? This can't be determined using wearable technology, again seems to be outside of the focus on wearable technology in youth athletes.

How much variation is there between wrist based vs chest worn HR straps? How would this change the determination of which is more important the athlete comfort v data quality. What recommendations would you make?

Energy Expenditure

Same point re HR. How do the wearable estimates of EE compare to lab based measures? This is key information for people trying to understand the data that they might collect using these devices.

Training monitoring and assessment

Kalman filter- what is the relevance of this? How does it impact the data that is collected/reported by the device?

Is the topic of the review discussed comprehensively in the context of the current literature?

Partly

Are all factual statements correct and adequately supported by citations?

Yes

Is the review written in accessible language?

Yes

Are the conclusions drawn appropriate in the context of the current research literature?

Partly

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Wearable technology, remote monitoring, athlete performance

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.

Reviewer Report 30 December 2024

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Stuart Evans

La Trobe University, Bundoora, Victoria, Australia

Dear authors,

I commend you all for taking on what is a huge subject that requires much focus and dedication. However, I cannot recommend your indexing in its current form as much of your literature and topics simply do not provide a clear link to youth. Firstly, you need to define what you mean by youth. A youth athlete will vary significantly depending on their age - biomechanics, physiology, motor control, sleep, reaction time ... all will vary simply due to the level of maturation of the youth athlete. You need to consider these factors when reviewing why a wearable will be used, how it will be used, when it will be used, why it will be used (i.e., as a motivational tool?), and where (in school, out of school, recreational activity, sport).

I have provided examples below.

Abstract

Comment 1: Define Youth.

Assessment of activity and health

Comment 2: The subheading talks to movement and physical activity tracking, yet the opening paragraph mentions sport. There is a huge difference between sport, physical activity and movement tracking. I suggest you define these terms.

The information listed here is very informative, yet I cannot see a tangible link to youth. What evidence exists that youth are using wearables to monitor step count? A school-based intervention may increase youth participation in wearable usage, but it is unclear how your summary relates to youth either in an education setting or external (recreational).

Heart rate and heart rate variability monitoring

Comment 3: The same issue exists here I'm afraid as this reads more like a literature review of wearables and not a review of how, why, when, and how youth use them. For instance, you talk about an athlete's heart. The youth heart and contractile elements are still growing depending on the child's age. How would wearable technology be used here? And why would a youth athlete use it and not the coach? There is no linkage between the information presented and the contemporary youth athlete.

Energy expenditure, Sweat sensing and Sleep monitoring

Comment 4: And again. Great information, but why is this relevant for a youth athlete? It is highly debatable if a youth athlete would monitor sweat rates as this implies that the youth understands basic physiological changes and responses to activity. Moreover, given that youth athletes have immature physiological systems and varied responses to exercise intensity, how would the wearable data be used? There must be a stronger and more robust link to the information provided and the topic of youth athletes.

Performance feedback for training

Comment 5: You state that 'most existing technology uses wearable inertial measurement unit (IMU) or force sensors to measure the joint angles, accelerations, and interaction forces of young athletes.' This needs a citation. Also, an IMU won't measure the joint angle but will provide angular acceleration or a velocity component.

You also state that 'these devices then use data analysis methods and classification-based machine learning (ML) algorithms to assess performance during the training session.' Is this

correct? Many IMU do not rely on machine learning but simply require the transfer of raw data. Also, you are implying that this is real-time data analysis. How is the data being fed back to the youth athlete?

The rest of this section is confusing. You mention a Kalman filter but there is no context applied whatsoever. Also, laboratory wearable systems are mentioned. The general purpose of wearable systems is to avoid the lab environment. My biggest concern is that much of the literature stated here does not relate to youth. Many of the studies that you have cited are not based on youth activity or youth wearables.

Resistance training

Comment 6: How can “wearable devices can also improve the performance of young athletes during resistance training.”? Adolescent resistance training requires knowledge of sets, reps, recovery periods, relative strength of the youth, appropriate loading and correct technique. You’ve included studies that have not focused on youth.

Biofeedback

Comment 7: What wearables are being referred to? Biofeedback is hugely complex and there is no consideration for the age of the youth or level of maturation. Is the wearable being used as a educational tool for the youth athlete? How is the data being used?

Muscle stimulation

Comment 8: There are huge ethical considerations with muscle stimulation techniques in children under the age of 18, yet these are not mentioned.

Athletic motivation

Comment 9: This is arguably the most important section as wearables and relative data can be used as motivational tool and/or as a learner centric tool for youth, yet this isn’t expanded on. I would expect to see references for efficacy, goal-setting, self-determination theory, etc.

Rehabilitation of athletes

Comment 10: Is “the US is experiencing a shortage of rehabilitation therapists”? If so, where is the citation?

There is no mention of tele-health or how wearables could be used by a therapist to monitor training loads or peaks with the athlete reporting back on progress.

Training and performance enhancement

Comment 11: Everything that you have stated is correct, but again the question is how? How does this relate to young athletes? How can young athletes uses wearables to monitor performance? How can this fit with long term athletic development models to progress performance?

Global positioning system

Comment 12: And here. Why would a young athlete use GPS? This has to link to a goal, a motivation or similar.

I reviewed the section on IMU sensors to Future directions of wearable technology in sports. The latter section at least makes a clear link to the youth athlete. The other sections simply do not provide a link or a rationale to the relevance of youth.

Is the topic of the review discussed comprehensively in the context of the current literature?

Partly

Are all factual statements correct and adequately supported by citations?

Partly

Is the review written in accessible language?

Yes

Are the conclusions drawn appropriate in the context of the current research literature?

No

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Wearable sensors, youth development, long-term athletic development.

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.

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