

[Athletic Training]

Wearable Performance Devices in Sports Medicine

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Context: Wearable performance devices and sensors are becoming more readily available to the general population and athletic teams. Advances in technology have allowed individual endurance athletes, sports teams, and physicians to monitor functional movements, workloads, and biometric markers to maximize performance and minimize injury. Movement sensors include pedometers, accelerometers/gyroscopes, and global positioning satellite (GPS) devices. Physiologic sensors include heart rate monitors, sleep monitors, temperature sensors, and integrated sensors. The purpose of this review is to familiarize health care professionals and team physicians with the various available types of wearable sensors, discuss their current utilization, and present future applications in sports medicine.

Evidence Acquisition: Data were obtained from peer-reviewed literature through a search of the PubMed database. Included studies searched development, outcomes, and validation of wearable performance devices such as GPS, accelerometers, and physiologic monitors in sports.

Study Design: Clinical review.

Level of Evidence: Level 4.

Results: Wearable sensors provide a method of monitoring real-time physiologic and movement parameters during training and competitive sports. These parameters can be used to detect position-specific patterns in movement, design more efficient sports-specific training programs for performance optimization, and screen for potential causes of injury. More recent advances in movement sensors have improved accuracy in detecting high-acceleration movements during competitive sports.

Conclusion: Wearable devices are valuable instruments for the improvement of sports performance. Evidence for use of these devices in professional sports is still limited. Future developments are needed to establish training protocols using data from wearable devices.

Keywords: wearable devices; GPS; accelerometers; sensors; sports performance

There is a growing trend in the athletic and health care environment to monitor human physiologic function and performance during real-time activities. Recently, portable and wearable sports devices incorporating sensor technology have benefited from increased media and commercial exposure as effective tools to assess physical activity in the general population. This has been driven by the increased availability, lower cost, and advancements of personal computing devices such as smart phones and digital watches. Pedometers, heart rate monitors, portable electrocardiogram monitors, and

accelerometers have been incorporated into personal devices to be used in a variety of applications (Table 1). These applications are diverse and range from ambulatory monitoring in the elderly population for falls, development of exercise programs to combat childhood obesity, and monitoring of military personnel on the battlefield.^{3,21,22,26,35,46,55}

Athletes present a growing niche for the use of wearable sensor technology. Advances in technology have allowed individual endurance athletes, sports teams, and physicians to monitor player movements,³³ workloads,^{41,58} and biometric

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Table 1. Wearable devices used in sports medicine

Wearable Device	Functional Mechanism
Movement sensors	
Pedometer	“Step” recorded each instance the vertical acceleration of a spring-loaded lever arm exceeds the force sensitivity threshold
Accelerometer/gyroscope	Acceleration causes deflection of a seismic mass between 2 electrodes, causing a change in capacitance
GPS	Signal transmissions from multiple orbiting satellites are acquired by a ground-based receiver; the relative delay is used to calculate the speed and position of the receiver
Physiologic sensors	
Heart rate monitor	1. Electrical activity from the heart recorded by electrodes in a chest strap 2. Peripheral pulse detected by optical-sensing technology in a wristband
Temperature monitor	1. Ingestible capsule transmits readings to external data log system 2. Armband measures skin convective heat flux in temperature
Integrated sensors	Multimodal platforms that incorporate components of movement and physiologic sensors

GPS, global positioning satellite.

markers^{13,44} in attempts to maximize performance and minimize injury. Monitoring these variables may allow for the identification of biomechanical fatigue and early intervention in an attempt to prevent injury during training and competitive matches. Monitoring may also facilitate the development of improved training regimens to optimize athlete performance.

The purpose of this review article is to familiarize health care professionals and team physicians with the various available types of wearable sensors, discuss their current utilization, and present future applications in sports medicine. Knowledge of these devices is important in counseling patients in the safe employment of these devices and potential limitations

MOVEMENT SENSORS

Pedometers

Pedometers are the simplest and arguably the most commonly used form of movement sensor. A “step” is recorded each time the vertical acceleration of the lever arm exceeds the force sensitivity threshold of the pedometer.⁶ Many fitness recommendations and corporate health programs are based on achieving a recommended number of daily steps.^{5,56} Adherence to step counts is more likely to correlate with an increased likelihood in meeting age-appropriate physical activity guidelines.³⁰ Pedometers have also demonstrated utility in pediatric and obese populations to promote active lifestyles.^{29,34,50} These findings show that pedometers may have some value as a first-line tool in tracking levels of fitness.

While pedometers have been shown to have acceptable reliability and validity for step-count monitoring in the

ambulatory setting, the application is unproven in competitive sports. Pedometers have limited use in quantifying athletic movements because of their inability to perceive changes of direction and are poor indicators of energy expenditure.^{7,57}

Accelerometers/Gyroscopes

Accelerometers and gyroscopes have demonstrated promise in the realm of personal fitness by giving the user access to advanced performance data and the ability to quantifiably alter exercise programs. These devices are composed of 2 components: a mechanical movement-sensing device and a microchip that interprets signals from the mechanical device. Technological progress and the development of microelectromechanical systems (MEMS) devices have allowed multiple transducers to be packaged together, giving a single sensor the ability to perceive movement in multiple dimensions.^{40,51}

An additional benefit of accelerometers is the ability to estimate energy expenditure by integrating vertical acceleration over time.^{19,32} Energy expenditure is a crucial parameter for assessing the intensity of a training regimen. Accelerometer-based energy estimation in elite Australian football players was comparable with more time-intensive video analysis.⁶⁰

Because of their low-cost design and portability, accelerometry has driven the development of portable wristband devices that have seen a significant rise in personal fitness in recent years. Devices such as the FitBit (FitBit Inc; www.fitbit.com), Jawbone Up (Jawbone; jawbone.com/up), Nike Fuelband (Nike; www.nike.com/us/en_us/c/nikeplus-fuel), and Microsoft Band (Microsoft; www.microsoft.com/microsoft-band/en-us) provide

data on a number of physiologic and movement parameters such as heart rate, caloric expenditure, sleep tracking, and steps that are then relayed wirelessly to a personal user account.

Accelerometers generate more accurate analyses of athletic movements with higher sampling rates and more accurate measurements.^{11,20,31,36,37} A series of studies in swimming have concluded that triaxial accelerometers are valuable in assessing stroke mechanics to optimize performance.^{5,8} Similar accelerometer-based systems have been used to perform time-motion analysis for rowing, tennis, and golf.^{1,16,45} Accelerometer data have been used during Australian football matches to show positional differences in physical demands between positions and varying levels of competition.⁴

Global Positioning Satellite

Global positioning satellite (GPS) devices are an alternative to accelerometers in measuring positional data in athletics. GPS devices require signal transmission from multiple GPS satellites orbiting the earth. Signals from the satellites, each with on-board atomic clocks, are acquired from GPS receivers that synchronize the signals to determine the speed and position of the receiver.¹² The performance of GPS devices is improved, particularly in the team sport setting, by employing a stationary ground-based reference receiver in addition to wearable receivers to refine timing errors from each satellite, with accuracy up to 1 meter.⁴³

GPS has been used to monitor the speed and position of athletes in football, orienteering, cross-country skiing, and field hockey.^{17,27,28} The most well-documented use of GPS in professional sports has been with Australian football and rugby.^{14,15,24,33,41,49,59}

Devices such as the Vivofit and Vivoactive (Garmin; www.garmin.com/vivofit), Polar M400 (Polar Electro Inc; www.polarm400.com), and Surge (FitBit Inc; www.fitbit.com/surge) have incorporated GPS technology in wearable devices for individual users. These devices are capable of displaying data such as mileage, steps, pace, caloric expenditure, altitude, and speed to the user in real time. In addition, data are then tabulated in software programs to allow the user to track their performance.

GPS has also been used to modify training regimens to improve athlete performance.³³ GPS devices have been used to collect both training and match time-motion data on 10 midfielders from an Australian Football League team. The study classified different drills into 3 groups based on training intensity, as measured by the distance traveled in certain velocity ranges. Additionally, higher intensity drills using the entire field more closely resembled competitive match play.³³ GPS systems have been used to correlate fitness tests and on-field performance, as well as determining energy requirements for specific player positions.^{41,59}

Several commercially available GPS systems for sports medicine have been introduced to the market with the ability to monitor an entire team. Catapult (Catapult; www.catapultsports.com) and GPSports (GPSports; gpsports.com) are examples of

systems that have been shown to produce reliable measurements of movement.^{23,47,48} The validity and reliability of GPS systems for court-based sports with shorter travel distance and greater intensities is still unproven.¹⁰

PHYSIOLOGIC SENSORS

Heart Rate Monitoring

Sensors that determine physiologic response to changes in competition and training are also crucial in promoting improved performance and decreased injury. Heart rate is a useful indicator of physiological adaptation and intensity of effort. Standard heart rate monitors comprise a transducer worn around the chest that transmits to a wireless wrist display. Newer heart rate monitors have been developed using optical sensor devices, such as a wrist band or smart phone, that detect heart rate directly from the wrist or fingertip. While arguably more cumbersome, there are data to suggest the chest strap devices are still more accurate at higher heart rates and less susceptible to motion artifact.⁵⁴ Newer commercially available heart rate monitors such as those produced by Polar Electro (Polar Electro Inc; www.polar.com/us-en) and Suunto (Suunto; www.suunto.com) are also capable of measuring heart rate variability, which has been shown to be an important indicator of fitness.

Heart rate monitors are often used as important tools for the measurement of exercise intensity. There is a linear relationship between heart rate and VO_2 over a large range of submaximal intensities.⁵³ Consequently, VO_2 and energy expenditure may be extrapolated from heart rate. Because of this relationship, portable heart rate monitors have become the most common method of estimating exercise intensity. Heart rate monitors have also been used in conjunction with kinematic analysis to determine physiologic response and metabolic demand experienced during competition in a number of sports, including basketball, rugby, and soccer.^{26,38}

Temperature/Heat Flux Sensors

Monitoring of core body temperature is important in conditions where hyperthermia is a concern, such as high temperature/humidity climates and indoor facilities without air conditioning. There is additional concern for abnormal core temperature changes during an athlete's initial acclimation to sporting activity. Accurate monitoring of core body temperature has presented a significant challenge in sports medicine. Core temperature can be assessed during athletic activities.⁴⁴ External temperatures have been shown to be an unreliable proxy for core body temperature.^{18,42} Newer commercial temperature sensors have circumvented this fact using a telemetric core temperature sensor relying on an ingestible capsule that transmits data systems using radiofrequency.^{39,52} Designs for temperature sensors all suffer from separate limitations. Cold water and food ingestion affect the validity and reliability of ingestible sensors.⁵² Armbands and skin-based dermal temperature sensors may cause skin irritation and have poor

reliability when assessing temperature and estimating energy expenditure in high-intensity exercise.⁹

Integrated Sensors

Multimodal integrated sensors have been developed for use in team and individual fitness activities. The manufacturers Catapult and Zephyr incorporate GPS technology with a number of variable sensing elements to obtain physiologic and movement profiles in athletes.^{2,48,58} The Catapult device is a small sensor placed most commonly between the shoulder blades and can be secured onto a jersey or protective gear. The Zephyr devices incorporate a respiratory rate monitor in addition to an electrocardiogram monitor.²⁵ The Zephyr BioPatch is designed as a wireless device that attaches to disposable electrocardiography electrodes and provides continuous monitoring. While relatively small, the Zephyr device requires a strap applied around the chest and over the shoulder, which can be cumbersome when safety gear such as shoulder pads are worn over the top. The straps are required for accurate measures of respiration and heart rate.

CONCLUSION

The development of wearable sensor technology has had a significant impact on athlete monitoring in sports medicine. Wearable sensors provide physicians, coaches, and training staff with a method of monitoring real-time physiologic and movement parameters during training and competitive sports. These parameters can be used to detect position-specific patterns in movement, design more efficient sports-specific training programs for performance optimization, and screen for potential causes of injury, such as concussion and fatigue.

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