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Benefits of IMU-based Wearables in Sports Medicine: Narrative Review

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ABSTRACT

Background: Inertial Measurement Unit (IMU) based wearables have been the focus of many recent sports medicine research efforts. **Objective:** The goal of this narrative-driven literature review is to provide the current state of IMU-based wearable technology in Sports Medicine for the benefit of practitioners and athletic trainers. **Method:** A search was performed using university library resources; specifically, PubMed, EBSCO Discovery and Google Scholar search engines were used to identify appropriate peer-reviewed studies in this field. **Results:** IMU wearables have shown to be a cost-effective way to measure biomechanical and physiological data for athletic training and rehabilitation compared to laboratory gold standards. While IMU wearables show potential, barriers such as IMU drift and complicated calibrations limit the technology's ability to flourish in the commercial market. **Conclusion:** IMU-based wearables provide kinematic information without the constraints and costs of gold standard laboratory equipment such as video-based motion capture and force plates; however, further innovation is required to overcome their major obstacles.

Key words: Technology, Sports Medicine, Machine Learning, Biomechanical Phenomena, Wearable Electronic Devices

INTRODUCTION

Technological advancements such as the miniaturization of sensors in the smartphone market often inspire innovations in other product markets. One of the more widespread innovations from the 2010's that transitioned out of the smartphone market is wearable technology (Burch, 2019). The wearable technology market is increasingly becoming more valuable, especially in both sports and the medical field (Luczak et al., 2020). The capability of wearables for assessing and measuring human performances enables them to become a fixture in the future for these fields especially in the area where they intersect: sports medicine. Athletes' physical performance can be quantified into physical load expenditures during training and competitions; wearables can provide this quantified data sought by practitioners to improve training regimens, load management, and the physical development of a player (Luteberget et al., 2018). The load output data captured by wearables can be used to enhance training efficacy, track performance, and provide real-time feedback for both the coaches and the players (Davarzani et al., 2020).

One common wearable sensor is the inertial measurement unit (IMU). The recent developments in IMU-based devices comprised of different microsensors (gyroscope, accelerometer, magnetometer, etc.) offer researchers a new means of investigation for biomechanical studies in sports. While IMU-based wearable solutions can vary in complexity, they are commonly comprised of one or more accelerometers and gyroscopes (Iosa et al., 2016). The intent of this narrative literature review study is to present an overview of IMU-based wearables commonly used within the sports medicine field and their future implementations.

Since IMUs are a common sensor found in the components of many electronic solutions, there is an abundance of research on their accuracy and validity. In the last 10 years specifically, research on IMU accuracy in biomechanics has grown exponentially (Seshadri et al., 2019; Hughes et al., 2021). IMU-based devices have been used to test movements such as jump height, impact force, truck rotation, joint flexion, and movement type. While research has consistently shown that IMUs in wearables have the capability to assist strength coaches, trainers, and practitioners (Luczak et al.

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2020), a review on the overall state of IMU in the field of sports medicine has yet to be provided. Because the overall sports sector is so broad, the authors of this study—who are presently practitioners of and researchers with sports science at the collegiate and professional sports levels of competition—believe a sports medicine motivated focus was warranted to aid the understanding of their peer practitioners in the field. We believe this paper to be beneficial for those within the sports medicine sector of the athletics and human performance technology space.

METHODS

Study Design

For this narrative literature review, a search was performed using university library resources; specifically, PubMed, EBSCO Discovery and Google Scholar search engines were used to identify appropriate peer-reviewed studies. Search terms such as "wearable devices," "IMU," "athletics," "performance," "sports," "rehabilitation," and "sports medicine" were used in these search engines to filter peer-reviewed studies related to the topic.

Literature Search

While no date boundary was used for much of the paper, inclusion criteria for use in the section "current and future implementation" is defined between January 2017 & July 2021. After curating a list of relevant works, the literature was organized by type of study and the variables measured. While this study was not intended to be comprehensive review, the purpose of this narrative is to provide practitioners a concise view into: (1) IMU availability specific to sports medicine, (2) the value IMU technology holds in sports medicine, (3) the accuracy of current IMU's in this field, and (4) the possible future implementation of IMU's. This study aims not to provide a comprehensive review but to demonstrate to practitioners in the sports medicine field the current state-of-the-art of wearable IMU devices.

Article Extraction

When searching the topic of IMU's, a result of 17,025 peer reviewed articles were found using the key word combinations provided in Table 1.

After the initial collection of papers was completed using these keyword terms, inclusion/exclusion criteria were based upon the paper's content as it pertained to addressing the following research questions:

1. Is this paper's outcome related to IMU data?
2. Is the research performed specific with sports or sports medicine?
3. What tier of research paper does this resource fall under? (Peer Review, conference paper, news article etc.)
4. Does this research show state of the art functionality and creativity with IMU technology?

Once the filter of peer reviewed research was completed, only 43 articles were left that met the target inclusion/exclusion criteria achieving the goal of providing the current state of IMU-based wearable technology in sports medicine for the benefit of practitioners and athletic trainers.

RESULTS

Current Wearable Device Availability

According to a recent report on the state of the sports medicine field, this area is predicted to grow in market size at an average rate of 5.8% a year and reach total market value of approximately 10 billion dollars by 2026 (Fortune Business Insights, 2018). While noncompetitive sports and athletics at the nonelite levels are shown to improve quality of life physically and mentally for those who participate (Hausberger et al., 2016), peak performance in competition is achieved when the risk for injury is at its minimum (O'Reilly et al., 2018). To monitor and assess athletes' injury risk factor, several methods are available including: "3D motion capture, depth-camera-based systems, visual analysis from a qualified exercise professional, and self-assessment" (O'Reilly et al., 2018). But several shortcomings and limitations are linked to each method such as overhead cost of 3D motion capture and biased results from self-assessment. Moreover, interpreting and processing data can be time consuming and requires an expert for a full-scale analysis (O'Reilly et al., 2018). IMUs have seen much improvement in their accessibility and reliability in the last 15 years due to their applications in smartphones which improved cost efficacy, non-invasiveness when donned, and motion and monitoring data accuracy (O'Reilly et al., 2018). Table 2 presents IMU-based wearable studies from different sports and sports medicine-related activities where IMUs are more commonly used and the specific data collection objective for the wearable technology.

Table 1. Keyword search combinations for narrative literature review

Research Question	Key Words
How are IMU's being used effectively to collect data for performance and training?	IMU Sports IMU Athletics IMU Training IMU Performance IMU Competition
How are IMU's being used effectively to collect data for injury prevention or rehabilitation?	IMU Rehabilitation IMU Injuries IMU Injury Prevention IMU Injury Risk IMU Health IMU Medical IMU Sports Medicine
What are the future possibilities, designs, and limitations for IMUs?	IMU State of the Art IMU Future Implementation IMU Research and Design IMU Prototype IMU Limitations IMU Obstacles IMU Efficiency

Table 2. IMU wearable technology in sports medicine

Study	Sport/Activity Performed	Sensors/Systems Used	Objective of Wearable
An Inertial Measurement Unit Based Method to Estimate Hip and Knee Joint Kinematics in Team Sport Athletes on the Field (Bastiaansen et al., 2020)	Linear Sprint	Five IMUs and sensor fusion algorithms	Estimating joint kinematics to evaluate training programs, aiming to reduce injury and optimize player performance
Integration of Wearable Sensors Into the Evaluation of Running Economy and Foot Mechanics in Elite Runners. (Muniz-Pardos et al., 2018)	Running	Foot-worn inertial sensors (FWIS) with dedicated signal processing algorithms	Assessing running biomechanics and foot mechanic for a better treatment and injury prevention.
3D trunk orientation measured using inertial measurement units during anatomical and dynamic sports motions (Brouwer et al., 2021)	Seventy-one sports motions (19 golf swings, 15 one-handed ball throws, 19 tennis serves, and 18 baseball swings) and 125 anatomical trunk motions (42, 41, and 42 trials of lateral flexion, axial rotation, and flexion/ extension)	Two IMUs and an optical motion capture system (gold standard)	Assessing trunk orientation during dynamic sports motions and isolated anatomical trunk motions for improving sports performance, prevention or rehabilitation of sports related injuries, or clinically relevant questions.
Verifying Head Impacts Recorded by a Wearable Sensor using Video Footage in Rugby League: A Preliminary Study (Carey et al., 2019)	Rugby	x-patch™ sensor and accelerometer	To observe and characterize the level of exposure to head impacts during game play.
Motion anlaysis in lower extremity joints during Ski carving turns using wearble inertial sensors and plantar pressure sensors. (Lee et al., 2017)	Skiing	Seventeen IMUs and pressure sensors	Assessing skier motion during turns to prevent injuries at the lower extremity of the body.
Increasing the Robustness of the automatic IMU calibration for lower Extremity Motion Analysis. Current Directions in Biomedical Engineering (Küderle et al., 2018)	Knee joint axis and knee position vector estimation for various sports activities; motions including free standing, walking in place, simple walking, repeated bench squats& dangling of the leg while sitting	Two IMUs	Improving the robustness of algorithm addressing the issue of soft tissue movements and the integration of algorithm into wearable systems, which would allow to test its performance under realistic conditions.
Validity of inertial sensor-based 3D joint kinematics of static and dynamic sport and physiotherapy specific movements (Teufl et al., 2019)	Bilateral squats, single-leg squats, and countermovement jumps	Seven Xsens MTw Awinda IMU	Assessing 3D joint kinematics in functional movements of varying demands.
IoT for Next-Generation Racket Sports Training (Wang et al., 2018)	Racket sports	Microelectromechanical (MEMS) IMU with Bluetooth low energy (BLE) module and cloud technology	Analyze the wrist motions and skill levels of players in racket sports (e.g., badminton, tennis, table tennis, and squash) for training and/or practice.
Monitoring Hitting Load in Tennis Using Inertial Sensors and Machine Learning (Whiteside et al., 2017)	Tennis	One IMU and six types of machine-learning models to classify true shot type	Develop an automated stroke-classification system to help quantify hitting load in tennis
Coordination Analysis of Human Movements With Body Sensor Networks: A Signal Processing Model to Evaluate Baseball Swings. (Ghasemzadeh & Jafari, 2011)	Baseball	Three IMUs	Assessing baseball swing and provide feedbacks to coaches.
Validation of an inertial measurement unit for the measurement of jump count and height. (MacDonald et al., 2017)	Volleyball	Three-axis accelerometer gyroscope	Assessing the jumping performance to improve physical preparation and prevent injury.

(Contd...)

Table 2. *(Continued)*

Study	Sport/Activity Performed	Sensors/Systems Used	Objective of Wearable
Validation of the VERT wearable jump monitor device in elite youth volleyball players (Borges et al., 2017)	Volleyball	VERT Wearable Jump Monitor	Assess and quantify jump performances in volleyball players for training and competitions.
Wearable sensor validation of sports-related movements for the lower extremity and trunk (Dahl et al., 2020)	Cutting, running, jumping, single leg squats, and cross-over twist	Wireless IMU system	Alternative to optical motion capture for assessing human movement.
External Workload Indicators of Muscle and Kidney Mechanical Injury in Endurance Trail Running (Rojas-Valverde et al., 2019)	Running	Six IMU	Analyze which external workload indexes have more influence on muscle and kidney injury biomarkers.

DISCUSSION

Wearable Device Accuracy

In sports medicine, IMU-based wearable devices can be used to estimate parameters such as impact severity, metabolic rate, and direct kinematic data to give practitioners the information needed to improve training regimens, load management, and the physical development of a player (Luteberget et al., 2018). In this section, studies discussing the accuracy of wearable devices are separated into two subsets of studies which performed assessments of: (1) absolute measurements and (2) relative measurements.

Absolute measurement

Due to a phenomenon called "IMU drift" which results from continuously integrated noise errors (Luczak et al., 2018; Narasimhappa et al., 2020), very few wearable devices use IMUs as a means of determining absolute position over a long duration. However, in cases where the device is repeatedly supplied with a positional or velocity reference or the action being measured is particularly short-lived, IMUs can be an accurate source of absolute position. One study in 2019 used this method using a wearable jump height measurement system (Nielsen et al., 2019). The IMU-based system starts numerical integration when a jump start condition is detected, minimizing the amount of time for errors to accumulate. Results for estimating the wearer's center-of-mass displacement were consistently within 4.0 cm of accuracy (Nielsen et al., 2019). In a non-position-based study, Bai et al. (2016) compared seven different wearable consumer and research-grade metabolic rate monitors to a known accurate metabolic monitoring system. Each of the wearable systems depend primarily on an internal IMU and pulse rate sensor to estimate activity which is synthesized into a metabolic rate estimate (Bai et al., 2016). The results showed these devices accuracy ranging from 15% to 30% error in caloric expenditure compared to the gold standard (Bai et al., 2016).

Relative measurement

Drift causes absolute IMU measurements to increase in error over time. Although, if continuous integration can be avoided or a consistent reference can be used, this error can be avoided. This type of setup can record relative measurements; for example, relative measurements can be a joint angle or impact energy. One study used two sets of IMUs on both segments of the leg to estimate the knee joint flexion angle with 1.0° accuracy (Fennema et al., 2019). This is a simple calculation which requires comparing the outputs of the two IMUs to determine the angle between them.

In other examinations, researchers use IMUs to estimate the impacts endured by players during contact sports (Carey et al., 2019; Wundersitz et al., 2015). Wundersitz et al. (2015; using a Catapult™ wearable system) were able to predict impact g-force within 0.27g; however, measurements were overestimated during walking, jogging, and sprinting and underestimated during tackles and jumping (Wundersitz et al., 2015). Carey et al. (2019) compared IMU measurements with a video analysis system using data collected during a game of rugby. Their impact sensors were able to classify impacts into three categories of severity which were later verified on video; the sensors and video agreed during approximately 70% of the captured events (Carey et al., 2019).

During a comprehensive review of the state of wearable sensors in swimmer performance analysis, Magalhaes et al. (2015) summarized the validations of 27 wearable swimming devices using IMUs. The metrics estimated by the wearables include stroke count, average velocity, stroke rate, and more variables of interest to practitioners. Results from these studies were satisfactory, with p-values lower than 0.01 correlating IMU data with video capture (Magalhaes et al., 2015).

Information and Value

Many IMU-based wearables capture data specific to reporting on two common areas for athlete's physical performance and conditioning evaluation: kinematic data (displacement, velocity & acceleration) and kinetic data (work, impulse, rate of force & power; McMaster et al., 2014). Sports practitioners such as athletics trainers and strength and conditioning coaches use kinematic and kinetic data to drive athlete assessments and thereby decision making for: (1) on-field performance, (2) specific training for performance improvement, (3) post injury evaluation, and (4) return to sports or RTS (McMaster et al., 2014). IMU-based wearables can provide the kinematic information required by practitioners without the constraints of a laboratory setting.

In a study conducted by Kim et al., (2020), IMU-based wearables provided information about lower-limb kinematics used to measure bilateral symmetry movement between injured and non-injured limbs (Kim et al., 2020). Practitioners use the data as a decision criterion for RTS after knee ligament injury (Kim et al., 2020). Clinicians and coaches also used the quantification of lower limb segmental excursion to make RTS decisions after a knee injury and to decrease reinjury risk (Kim et al., 2018). Both studies reported that IMU-based wearable technology donned on the knee used in rehabilitation provided data that drove practitioner decisions leading to decreased risk of reinjury after major knee ligament trauma (Kim et al., 2018; Kim et al., 2020).

Lower body power production capacity and counter-movement jump (CMJ) performance are key indicators of athletic ability (Burch et al., 2019) and are commonly used to monitor injury recovery (Teufl et al., 2019). The analysis of different functional movements, such as bilateral squat (SQ), single-leg squat (SLS), and CMJ, provide information about rehabilitation status or injury risks of lower body extremities. Teufl et al., (2019) validated the IMU-based 3D joint kinematics for lower extremity using a sensor-fusion algorithm in dynamic, clinically relevant movements (SQ, SLS & CMJ) with a high range of motion. The joint kinematics data obtained from the IMU included: hip rotation, hip flexion, knee abduction, knee rotation, knee flexion, ankle inversion, ankle rotation ankle flexion, pelvis obliquity, pelvis flexion and pelvis rotation (Teufl et al., 2019). Wang et al. (2018) proposes an Internet of Things (IoT) framework for racket sports training. The researchers propose a novel and "smart" racket action recognition and skill assessment system using low-power microelectromechanical systems (MEMs) IMUs with Bluetooth low energy (BLE), machine learning algorithms and cloud technology. With wrist motion being crucial for any racket sport, the sensor data were collected at the wrist to identify the player's level of performance (Wang et al., 2018). Since active performance and proper biomechanical movement are imperative to practitioners' ability to assess athletes, IMU joint kinematic data can be extremely beneficial for revealing the movement correctness (Wang et al., 2018).

The sports of both basketball and volleyball have benefited from IMU wearable technology usage. From a sports medicine perspective, players from these sports often get the condition called Patellar Tendinopathy or "jumper's knee" (Jarning et al., 2015). Since there is a known correlation between jumping frequency and Patellar Tendinopathy, estimating jumping frequency using accelerometer data has helped practitioners mitigate this condition due to an accurate quantification of movement (Jarning et al., 2015). In a similar study, IMU's jumping count data aided a coaching staff in understanding position-specific training, match demands, and athlete load management to mitigate volleyball players' general knee injuries (Windt et al., 2020). During a performance specific volleyball study, coaches and sports scientists utilized jump performance to monitor volleyball players' response to training or changes to training (Borges et al., 2017). Borges et al. (2017) evaluated a commercially available IMU-based wearable, Vert™, to measure professional volleyball player's attack and block jump performance.

Future Implementations and Limitations

While IMU's can be found in every day commercial wearable products such as smart watches, IMUs have grown a solid foundation in team sport data collection equipment such as Polar™, Zephyr™, Catapult™, Zebra™, Kinexon™ (Luczak et al., 2020), and Vert™ (Borges et al., 2017) as well as in individual biomechanical observations (Wang et al., 2018).

While still inherently constrained by some limitations, IMU's have proven in certain instances and studies to be comparable to the gold standard accuracy of motion capture given specific circumstances. More specifically to sports medicine, IMU's can serve as a replacement to laboratory gold standards optimistically providing a data collection alternative as wearable equipment may be much cheaper in cost yet accumulate similarly accurate data (Bastiaansen et al., 2020). For example, competitive tennis players typically utilize motion sensor data or rely on notational analysis to provide feedback on their stroke workload. When wearing a wrist wearable IMU, a group of tennis players performed over 20,000 tennis strokes which were categorized into their respective stroke type and entered in a machine learning algorithm leading to a stroke identification accuracy level of 97.4% (Whiteside et al., 2017). Other sports are also using IMU technology to obtain trunk motion data which in turn can be used to calculate athletic performance and, specific to the sports medicine practitioner, risk of injury by providing 3D-level accuracy of motion (Brouwer et al., 2021). Further, sports medicine data scientists have found IMUs could be a replacement for when force plates for jump tests are not available; high correlation between IMUs and force plates has been found specifically for more critical physical assessment jumps such as the CMJ (Rantalainen et al., 2020).

While IMU have shown promise, there are still barriers to overcome for future implementation in sports medicine. While in a controlled system such as a laboratory environment, IMUs hold their accuracy well; however, IMU-based wearables struggle when in a commercial, nonlaboratory environment without professional oversite. Küderle et al. (2018) stated that "in existing systems, the process of aligning the mounted sensors with the body coordinate system is either not robust enough or too complicated for fully unsupervised usage." Restated, many of these IMU-based solutions sensors require a level of set up or calibration that is unreasonable for some commercial users. Proper set up is crucial since it has been observed that accurate sensor placement and appropriate calibration to biomechanical movements are essential when determining validity of the wearable (Hughes et al., 2021). Another systematic review found limitations of current IMU technology with "calibration, magnetic field disturbance, and sensor bias" (Marin, 2020). While the researchers recommend modifications in the algorithms and increase stability by implementing calibration motions, more work is still required to reach gold standard level of quality during data collection events in uncontrolled, nonlaboratory environments.

CONCLUSION

This narrative literature review evaluates peer-reviewed, IMU-based wearable device research papers to provide the current state of their application for sports medicine practitioners. There is an increasing interest in using IMU-based wearables because they provide kinematic information without the constraints and costs of laboratory gold standard equipment such as video motion capture and force plates. Sports medicine practitioners use IMU-based wearables to collect athletes' performance data, manage athlete's load during training and competition, direct activities for performance improvement, and make decisions about return to sports after injury as well as to mitigate re-injury.

Even though the accuracy and reliability of the information provided by IMU-based wearables are still concerns for some practitioners, IMU's have proven to be relatively accurate compared to the gold standards given specific situations and use cases. More specifically to sports medicine, IMU's offer a cheaper equipment solution for similar performance data, delivering a product with the capability to keep athletes healthy while maintaining a reasonable budget. While IMU-based wearables shown promise, there are still barriers to overcome for future implementation. IMU drift is a considerable restraint which can be challenging to overcome in the goal to replace laboratory golden standards in the commercial market. Further, many of the IMU sensor solutions require a level of setup or calibration that is unreasonable given the expertise level of some general consumers. Therefore, further research and innovation is required to overcome those obstacles.

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