EXPLORING THE USE OF WEARABLE TECHNOLOGY BY ATHLETES: A NARRITIVE REVIEW

by

Morgan Gelinas

Bachelor of Arts in Psychology, University of Victoria, 2019

A Major Research Project

presented to Ryerson University

in partial fulfillment of the

requirements for the degree of

Master of Digital Media

in the program of

Digital Media

Toronto, Ontario, Canada, 2020

Author’s Declaration

AUTHOR'S DECLARATION FOR ELECTRONIC SUBMISSION OF A DISSERTATION

I hereby declare that I am the sole author of this MRP. This is a true copy of the MRP, including any required final revisions.

I authorize Ryerson University to lend this MRP to other institutions or individuals for the purpose of scholarly research.

I further authorize Ryerson University to reproduce this MRP by photocopying or by other means, in total or in part, at the request of other institutions or individuals for the purpose of scholarly research.

I understand that my MRP may be made electronically available to the public.

EXPLORING THE USE OF WEARABLE TECHNOLOGY BY ATHLETES: A NARRITIVE REVIEW

Master of Digital Media, 2020

Morgan Gelinas

Digital Media

Ryerson University

Abstract

At the elite level, success is often separated by centimeters or milliseconds. Arguably, integrating technology offers a competitive advantage in closing this gap. Wearable technology has become an increasingly adopted tool used in all levels of sports. Considering elite athletes, and applying a self-efficacy theory lens, the purpose of this narrative review is to explore the use of wearable technology in elite athletes. Specifically, (a) the major types of wearable technology used by athletes; (b) how wearable technology may affect performance; and (c) trends and gaps in the field.

Key Words

Wearable Technology | Sport Technology | Sport Psychology | Athlete Performance | Internal Load | External Load

Acknowledgments

Dr. Forrester, this has been an incredible journey! You showed tremendous guidance during this venture. Without your support and encouragement, I would not have had as many opportunities to grow my knowledge in this field. I am so grateful to have had you supervising this project, I admire you and the person you are and look forward to working together to pursue publishing.

Dr. Pegoraro, thank you for jumping through the hoops to be my second and for so kindly taking the time to support me in this process. I am very grateful Dr. Forrester has connected me to you and am very excited to stay in touch with you.

Thank you to the program directors, Micheal, Alex, and Lissa, as well as the professors in this fabulous program for guiding us along in this journey. I will always remember how special this program, group, and the year was to me and am beyond thankful you put it together.

Finally, thank you to my family for encouraging me and my decision to pursue my masters. Your unwavering support for my passions is something I feel truly grateful for. And for putting up with my 'student writing a master thesis' attitude - I don't know how you did it.

Table of Contents

List of Tables

Introduction

High-profile sporting events are used as a surrogate battlefield for nations to demonstrate their power and superiority in what is seen as the global arms race of sports (De Bosscher et al., 2006). The relationship between athletes' success in high-profile events like the Olympic Games and supporting governing bodies is mutually beneficial. Countries use medal counting as a means of demonstrating their superiority to other rival nations (De Bosscher et al., 2006). Thus, national sports organizations (NSOs) feverishly pursue excellence as a means to outperform their competition. In some cases, NSOs may go so far as to engage in unethical practices. The Russian doping scandal, is an excellent example of the 'win at all cost' mentality, in that the NSO and government were a part of the elaborate system that encouraged Olympic athletes to participate in the use of illegal performance-enhancing drugs (Altukhov & Nauright, 2018). This scandal reflects the lengths to which some nations will go to demonstrate their greatness on the world stage.

At the elite level, success is often separated by centimeters or milliseconds. NSOs are eager to optimize performance through improved training predictions, and, in doing so, embrace new technologies to gain a winning edge over the competition. Arguably, integrating wearable technology offers a competitive advantage in closing this gap (Zok, 2016).

For an elite athlete to succeed, the Director of Technology and Innovation at the United States Olympic Committee posits minimal mitigating differences separate medalists from non-medalists (Zok, 2016). As a result, using technology to enhance athlete performance is of increasing interest to many stakeholders. Wearable technology has emerged as an effective solution to process almost every point of information related to athletes' performances and to make adjustments that render a higher success rate. Considered a core ingredient in high-performing athletes' recipe for success, wearable technology allows them to use data as the guidepost for good performances (Zok, 2016). Wearable technology was born in the latter part of the Cold War as a byproduct of the global arms race (McCann et al., 2009). Initially, wearables were to be used at a military level; however, in the 1990s, the devices saturated the consumer and prosumer markets for health and fitness reasons, and remain technological weapons that support elite athletes in the so-called global arms race of sports (McCann et al., 2009).

Wearable technology consists of an electrical device that relies on high-quality sensors worn on or close to the body (McCann et al., 2009). Sensors convert physical or physiological information about the users into digestible information that can be read through numerical data (Chen et al., 2012). Wearables measure many types of data points by using different sensors and the internet of things (IoT) to cultivate information about the body, like speed, acceleration, heart rate, and temperature, among others (Swan, 2012). While there are a plethora of sensors on the market, they are typically classified as movement or physiological sensors (Li et al., 2016). Movement sensors aggregate data on physical characteristics of the body, such as speed or acceleration, and can be used to estimate energy expenditure with substantial merit (Li et al., 2016). Examples of motion sensors include accelerometers, gyroscopes, and Global Positioning Systems (GPS) (Cardinale & Varley, 2017). Physiological sensors examine an athlete's stress levels or optimal state of arousal by measuring heart rate, brain activity, or muscle tension (Cardinale & Varley, 2017; Chen et al., 2012). Sensors can work independently (e.g., heart rate monitors), but are more popular when combined to give a holistic view of the body (Cardinale & Varley, 2017). At the elite level, wearable technology is used for three primary reasons: to monitor performance, reduce injury, and enhance the efficiency of training. This technology is integrated into techniques such as load monitoring, biofeedback training, or virtual reality (VR) that help athletes receive better information about performance, in order to perfect their craft. Together, these technologies offer athletes the ability to achieve superior performance in this global sporting arms race.

The process of collecting information about the body's response to exercise is formally known as load monitoring (Bourdon et al., 2017). Load monitoring has become a standard practice in most professional sports and is widely adopted due to the advancements in wearable technology. Training load refers to the relative impact of training and involves manipulating variables such as intensity, duration, and frequency (Smith, 2003). The total load imposed on an athlete can be divided into two components that can be measured using wearable technology: internal and external loads (Cardinale & Varley, 2017). External load is the physical work completed by an athlete during exercise and typically requires motion sensors like GPS or accelerometers (Cardinale & Varley, 2017; Heishman et al., 2018). By contrast, the internal load is the physiological and psychological stress imposed during a workout (Cardinale & Varley, 2017). An athlete's internal load is often measured using electroencephalograms (EEG), electroencephalogram (EEG), electromyography (EMG) sensors.

Generally, findings reveal training load monitoring is valuable in assessing the training-recovery relationship, increasing the physical fitness of athletes, and providing greater insight into the athlete's relative training stress (Bourdon et al., 2017; Marlone et al., 2016). In the scientific community, it is generally agreed that external and internal loads should be used in an integrated approach, as this provides the most holistic view of the athlete (Cardinale & Varley, 2017). Nevertheless, many popular wearable devices on the market, such as Catapult, Zebra, KINEXON, Omegawave, GPEXE, and PolarPro, are limited to monitoring one aspect of an athlete's total load. For example, Catapult technologies use GPS to measure external parameters, while Omegawave uses heart rate and brain wave data to measure internal load. Some systems are designed to suit certain sports or demographics better. For example, KINEXON overcomes challenges in Wi-Fi and signal interference presented when measuring indoor activities, thus making it more popular among the NBA, NHL, and NCAA indoor sports. Comparatively, Catapult and Zebra technologies are popular among professional and college football teams because they capture high-speed player data in real-time. Regardless of the brand, all popular wearable monitoring systems allow athletes and trainers a non-invasive method of assessing athletes' load, so that experts can use data to make better decisions about training.

Load monitoring has also been critiqued for its information overload, where too much data too fast makes it difficult to understand (Halson et al., 2016). Biofeedback training draws from elements of load monitoring, but in a much slower manner, so athletes can understand how to manage their physiological state. Biofeedback training is particularly important when evaluating nonconscious physiological processes that affect athletes' performance, such as stress (Lehrer et al., 2007). When our minds perceive an arousing situation, our bodies think we are in danger and engages in a fight or flight response. As a result, we experience involuntary reactions, such as increased heart rate, blood pressure, electrodermal response, distributions in breathing, reduced brain functioning, or loss of attention (Lehrer et al., 2007). These involuntary bodily reactions can negatively affect athlete performance (Lehrer et al., 2007). Commonly used by sports psychologists, biofeedback training is a useful technique that helps high-performing athletes monitor physiological reactions in competitive scenarios and reflect on how to control them (Bar-Eli & Blumenstein, 2004). The technique has been used in preparation for the Olympic Games, with encouraging results (Pop-Jordanova & Demerdzieva, 2010). The process works by attaching multiple physiological sensors, like heart rate monitors, EMG, or EEG, to the body to measure the athlete's reaction to an arousing scenario (Bar-Eli & Blumenstein, 2004). The athlete learns how to apply cognitive strategies to control their body response. In sports, biofeedback training has been used in a variety of contexts, such as in treating competitive anxiety, reaching an optimal state of arousal, increasing performance, skill development, or reaction time (Bar-Eli & Blumenstein, 2004; Caird et al., 1999; Lagos et al., 2011; Paul & Garg, 2012).

Finally, an innovative application of wearable technology can be seen in VR. VR uses accelerometers, magnetometers, and gyroscopes to translate human movement into a virtual environment. Naturally, the more convincing the VR experience is to the users, the more representative their behaviors will be in the natural world (Craig, 2013). Mitigating the environmental discrepancies between training and competition allows athletes to manage the physiological and psychological stressors that arise when stakes are high (Akbaş et al., 2019). Moreover, VR can be used to manipulated single variables so athletes can practice skills training. As a result, VR has been adopted into various professional sports leagues to improve athletes' performance.

Theoretical Framework

Bandura's (1977, 1986, 1997) concept of self-efficacy was initially developed under the social cognitive theory as a clinical application to treat anxiety (Feltz et al., 2001). Since the inception of the self-efficacy theory, it has been widely received by sports psychologists as a useful framework to understand athlete performance and exercise behaviour (Feltz et al., 2001). Self-efficacy refers to one's belief that he or she can execute behaviors that will produce a desired effect (Bandura, 1977, 1986, 1997). It should be noted that self-efficacy does not refer to what has been done, such as winning a medal or scoring a goal, but rather, what one thinks they can do (Feltz et al., 2001). In sports, self-efficacy can best be described as confidence in a particular domain (Feltz et al., 2001). For example, a professional hockey player may feel confident in his/her ability to play a defensive role, but these skills do not generalize to other positions in the sport. Self-efficacy is a shared characteristic among high-performance athletes and is one of the most salient psychological predictors of performance (Watson et al., 2011). High self-efficacy influences how motivated an athlete is, how much effort they will put forth in the face of adversity, and how likely it is that they will attempt challenging tasks (Bandura, 1986). In contrast, those with a weak sense of self-efficacy avoid challenging tasks, focus on personal failings and negative outcomes, and quickly lose confidence in their abilities (Bandura, 1986). Studies show that self-efficacy is a highly influential factor in Olympic athletes, distinguishing gymnasts who made the US Olympic team from those who did not (Mahoney & Avener, 1977). Bandura notes four primary sources that can lead to the development of efficacious beliefs: enactive mastery experience, vicarious experience, verbal persuasion, and physiological or affective states management. Sources of self-efficacy are not mutually exclusive or weighted equally and tend to catalyze other sources.

Previous success or failure is the most influential predictor of efficacious beliefs because it is based on one's own mastery experience (Bandura, 1997; Feltz et al., 2001). The excitement of winning triggers the release of testosterone in the brain and causes the athlete to become more motivated and aggressive, thus creating a phenomenon called the 'winning effect,' which suggests previous success breeds future success (Robertson, 2017). Likewise, a failed or inferior performance can equally cause a loss in self-efficacy, resulting in subsequent negative performances. Bandura (1977) notes that not all success is created equal. The amount of self-efficacy is dependent on the athlete's motivation, task difficulty, guidance, and previous success or failure (Bandura, 1986; Feltz et al., 2001). Tasks that are easily achieved, done without external guidance, and accomplished with minimal errors render more value than tasks that are easily accomplished, done with external guidance, or are repeatedly failed (Bandura, 1997; Feltz et al., 2001). Thus, victories that challenge the athlete and require some level of self-direction result in higher levels of self-efficacy (Bandura, 1986; Feltz et al., 2001). While mastery experiences, such as winning and losing, cannot be controlled in sports, three other sources of self-efficacy can; these are vicarious experiences, persuasive techniques, and physiological or affective states management (Feltz et al., 2001).

Verbal persuasion, another source of self-efficacy, can be obtained through what one says to themselves, as well as the performance evaluation of others (Bandura, 1997). Evaluations from others tend to be more effective when it comes from a credible source, such as a coach or teammate, as these evaluations are supported by a deeper level of knowledge (Feltz et al., 2001). The US Olympic team noted that their coaches' efficacy expectations were vital in enhancing the athlete's performance (Gould et al., 1999). Feltz (2001) notes that a well-respected team captain can lift the spirits of a team or, by contrast, belittle the group. These experiences can narrate what one thinks they can or cannot do. While verbal persuasion contributes to self-efficacy, Bandura (1977) notes that it is only as impactful as the individual's level of self-confidence. As it appears, evaluative feedback is particularly influential in less experienced athletes who may rely on external judgment to develop their own beliefs (Feltz et al., 2001). By contrast, elite athletes have a stronger level of confidence in their abilities and are less swayed by external judgments.

Arguably, an elite athlete's own self-evaluation is a stronger source of efficacy than external evaluations. This is particularly important when considering the average individual has 50,000 thoughts on a given day (Canfield, 1990). This internal dialogue is considered one's self-talk, which can be negative or positive, and reciprocally contribute to an athlete's self-efficacy. Positive self-talk reduces somatic anxiety and heightens self-confidence, self-optimization, self-efficacy, and performance in athletes (Walter et al., 2019). Research demonstrates that successful Olympic athletes spend a considerable amount of time practicing mental training and cognitive strategies so that this internal dialogue can be positive (Gould & Maynard, 2009). Moreover, self-talk emerged as the most significant contributor that separated medalists from non-medalists in the 2000 Sydney Olympic games (Taylor et al., 2008).

Self-efficacy can also be obtained by vicarious experiences (modeling and imagery), where an athlete watches a behavior and appraises their abilities in relation to it (Feltz et al., 2001). The relative intensity of the vicarious experience is governed by social comparison, the perceived failure of the model, and the beliefs about one's own abilities (Feltz et al., 2001). For example, if one observes someone with similar abilities successfully perform a task, they are more likely to think they can execute it as well. Because of this, modeling procedures may be more valuable in team sports where the members are in a relatively similar skill category; however, in individual sports, this might be evaluated through opponents' performance.

A particularly influential source of modeling is self-modeling, where an athlete observes all the best parts of their performance (Feltz et al., 2001). Video self-modeling (VSM) is the most widely adopted modality in sports training and has a positive relationship with self-efficacy (Dowrick, 2012; Jennings et al., 2013). VSM was influential in Olympic gold medalist Laura Wilkinson's pre-game preparation. In Ste-Marie et al. (2011) research study, gymnasts used VSM strategies to attain significantly higher beam scores and higher self-efficacy measures. In football, VSM helps athletes learn to adapt effective behaviors in high-pressure situations (Middlemas & Harwood, 2019).

Additionally, athletes can practice imagery, visualizing the skill they are executing while engaging their various senses, which also encourages self-efficacy. For example, a hockey goalie might use effective imagery to see the opponent wind up a shot (visual), engage his/her muscles to prepare for a save (kinesthetic), and hear the blade of the stick smack the puck (auditory), all in the absence of real sensory stimuli (Weinberg, 2008). The more vivid the image, the more likely the brain will interpret it as a real stimulus experience (Weinberg, 2008). Imagery has positive effects on athletes' self-efficacy because it can create feelings of competency and success, reduce competitive anxiety, and help athletes see arousal as facilitative rather than debilitative (Weinberg, 2008).

Self-efficacy can also be obtained through assessing and regulating the body's physiological state. The athlete's state of arousal can provide information about their emotions, fatigue, or fitness level, or how excited or scared they are to perform (Feltz et al., 2001). This is said to be particularly influential in sports, as the body's reaction can tell a lot about the athlete's state of readiness (Feltz et al., 2001). Of particular interest to athletes is the physiological arousal in response to competitive scenarios. How the individual appraises stress is related to their self-efficacy, with those who score higher on self-efficacy, interpreting stress as a protagonist rather than an antagonist (Humara, 1999; Paul & Garg, 2012). Self-efficacy obtained through physiological or affective states management is the primary mechanism that guards against the adverse effects of competitive anxiety (Humara, 1999). Several cognitive strategies, such as positive self-talk or breathing and relaxation techniques, can be utilized so the body optimally responds to elevated arousal levels (Robertson, 2017). In contrast, if an athlete cannot self-regulate in highly arousing situations, like the Olympic Games, they may interpret their physiological state as a lack of ability that can undermine their self-efficacy. Consequently, athletes strive to understand their optimal performance zone and maintain this level, which can have energizing and performance-enhancing effects and positively influence self-efficacy (Stinson & Bowman, 2014).

Self-efficacy is arguably the secret weapon of success for an elite athlete. It is one attribute that is consistently associated with great performances (Gould & Maynard, 2009). While world champions tend to look the part - strong, fast, nimble - we often do not understand the mental components that lead to their success. Some athletes fail to reach performance expectations due to the psychological demands of the sport. Certainly, there is a glass ceiling on sports performance, in that the athlete's physical abilities can only take athletes so far, but the mental component can give them an edge. Self-efficacy is among the most powerful mental agents to aid in successful performance (Feltz et al., 2001). Bandura notes that self-efficacy influences an athlete's confidence, motivation, and the amount of effort he or she is willing to put forth in the face of adversity (Bandura, 1997). In a sports culture that demands excellence, self-efficacy is an important characteristic that can provide a competitive edge.

Overall, self-efficacy is built on the belief that one can successfully perform a task (Bandura, 1997; Feltz et al., 2001). While past performance is thought to be the most influential source of efficacy, it cannot be readily controlled (Bandura, 1997). Thus, physiological mechanisms and cognitive appraisal allow athletes to build self-efficacy on their own. Self-efficacy is not static, but rather, it can change from moment to moment and requires an athlete to use feedback to respond and demonstrate self-regulation appropriately.

Characteristics of elite athletes

Top-performing athletes are generally defined by their high levels of physical fitness, natural endowment, and technical motor ability (van Rossum, 1996). Athletes spend years training in their sport before reaching the highest level. Studies show that it takes 10-years of deliberate practice to perform at an international level (Ericsson et al., 1993). Genetic traits play a significant role in physiological and anatomical factors, such as muscle fiber types, height, bone density, and collective are outside the athlete's control (Smith, 2003). However, within an athletes' control is their commitment to training, which is said to account for half of their success. With a highly developed work ethic, elite athletes can modify their bodies with physical training (Smith, 2003). Of course, training is relatively domain-specific, with different variables such as speed, endurance, coordination, and strength influencing one's success (Smith, 2003). For endurance sports, elite athletes have a higher anaerobic threshold, running economy, and maximum oxygen uptake. In contrast, court sports (e.g., basketball, hockey) place a higher value on maximal power output (Lorenz et al., 2013). Most athletes develop sport-specific characteristics, such as strength for weightlifters, speed for tracker runner, and endurance in marathon runners (Smith, 2003). The athlete's physical ability is hugely important to their success; however, differences in physical skill among high-performing athletes are so minimal that the psychological component makes the difference in winning and losing (van Rossum, 1996).

Athletes do not question the relevance of psychological factors. For example, baseball player Yogi Berra is famous for saying: "Baseball is 90 percent mental, the other half is physical." Successful athletes have a high level of self-efficacy, are highly motivated, goal orientated, more resilient, competitive, and have a strong mental toughness (Gould & Maynard, 2009; Greenleaf et al., 2001; van Rossum, 1996). One of the most consistent findings of these underlying psychological characteristics is the connection between self-efficacy and positive sports performance (Feltz, 1988; Watson et al., 2011). Top athletes have identified self-efficacy as the defining factor influencing their game, separating gymnasts who made the US Olympic team from those who didn't, and characterizing athletes performing in the Nagano Olympic games (Feltz et al., 2001; Gould & Maynard, 2009; Mahoney & Avener, 1977).

As seen through a self-efficacy theory lens, the purpose of this narrative review is to explore the use of wearable technology in elite athletes and its effect on performance. Specifically, (a) the major types of wearable technology used by athletes; (b) how wearable technology may affect performance; and (c) trends and gaps in the field. By exploring previous literature addressing the use of wearable technology within the context of sports, this paper seeks to understand how this technology is used to support elite athletes' success and development.

Methods

A literature search was conducted using the databases ProQuest and Scopus. The following search terms were included in the initial search: "sport psychology," "sport technology," "wearable Technology," In combination with a Boolean search all the search terms included: ("Sport Psychology" AND "Technology"), ("Sport Psychology" AND "Wearable Technology"), ("Sport Psychology" AND "Athlete Performance"), ("External" AND "Internal load"), ("Sports Technique"), ("Sport psychology"), ("Sport technology"), ("Wearable technology"), ("Sport Performance" AND "Internal load"), ("Sport performance" AND "External load"), ("Technology" AND "Sport training"), ("Innovation" AND "Sport"), ("Technology" AND "athlete performance"), ("Wearable technology" AND "Athlete performance").

To meet inclusion criteria, articles needed to be peer-reviewed, published between January 1, 2010, and May 30, 2020, and written in the English language. Though warble technology has been around since the 70s, the last ten years have seen major shifts in both form factor and application of the device. As a result, reviewing articles published in this time frame was important.

Collectively, the initial search yielded 14,635 results. Articles were organized based on relevance deemed by the database. The first 200 articles of each individual search were screened based on titles and abstracts, and 67 articles (35 from Scopus and 32 from ProQuest) were selected. Eligible articles included in the first pass of the selection process revealed two results duplicated in the databases, resulting in a total of 65 different sources to review. With the assistance of an expert researcher - titles and abstracts were assessed for relevancy, and twenty articles were eliminated from the list, yielding 45 articles that met the inclusion criteria and needs for this review. All reference lists of included articles were scanned, and 38 eligible articles were included for review. Three major themes were identified in the literature search: load monitoring, virtual reality, and biofeedback. A detailed table indicating all studies included in this review is listed in Table 1.

Discussion

The following discussion explores research studies presenting findings from the major themes: biofeedback, load monitoring, and virtual reality. The discussion outlines the primary applications of the technology as it is used to support athletes in various aspects of training and performance. First, the discussion will start with an initial overview of the technology followed by a literature review on applications within the context of sports.

Virtual reality

VR is a computer-generated visual simulation system that tricks the human brains' coding mechanisms into thinking the users are interacting in real three-dimensional space (Akbaş et al., 2019). The technology relies on electronic equipment such as a virtual reality headset and haptic suits/gloves to translate physical movement into the virtual environment. VR has been used to support various applications, including military, education, health, gaming, and sports (Akbaş et al., 2019). Using VR in the context of sports offers several advantages over real-world training. Athletes can practice infinite repetitions in a space that can be manipulated to account for a single variable that cannot be in the real world (Bideau et al., 2004). The scalability of VR allows for customizable experiences that can be used in almost every sport, with the high levels of immersion making VR an excellent learning tool for skill development, and valid enough to translate performance improvements into the real-world. For this review, we identify two categories of engagement with VR in elite athletes that can be separated into 'doing' and 'observing' methods. Doing experiences allows athletes to interact with the environments while observing experiences allows them to conceptualize the game in a highly immersive environment.

Doing experiences in VR

Several studies have found that VR in sports training provides immersive environments positively correlated with better training outcomes (Craig, 2013; IJsselsteijn et al., 2004). For example, IJsselsteijn and colleagues (2004) explored how various immersion levels in a virtual environment (VE) could impact 24 inactive participants' motivation. In this study, participants were randomly assigned to either a highly immersive condition or low immersive condition. Participants in the highly immersive group performed a cycling task from an egocentric viewpoint, whereas the low immersion condition performed the same task from a birds-eye view. Results indicated that cycling in more immersive environments resulted in higher motivation and faster cycling speed. The quote "we must perceive in order to move but we must also move in order to perceive" Gibson (1979), could not be truer. The level of perceived presence within an environment, as seen by egocentric conditions, affects the level of engagement an athlete is willing to put forth. When applying IJsselsteijn's and colleagues' (2004) results to elite athletes, it can be assumed that VR is more beneficial than traditional video analysis methods, which are limited by a fixed viewpoint (Craig, 2013). These findings indicate that VR invokes a higher motivation, more significant learning outcomes, and a more competitive response when acting in environments that feel true to the real world. Thus, the more convincing the VR experience is to the users, the more representative their behaviors will be in the natural world (Craig, 2013).

Engaging in physical tasks in a virtual environment is somewhat limited due to the constraints of the device, which makes it particularly valuable in sports that require repetitive motions such as baseball, darts, cycling, rowing, or table tennis (Gray, 2017; Michalski et al., 2019; Murray et al., 2016; Tirp et al., n.d.). Despite the physical limitations of VR, all sports benefit from technical skill development which can be practiced in VR. It has been suggested that efficacy in a skill is related to high levels of accuracy, repeatable outcomes, high-performance measures, minimal exhalation, reaching automatic performance, and an appropriate level of flexibility in adapting to various conditions (e.g., competition) (Bakit & Mohamed, 2011). In this respect, VR training posits several advantages to real-world training, primarily the ability to control single variables that affect performance outcomes (Akbaş et al., 2019).

For example, Hoffmann and colleagues (2014) explored how VR could be used to facilitate a better pace strategy in 15 novice rowers. Rowers were randomly assigned to a control group or avatar group. The avatar group benefited from a VR simulated virtual opponent who set an optimal pace for a 2000-meter row. In contrast, the control group did not observe the virtual boat and consequently adopted spontaneous row behavior during the training period. After 8 training sessions, both groups performed a 2000-meter rowing race without the assistance of a virtual avatar. Results indicated that the control and avatar group adopted district row behavior after the initial training. Those who used the virtual boat as a reference point for pace had better pace, reduced race duration, and better performance than the control. The study indicates that VR is a useful space to develop facilitative skills that can transfer to events in the real world.

Bideau and colleagues (2010) identified that small subtitles in visual information could affect an elite athlete's reaction. Isolating these visual components and examining anticipatory behaviors is relatively limited in traditional video analysis due to low immersion levels. VR overcomes these limitations as it accounts for the biomechanical, physiological, and psychological factors that affect performance during competition. As a result, VR gives a better indication of a player's perception-action loop. Exploring two case studies, Bideau et al. (2010) demonstrated that VR could inform a player's course of action in perception-action and deceptive tasks. Moreover, VR could be used to control visual information and manipulate ques (e.g., an athlete's hip rotation) that would otherwise be impossible to control in the real world. Thus, the benefits of computer-generated visual environments allow athletes to practice infinite repetitions in a space that can be manipulated and controlled.

Bibeau and colleagues' (2010) study is particularly useful when isolating competitive differences between athletes in elite sports. Striva is an industry leader in athletic VR, supporting members of the National Football League (NFL), the US Olympic Ski and snowboarding team, and others. The system uses real players and playbooks to isolate for competitive differences, such as Clayton Kershaw curveball that holds opponents to a 0.134 batting average. Consequently, Striva provides a unique opportunity for elite athletes to simulate conditions they may experience in a game and focus on the patterns they need to execute challenging tasks successfully (MLB.com). Several other studies demonstrate the effectiveness of VR in skill and performance acquisition, such as optimizing basketball free throws or rowing skills and pace strategy (Covaci et al., 2012; Hoffmann et al., 2014). These studies indicate the ability of VR to simulate optimal performance and clarify skills before facing a high steak task (Bakit & Mohamed, 2011).

VR has been used to recreate stress eliciting situations that draw attention away from the physical tasks, such as those felt in high-pressure competitive situations (Argelaguet Sanz et al., 2015). The impact of pressure in a competition can affect the ability of an athlete to execute superior performance and lead to the perception of increased heart rate, blood pressure, electrodermal response, distributions in breathing, reduced brain functioning, or loss of attention, resulting in competitive anxiety (Argelaguet Sanz et al., 2015; Lehrer et al., 2007). While these reactions vary depending on personal characteristics, such as individual trait anxiety, self-regulation, or perceived expectations, they generally can result in a negative relationship to performance (Argelaguet Sanz et al., 2015; Lehrer et al., 2007). Thus, VR's applications in recreating competitive scenarios to treat competitive anxiety is a valuable training resource.

Stinson and Bowman (2014) tested whether high fidelity VR could be used to induce anxiety in soccer goalkeepers. Twenty-eight participants from the university were presented with two levels of stimulation, the low stimulation condition consisted of a field, net, ball, and kicker, while the high stimulation condition included the low stimulation conditions as well as a stadium, crowd, scoreboard, teammates, opponents, and referees. Heart rate (HR), heart rate variability (HRV), and galvanic skin response (GRS) were used to measure athlete's anxiety levels in response to the stimulation conditions. Their results revealed an interaction between the athlete's trait anxiety and the stimulation level of the experience, suggesting a multifaceted relationship between competitive anxiety. Additionally, this study shows a practical methodology for introducing competitive anxiety and pressure in VR sports training, which could be used to develop optimal self-regulation skills in preparation for high steak games.

The application of Stinson and Bowman's (2014) work can be seen in Lagos's (2011) study that proposed a novel way for treating competitive anxiety using VR and heart rate variability (HRV) biofeedback training (BFB). In this case study, HRV was used as the measure to estimate a golfer's reaction to a competitive scenario. High HRV represents a flexible automatic nervous system that can adapt to environmental conditions and is positively correlated with performance. Three weeks of HRV BFB training were completed before transferring the learned regulatory skills into a virtual reality golf course. After a total of 10 weeks of training, the golfer was able to significantly lower her heart rate and increase performance on the VR golf simulation, shaving 16 strokes off her initial game. The study indicates how VR can be used to mimic competitive scenarios where athletes can practice various regulatory skills. In doing so, self-regulation skills can be optimized, and performance can be improved.

Observing experiences in VR

While learning in VR can be done through 'doing' as shown in the above discussion, it can also be done by observing.' This is important as it applies to athletes because some sports present too many technical challenges to recreate 'doing experiences, 'however, they still can benefit from passively viewing the skill (Michalski et al., 2019). This form of learning is utilized in video-based feedback; however, due to the high levels of immersion and presence, VR is hypothesized to be a better training tool than conventional video training (Michalski et al., 2019; Witmer and Singer, 1998).

Bakit & Mohamed (2011) explored the effectiveness of VR in improving young hurdlers' skills and performance through highly immersive observational learning. The pre- and post-test analyses measured the record level of hurdlers in a 60 meters race using video analysis. In hurdling, record level refers to the clearance distance between the athlete and the hurdle. In general, young hurdlers tend to approach hurdles with apprehension and tension and compensate by going to extreme lengths to clear the height of the hurdle, contributing to slower performance times (Bakit & Mohamed, 2011). Participating in an immersive VR training over 15 days, hurdlers experienced an increase in their performance levels and decreased record levels. These results demonstrate how training with VR can assist athletes in conceptualizing kinetic skills needed for optimal performance. This method was also found to reduce the hurdles fear and apprehension and enhance their confidence when approaching a hurdle so that they did not overshoot the hurdle and reduce race time.

As athletes feel more immersed in an experience, they will better understand all pathways for action - making virtual reality an appealing means of preparing for cognitively demanding sports (Kulpa et al., 2013). This is vital in the mental preparation needed in sports, especially for player positions that require a high level of mental focus and strategy. VR has a wide range of uses, including allowing athletes to run through plays, prepare for opponents' offensive strategy, or anticipate opportunities for quarterbacks. Being fully immersed in possible game-time scenarios allows athletes to better focus on the mental component of the game rather than the physical. In particular, various NFL teams like the Dallas Cowboys, New England Patriots, and San Francisco 49ers, as well as collegiate players, benefit from training with VR.

VR and Self-efficacy

As stated, athletes use VR in various applications such as skills training, psychological preparation, and strategy, but engage with this tool by performing a task or observing a task. By doing so, they are also positioned to produce verbal persuasion, vicarious experience, physiological and emotional arousal, key sources of self-efficacy, as well as, establish a positive past performance. It should be noted that directly performing a task in a VE will not bring about the same mastery experiences as directly performing a task in the real world (Loke, 2015). However, efficacy in a skill is related to high levels of accuracy, repeatable outcomes, high-performance measures, minimal exhaustion, reaching automatic performance, and an appropriate level of flexibility in adapting to various conditions (e.g., competition) (Bakit & Mohamed, 2011). In this respect, VR training has significant advantages to the development of skill efficacy as the environment can be highly manipulated, and athletes can practice an infinite number of repetitions. For example, successfully batting a simulated version of Clayton Kershaw curveball may influence the athlete's confidence when batting against Kershaw during a game.

Athletes realizing they can successfully perform a skill in VR may begin to engage in positive self-talk or other persuasive strategies.

In sports, modeling is traditionally done through video analysis, whereby the best parts of one's performance are sequenced together (Ste-Marie et al., 2011). Though video modeling appears to be influential in sports performance, it is limited in the single viewpoint – making the educational value of this method less effective than a more immersive vehicle (Oliver Farley et al., 2019; Witmer & Singer, 1998). It has been well documented that immersion and presence influence one's eagerness and motivation to learn, thus contributing to more powerful learning outcomes (Witmer & Singer, 1998). As suggested by Bakit & Mohamed (2011), VR is a preferred educational channel due to the highly immersive vicarious experiences. The ability to use VE to stimulate vicarious observational experiences in sports has proven to be successful in studies mentioned above, such as the case for young hurdles (Bakit & Mohamed, 2011). In this study, it was found that higher immersion levels in VE resulted in a clear kinetic conceptualization of the athlete's skills, contributing to better performance outcomes (Bakit & Mohamed, 2011).

Vicarious experiences can also be obtained through self-modeling, whereby an individual gains efficacious information through the observations of themselves. Using VR can provide a unique clear conceptualization of their performance (Bakit & Mohamed, 2011). The opportunity for higher immersion and presence in VR makes it a particularly useful learning environment. In professional football, these techniques have been used to produce adaptive behavior responses for quarterbacks who need to be fully immersed in an environment to understand all potential pathways of action, in doing so, the athletes gain confidence.

VR can be used to induce physiological arousal similar to that experienced during a real game. Thus, athletes can use VR to practice self-regulation strategies and obtain self-efficacy through better arousal management techniques. Striving to maintain optimal levels of arousal in VR can translate to more effective techniques in real life.

VR offers a similar experience to that produced when athletes practice effective imagery. Imagery has been described as a multisensory experience that occurs in the absence of sensory stimuli but feels similar to the actual event (T. Morris et al., 2005). Imagery can trigger physiological responses such as the heart rate and muscle tension as if the individual was really experiencing the event (T. Morris et al., 2005). The power of imagery is unquestioned, and it has been said that almost all elite athletes intentionally employ imagery to aid their performance (T. Morris et al., 2005). Like VR, imagery offers the ability to engage all five senses. The more vivid the image, the more likely the brain will interpret the imaged as a real stimulus experience (Weinberg, 2008). Imagery has positive effects on athletes' self-efficacy because it can create feelings of competency and success, reduce competitive anxiety, and help athletes see arousal as facilitative rather than debilitative (Weinberg, 2008). Some sports teams have incorporated virtual reality-assisted imagery, which uses auditory cues and visual information to aid in the acquisition of imagery skills and build confidence during practice and games. Though no studies to date investigate the relationship between athletes, VR, and self-efficacy, others have demonstrated the ability to use VR to induce self-efficacy in student teachers (Nissim & Weissblueth, 2017).

Load Monitoring

In response to the increasing demands of professional sports, most athletes and trainers have developed a considerable interest in a more robust scientific approach to training (Hamlin et al., 2019). Wearable activity trackers provide an opportunity to approach training through a scientific framework without being limited to laboratory-based methods (Kiernan et al., 2018). Wearable athlete monitoring systems have been developed to scientifically assess the load imposed on an athlete during a workout (Hamlin et al., 2019). Training load refers to the relative impact of training and involves manipulating variables such as intensity, duration, and frequency (Smith, 2003). The total load imposed on an athlete can be divided into two components that could be measured using wearable technology: internal and external loads. External load monitoring can be defined as work completed by the athlete, including duration, speed, power, acceleration, and distance covered, among others (Cardinale & Varley, 2017; Heishman et al., 2018). Internal load monitoring is defined as the physiological and psychological stress felt by an athlete during training (Cardinale & Varley, 2017).

Applying a load monitoring approach to training helps in the development of individualized programs. That way, athletes can increase the efficiency of training while also minimizing the harm done by overexerting (Hamlin et al., 2019). For example, two players can have the same physiological load but can show different physiological intensities, indicating that one player is achieving the same results with less effort (Zedeh et al., 2020). In recent years, the increasing availability of wearable technology has made monitoring training load accessible during practice and games. Moreover, athlete data can be communicated to coaches or trainers in real-time, so that changes can be made from moment to moment. GPS and inertial sensors, such as accelerometers, are commonly used to quantify an athlete's external load, while cardiovascular and respiratory measurements, such as heart rate, can gauge one's internal demands (Cardinale & Varley, 2017; Heishman et al., 2019). There are currently several companies that professional teams and athletes use, due to their ability to produce technologies capable of informing athletes of their relative training load. Like VR they include Catapult, KINEXON, GPEXE, Polar USA, and Omegawave.

Subjective appraisal of performance may result in a disconnect between the coach and the athlete's perceived level of exertion. Murphy (2015) studied the discrepancies between athletes' and coaches' perceptions of training load (internal and external) during on-court training sessions. Fourteen high-performance junior elite tennis players and six qualified coaches who worked with the athletes were recruited for the study. Over 16 weeks, external and internal load data was collected during the training sessions to measure the athletes' rating of exertion. After each session, coaches and athletes were asked to report their perceptions of the number of shots and errors, rating of perceived exertion (using Borg scale), and mental exertion. Results indicated that perceptions between coaches and athletes were strongly correlated with perceived shots of error and mental exertions. However, coaches significantly underestimated both the self-report and objective analysis of the athlete's rating of perceived exertion. This study shows that without an objective appraisal, athletes are coaches are subject to bias views of performance. The coaches' underestimate of the athlete's load may mislead them to prescribe inappropriate training levels and increase the risk of injury. The study highlights the risks that are associated when prescribing training through subjective analysis only. Even using credible measures such as the Borg scale to estimate the rating of perceived exertion does not necessarily provide an accurate method of establishing good training protocols. Subject measures in performance may facilitate negative behaviors that undermine an athlete's performance. Objective observation through wearable technology is important in connecting athletes and coaches through empirical data so that feedback can be constructive, and training error can be minimized.

The importance of objective analysis is further explored in Kiernan and colleagues' (2018) study, who examined how accelerometer-based wearable devices could predict running-related injury in national collegiate track athletes. Over 60 days, nine collegiate athletes wore a hip-mounted activity tracker to estimate the athlete's number of strides, weighted cumulative load, and vertical ground reaction force. Data was collected during 60-days of the track and field season, and coaches provided training prescriptions based on each athlete's optimal training factors. After each training session, athletes reported their overall pain and fatigue. The subject measures of pain and fatigue did not predict the athlete's running-related injury; however, objective measures such as high load magnitude repeatedly applied increased their risk. The study illustrates the need for objective measures to better-quantifying athletes' risk of injury as subjective measures alone cannot sufficiently predict injury. Arguably, load monitoring offers objective data related to athletes' relative risk of injury and can allow trainers, coaches, and athletes to evaluate these risks in real-time to buffer against potential injury.

Additionally, training load monitoring provides a performance advantage as it relates to assessing the athlete's stress-exercise relationship. When stress overloads an athlete, through psychological or physical means, the opportunity for negative performance effects increases, as does the risk of injury (Smith, 2003). Stress can plague the muscles with tension, which results in a lack of flexibility and motor coordination (Smith, 2003). Thus, internal and external load monitoring assists athletes in establishing a functional state to perform. Morris (2015) explored how wearable technology could be used to estimate these stress levels and establish when an athlete will perform best. 59 D-1 American football players were recruited to participate in the study. Each participant was measured using Omegawave wearable technology to gauge the athlete's functional state of readiness, providing an index of the body's relative stress levels and an estimate of which arousal levels resulted in the most optimal performance states (Morris, 2015). Athletes were randomly assigned to the control group (n=28) or the experimental group (n=31). Both groups participated in an 8-week training intervention using the same program workouts, however, athletes in the treatment group used Omegawave assessment to modify the relative intensities of exercises. Modifications based on Omegawave assessment were utilized in resistance training exercises such as Olympic lifts and other high central nervous system tasks. Performance outcomes were measured using various skill tests such as a vertical jump test, ball overhead throw, and tempo test. In response to the Omegawave assessments of the experimental group, athletes reduced the amount of time spent on resistance training. Consequently, performance measures such as vertical jump, vertical power, broad jump, and aerobic efficiency were significantly improved compared to the control group. The study indicates the benefits of using wearable systems, such as the Omegawave device that can guide athletes' strategic training and, consequently, enhance performance. Nevertheless, it is important to consider how experts interpret this data as these individuals need a strong understanding of what the values mean to prescribe appropriate loads.

Heishman and colleagues (2018) conducted a similar study that used Catapult and Omegawave wearable technologies to measure an athlete's external and internal loads to optimize performance patterns in 10 elite NCAA basketball players. Omegawave technology measured HRV and brain activity to assess the athlete's internal stress, readiness to perform, and neurological function. In contrast, the Catapult system measured the athlete's player load using a triaxial accelerometer. Data was collected using these systems for 5 weeks during preseason training with 8 hours per week allotted to strength and condition and 3 hours per week for basketball-related activities. Athletes were evaluated on their functional state of readiness using the Omegawave system prior to strength and conditioning sessions, with a higher score (scale of 1-7) reflecting a better functional state to perform. During basketball-related activities, athletes wore a heart rate monitor to measure their internal stress and intensity, and a Catapult sensor to measure the player load. Subjects performance measures were evaluated 3 times a week using a vertical jump test. Results indicated that higher functional state of readiness scores on the Omegawave test resulted in significantly better results on the vertical jump test. In contrast, higher player load as measured by the Catapult system resulted in lower jump scores on the performance test. These findings suggest a significant relationship between training and recovery, as overexerting the day before resulted in inferior performance measures. Thus, wearable systems can be used to evaluate athletes based on internal and external loads and, subsequently, tailor training prescriptions to ensure the players perform at optimal levels. However, this data is only as effective as what the trainers do with it. Without a thorough understanding of how load affects performance, load monitoring may be ineffective.

Using wearable technology can help athletes and coaches better understand the relationship between internal and external loads to reduce the risk of injury. Today, innovative methods of using wearable technology prove its effectiveness in predicting injury so athletes can stay focused, and professional sports leagues can avoid costly mistakes (Marlone et al., 2016) (Alistair et al., 2015). Zadeh and colleagues (2020) explored if the Zephyr BioHarness could accurately predict injury. Thirty-one male cadets used the system for 12 weeks. The device recorded EEG, respiration, accelerometry, time and location, and the software interpreted HR, breathing rate, peak force explosiveness, HR confidence, core body temp, and others. Seventy potential markers from the Zephyr BioHarness were used to generate a subject's potential risk of getting injured. Throughout the data collection period, a total of 16 cadets suffered multiple injuries. The study found that high body mass index and high mechanical load could predict which individuals were at high risk of injury. In sports, injury prevention is critical as it minimizes the time spent training and creates costly mistakes for professional sports leagues (Marlone et al., 2016) (Alistair et al., 2015). Using wearable systems provides a method to assess when an athlete is experiencing too much physical, mechanical, or mental stress, which decreased performance, increases the risk of injury, and results in less available mental resources. In monitoring these values, training can minimize injury and maximize performance to get the most out of their athletes.

These studies collectively demonstrate the ability of wearable technology to assess one's internal and external demands noninvasively. In doing so, wearables provide an objective appraisal of an individual's load, assessing when the athlete is subject to much mechanical or mental stress. When athlete monitoring is applied correctly, the training recovery relationship can optimize performance outputs so that an athlete can achieve optimal results and minimize the risk of injury (Heishman et al., 2018; Morris, 2015). However, a wearable monitoring system has been critiqued for a data overload, whereby too much data makes it difficult to understand. The effectiveness of these tools is only as valuable as how they are interpreted and applied. Without a good understanding of how load affects the body, wearable technology can be ineffective or counterproductive.

Load monitoring and self-efficacy

A crucial aspect of the development of self-efficacy is how challenged an individual is by a task. If one's skills do not match a challenge, it may generate doubt or uncertainty in their ability (Feltz et al., 2001; Sklett et al., 2018). In contrast, if the task is not stimulating enough, and the individual exceeds expectations, they may become disinterested or bored from the task

(Feltz et al., 2001; Sklett et al., 2018). The task difficult affects one self-efficacy, with tasks that are too difficult and unmanageable, undermining one's self-efficacy (Feltz et al., 2001; Sklett et al., 2018). Thus, establishing a task that is not too easy nor too difficult yet challenging enough that one knows they need to be physically and mentally engaged to master it (Sklett et al., 2018). In this case, load monitoring allows trainers to develop plans that will provide an appropriate amount of challenge in a session.

In sports, tasks that are too challenging may lead to fatigue, overexertion, or anxiety, which are coded as negative affective states. The body's physiological reaction to a task (eg., workout, practice, game) can lead to thinking the experience was too challenging and unachievable. Thus, the physiological reaction one has to a task is an important source of self-efficacy (Feltz et al., 2001). Several hypotheses are used to support athletes' efficacious gains experienced during training. According to the aerobic power hypothesis, self-efficacy measures should correlate with one's aerobic gains during training, whereby seasonal progression leads to higher levels of fitness and more self-efficacy in one's ability to compete (Maddux, 1995). Consequently, good training should not only develop once physical ability but also lead to a higher level of confidence in their capacity to outperform opponents. Therefore, load monitoring is important to systematically tailor load for each individual athlete needs and fitness level, so the load does not overexert their bodies and lead to doubt in their abilities

The psychological expectancy theory suggests that exercise bouts should correlate with notable changes that the athlete could observe, such as better distance-time measure, higher acceleration, or more endurance (Maddux, 1995). At the elite level, annual within athlete differences are lower than variation in the general public, so making small incremental performance changes is pivotal in the success of an athlete's career (Haugen et al., 2019). Using load monitoring to evaluate performance and monitor improvements throughout the season may make an athlete engage in positive self-talk, an influential ingredient in forming one's self-efficacy.

Collectively, objective appraisals through load monitoring can create training prescriptions that induce an appropriate level of challenge, create positive physiological states, and allow athletes to observe their progress, which facilitates persuasive techniques like self-talk.

Biofeedback

Biofeedback training is a technique for gaining control of self-regulation, based on information or feedback received from the athlete's body and mind (Blumenstein & Orbach, 2014). The most fundamental part of biofeedback training is the use of sensors and transducers to provide insight into how the body reacts to external events (Bar-Eli et al., 2002). Several biofeedback modalities are used to measure information about the athlete's internal state, such as heart rate (HR), muscle tension (EMG), brain activity, galvanic skin response (GRS), and electrographs (EEG) (Blumenstein & Orbach, 2014). Several programs have been developed using a combination of these modalities. For example, regulating cortical activity for sports that require much mental focus relies on EEG feedback (Blumenstein & Orbach, 2014). Conversely, motor performance skills, such as those needed in gymnastics or swimming, utilize EMG, GSR, or HR (Blumenstein & Orbach, 2014). Finally, psychological skills training is the most widely adopted use of biofeedback, which relies on EEG, EMG, and GSR (Blumenstein & Orbach, 2014). These modalities are often used in conjunction with training programs, such as the Wingate five-step approach, psychosocial skills training, or heart rate variability biofeedback training (Blumenstein & Orbach, 2014). The main objective of these programs is to regulate various mechanisms of the body better.

At an elite level, physical, technical, and tactile abilities are relatively equal across athletes, and it is the mental component that distinguishes those who succeed. The benefit of strong psychological qualities in top-level sports is not questioned, especially considering the immersible demands placed on an athlete. Biofeedback training has been widely adopted to assist elite athletes in regulating arousal to achieve optimal psychological performance states, which is especially useful in high-pressure times such as competition. At these times, many athletes suffer from competitive anxiety, which has inverse effects on performance. Athletes underperform and make poor decisions when they experience too much anxious arousal but become disinterested and de-energized when there is not enough (Stinson & Bowman, 2014). Consequently, athletes strive to maintain optimal levels of anxiety, which can have energizing and performance-enhancing effects (Stinson & Bowman, 2014).

Managing adverse effects of competitive anxiety were explored in Paul & Garg's (2012) study that examined how biofeedback training could be used to regulate physiological arousal in anxious athletes. In this study, heart rate variability (HRV) biofeedback (BFB) training was used to enhance the performance psychology of 30 university, state, and national level basketball players. HRV BFB is a method of regulating anxiety by maintaining an unusually low breath rate. HRV is considered a window to the autonomic nervous system and is highly connected to optimal performance states. Thus, regulating HRV is important when predicting one's ability to cope with competition demands. In this study, athletes were randomly assigned to an experimental group, control group, and a placebo group. For 10 days, the experimental group received HRV BFB training, the placebo group was shown motivation videos, and the control group received no treatment. Performance improvements were based on passing, shooting, and dribbling skills. The study revealed that athletes who received HRV BFB training were able to significantly reduce trait anxiety compared to the placebo and control groups and consequently improve on performance measures (shooting, dribbling, passing) even at a one-month follow-up. The results highlight the importance of self-regulation in sports, as a lack of it can impair good performance. When pressure and stress are applied in competition, the athlete's ability to regulate those pressures will determine their success, indicating a great need to incorporate methods like biofeedback into elite training protocols. However, it should be noted that the small sample size in this study, as well as the lack of control during the performance tasks (e.g., athletes retrieved their own balls), may interfere with the test validity. Future studies should consider larger sample sizes and more control.

While regulating arousal is important for an athlete's success, each athlete has their own individual zone of optimal functioning; this refers to the range of arousal that results in the highest probability of performing optimally. Using biofeedback, experts can measure each athlete's zone of optimal functioning, as well as facilitate adaptive techniques to maintain those zones. Edmonds and colleagues (2008) explored how biofeedback training could facilitate good psychophysiological regulation skills so that athletes can enter an optimal performance zone. To do so, researchers studied various BFB regulations conditions on 9 participants using a simulated racetrack. The benefit of studying this sport is the relatively low levels of physical involvement, which could otherwise interfere with participants' physiological measures. Participants were randomly assigned to one of three arousal regulation treatment conditions: optimal, poor, or control. Two of the conditions (optimal and poor) participated in a biofeedback intervention based on the Wingate five-step approach, a method used to teach arousal regulation techniques

(Blumenstein & Bar-Eli, 2001). Each participant was assessed to determine their optimal performance zone using four affect-related modalities: skin conductance, heart rate, pleasure, and arousal. The optimal group received BFB training to perform in their optimal zone, the poor group received BFB training to perform in the poor zone, and the control group received little biofeedback training. The study highlights two major findings. First, of the 9 participants, no two shared the same zones of optimal performance, suggesting this index is highly dependent on the person. While one person may perform better at a heart rate of 69-75 beats, and a skin conductance of 9.5-11.0 mmho, other participants may fall significantly below or above this range. The second finding was that individuals who participated in either one of the BFB training conditions were able to better utilize self-regulation techniques to sustain optimal performance zones and decrease the time spent in poor performance zones. The study identified that each athlete performed optimally under different levels of arousal and that biofeedback techniques are useful in regulating their affective states to enter these zones. While these studies demonstrate the effectiveness of biofeedback training, they also require experts to quantify the athlete's optimal zone of performance and teach self-regulation techniques. Thus, biofeedback does not work in isolation, it is most effective in conjunction with a self-regulation program. By nature, this approach requires both times and space – the form factor does not afford athletes to take this equipment on the go as it did for load monitoring systems, introducing more limitations into the actual biofeedback applications.

Regulating the body's physiological state should not be stigmatized as just a method of coping with nerves. Caird and colleagues (1999) studied how regulating arousal states using biofeedback could improve the running economy in long-distance runners. Running economy is defined as the oxygen consumption at a given velocity and is associated with successful running performance. In this study, seven sub-elite long-distance runners received supervised relaxation training sessions. After the initial training, runners were separated into control or biofeedback conditions. Runners in biofeedback condition were measured on heart rate, oxygen, and ventilation every 20 seconds while maintaining 70% of their peak running velocity. Athletes were told to use the relaxation techniques learned in the previous phase to lower their physiological modalities. In contrast, runners under control conditions were provided with no biofeedback on heart rate, ventilation, or oxygen. Those who received biofeedback training improved their running economy and were able to lower their O2, HR, and ventilation lactate threshold by 7.3%, 2.5%, and 9.2%, respectively. While a higher level of fitness may explain improvements in running economy, the control condition remained similar over all trials, suggesting that BFB has a significant effect. The results highlight the importance of the mental side of sport, as often, this influences an athlete's physical outputs. Biofeedback can support self-regulation strategies so athletes can work more efficiently and perform better.

As previously mentioned, success at the top level often comes down to milliseconds. This is especially true in elite short track speed skating as having the fastest reaction time to the starting signal provides skaters with considerable advantages to claim insider positions on the rink. Harvey and colleagues (2011) examined how biofeedback training could be used to find an edge and increase the reaction time in the 2010 Vancouver Olympic short track speed skating team. Athletes participated in a five-week RT training program, where they used a simulated video of an international speed skating competition and pedals that recorded their reaction time to the starting signal. Various biofeedback modalities were measured to develop competencies in self-regulation of heart rate variability (HRV), muscle tension (EMG), respiration, heart rate (HR), skin conductance (SC), skin temperature (ST), and alpha training (using electroencephalography [EEG]). Throughout the BFB training, athletes become accustomed to regulating and controlling these various modalities. The ability to self-regulate is especially crucial during high profile events like the Olympic games as stress and pressure increase muscle tension and respiration, which can kill a good performance. With better control of these modalities, skaters significantly improved reaction time during weeks 4 and 5 of training. Moreover, the program was so effective that the Canadian short track speed skating team brought home gold and bronze medals. Despite the positive results in this study, it lacked a control group, making it difficult to confirm with any certainty that BFB correlates to better reaction time, making the results anecdotal. Nevertheless, the study illustrates the relative difficulty of obtaining elite athletes for researcher purposes as professional sports teams approach any uncredible technology or study with caution. Therefore, despite the lack of control in the speedskating Canada team, the sample of athletes provides an interesting look at how this technology can be integrated in elite sports.

Self-efficacy and Biofeedback

Regulating physiological modalities through biofeedback has proven to benefit athletes in areas such as psychological regulation, reaction time training, running economy, and performance and execution of dribbling and shooting skills (Caird et al., 1999; Edmonds et al., 2008; Harvey et al., 2011; Paul & Garg, 2012; Rijken et al., 2016). However, these studies fail to address the influence of biofeedback as it pertains to self-efficacy. According to Bandura, self-efficacy can be obtained through physiological and affective state management. This source of efficacy is said to be particularly influential to athletes.

Biofeedback training is the link between an athlete's internal condition and external environment; without this information, athletes would not understand how their bodies and behaviors affect their performance (Bentley et al., 2013; Tholander & Nylander, 2015). Specifically, how objective data, such as heart rate readings, affect their understanding of their subjective feelings, like perceived stress experienced during an international competition (Tholander & Nylander, 2015). The role of biofeedback training is important in assisting athletes in regulating and assessing their physiological state and, in doing so, developing self-efficacy and, in turn, good performance.

To date, the primary application of biofeedback training within elite athletics has been to regulate stress. Stress is the psychophysiological response to the environment or social variables (Lehrer et al., 2007). Stress can manifest itself as distress or eustress, referring respectively to negative or positive appraisals of stress (Lehrer et al., 2007). While stress can be perceived as different emotions, the physiological mechanisms which activate it are all the same. Stress manifests in the human body as an increased heart rate, blood pressure, electrodermal response, and distributions in breathing, and reduced brain functioning and attention (Lorenz et al., 2013). The discussion of stress and anxiety is important when considering that self-efficacy can be derived from one's physiological and affective states management. How the individual appraises stress is related to their self-efficacy, with those who score higher on self-efficacy interpreting stress as a protagonist rather than an antagonist (Humara, 1999; Paul & Garg, 2012). Moreover, self-efficacy is considered a factor guarding against the adverse effects of competitive anxiety (Humara, 1999). Advancements in technology, like biofeedback training, make it possible to appraise the physiological indices related to stress and make better judgments on how to approach it (Lehrer et al., 2007). An elite athlete's ability to regulate their stress is important for successful performance, with studies above indicating performance-enhancing effects as a result of good regulation skills.

In closing, psychological responses to the environment, such as worry, frustration, and excitement, manifest themselves as tension in the body (Lehrer et al., 2007). Athletes use their physiological symptoms to interpret an emotion and, in turn, derives self-efficacy. Learning to control the body's physiological state was shown to be particularly influential in the 2010 short track Olympic speed skating team (Harvey et al., 2011). Using biofeedback, the athletes develop a better understanding of their bodies' unconscious reactions. Through observation and self-regulatory strategies, they learned how to control their arousal through multiple modalities (HRV, HR, EEG) (Harvey et al., 2011). Athletes could use these techniques in competition to maintain optimal levels of arousal, which was seen to be particularly valuable at the beginning of a race where a good starting position benefited the player throughout the entire race (Harvey et al., 2011). As noted by Dr. Pierre Beauchamp, the sport psychologist behind the success of the Olympic speed skating team, biofeedback training is a tool to help regulate the body's modalities with the end goal of increasing one's confidence. Dahlbeck & Lightsey's (2008) suggest that reduced anxiety can be attributed to higher self-efficacy, as demonstrated in the athlete's improved performance.

Gaps and Future Directions

The pursuit of excellence demands innovation for athletes to succeed on the world stage. Success stories of technology meeting sports prove that technological innovation does have a powerful place. For example, Speedo's LZR swimsuit was so influential in the 2008 Beijing games that swimmers wearing the suit broke more than 108 world recorders, making it more impactful then doping. With marginal differences in performance making huge impacts on podium placement, innovation has never been more needed than now. However, as we enter a period where technological trends come and go, the question is not whether the innovation is there, but rather if athletes and coaches plan to integrate it into their training. A search of wearable technology reveals a plethora of articles and reviews, with little focus on how elite athletes are using this technology. Of the 83 articles reviewed for this paper, only 8 included elite participants, suggesting a deficit of these types of studies. Yet, on the advertising and marketing front, wearable technology companies like Catapult, Solos, Omegawave, and Fitbit are making strong claims that their products have performance enhancing results with only anecdotally evidence to back it up. Exploring previous literature that addressed the use of wearable technology within the context of sports will improve our understanding of how this technology can be used to support the success of elite athletes in the future.

After a systematic search of keywords, three themes emerged as common applications of wearable technology: biofeedback training, load monitoring, and virtual reality. Forty-five articles met the inclusion criteria and needs for this review, and 16 studies pertaining to wearable technology were included in this paper. Articles that did not meet the inclusion criteria focused too much on consumer products and motivations, the accuracy of the devices, or lacked a connection to sports performance. Based on the discussion, there is a lack of literature exploring wearable technology in elite athletes. Of the 16 articles reviewed, only 4 studies included samples of elite or professional athletes. This is an important gap as the results from studies using recreational, or novice athletes cannot be generalized to the elite level. There are significant differences between the performance motivation, physical capabilities, and psychological skills among these two cohorts. In a survey with 663 recreational and elite runners, competitive runners valued biometric and running-related data more than recreational runners who viewed wearable technology as a motivator to run (Clermont et al., 2019). Accuracy of data may reflect the marginal performance differences that exist at top-level sports. While recreational users may use wearable technology to motivate them to live a healthy lifestyle, elite athletes are using the technology to make incremental improvements in performance. Thus, the vastly different use cases of wearable technology in elite and recreation athletes cannot be viewed in a general sense. While these sample demographics may reflect the relative difficulty of obtaining elite athletes in research studies, the non-invasive wearable technology methods should make studying this cohort more accessible to researchers. More research is needed to investigate how wearable technology is used to support elite athletes, as this sample can produce completely different results than those obtained from the general public.

Secondly, of high interest to athletes and supporting bodies is to improve performance. The above discussion highlights the multifaceted approach to understanding performance and seeing it through physical and physiological measures. As noted, to be successful as a top athlete requires competence in all domains. Despite the variables that make differences in elite performance, most research on wearable technology focuses on physical performance and lacks a connection to the role of one's psychology. For example, incremental improvements in research are often marked by observable physical parameters such as increased speed, acceleration or power, a more successful free throw, a higher vertical jump or more efficient running economy, or arousal regulation (Bakit & Mohamed, 2011; Craig, 2013; Hoffmann et al., 2014; Lagos et al., 2011; Paul & Garg, 2012). While these studies are important in assessing how wearable technology is being used, all but one failed to address how wearable technology may influence performance through various psychological parameters. In particular, and among the most influential to elite athletes is self-efficacy. Given the three sources of self-efficacy that can be controlled by an athlete, it can be argued that wearables can influence self-efficacy through vicarious experiences, physiological state management, and verbal persuasion.

In the case of biofeedback training, we see a primary application that involves gaining greater awareness of the physiological functions of one's body. Studies have identified biofeedback to be most effective when combined with either the Wingate 5 step approach, psychological skills training, or heart rate variability biofeedback training (Edmonds et al., 2008; Paul & Garg 2012). Many biofeedback training applications use this technique to regulate one's physiological functions to reach optimal performance zones, while others may use it to regulate competitive anxiety (Caird et al., 1999; Edmonds et al., 2008; Paul & Garg, 2012). Studies conducted on biofeedback have validated the effectiveness of this tool to control and regulate physiological arousal, however, research has failed to connect the physiological and affective state management to measures of self-efficacy. Through biofeedback techniques, athletes can learn to regulate their arousal levels and, in doing so, feel more in control of their body's mechanisms and more confident during competition. Those with higher self-efficacy will interpret physiological arousal as facilitative to their performance, buffering against competitive anxiety.

Studies conducted on load monitoring have validated its effectiveness to systematically assess the training-recovery relationship to improve the efficacy of training and minimize the risk of injury. However, the approach has been critiqued as a data overload whereby too much data becomes overwhelming. Consequently, the tool only offers value to experts who understand the data and can make appropriate decisions. It can be inferred using the self-efficacy theory that data monitoring can help athletes reflect on performance improvements throughout a season or longitudinally across years. Using data as the guideposts of success may facilitate positive self-talk or imagery, consequently affecting the athlete's self-efficacy.

In the case of VR, we see the primary application in sports is skills training, observational learning, or inducing competitive anxiety. While this has been reportedly used in many professional sporting leagues, there is a lack of studies examining how elite athletes incorporate VR as part of their training procedures. Potentially, the lack of literature reflects the difficulty of obtaining elite athletes for studies, or the unwillingness to share positive results. It can be inferred using the self-efficacy theory that VR can improve performance through various realms of self-efficacy. For example, the experiences in VR are similar to imagery, whereby an athlete engages all their senses to make a lifelike representation of an event. In the case of imagery, the more vivid the image, the more likely the brain will interpret the imaged as a real stimulus experience (Weinberg, 2008). Imagery has positive effects on athletes' self-efficacy because it can create feelings of competency and success, reduce competitive anxiety, and help athletes see arousal as facilitative rather than debilitative (Weinberg, 2008). Thus, it can be assumed that VR can induce similar effects imagery and, in this way, increase the athlete's self-efficacy. Moreover, if an athlete successfully practices skills in VR, and feel they are performing well, they may begin to engage in positive self-talk or mental imagery.

Conclusion

As seen through a self-efficacy theory lens, the purpose of this narrative review is to explore wearable technology use in elite athletes. Specifically, (a) the major types of wearable technology used by athletes; (b) how wearable technology may affect performance; and (c) trends and gaps in the field. After a systematic search of keywords, three themes emerged: biofeedback training, load monitoring, and virtual reality. Studies included in this review identified that wearable technology is currently being used to monitor performance, reduce injury, and enhance training efficiency. Based on the analysis of available information, it would appear that there are gaps in the types of studies available on this topic, specifically with regards to participants and samples. To better understand how wearable technologies are used in elite athletes, more studies need to be conducted using samples from elite athlete populations. Additionally, most research on wearable technology appears to focus on physical performance and lacks connection to the psychology of performance. Arguably, wearable technology may offer psychological mediating effects on performance, which should be explored in future studies. Considering the positive correlation between self-efficacy and performance, understanding the role wearable technology may play with the promotion of self-efficacy could prove to be valuable. Exploring and adding to previous literature that addressed the use of wearable technology within the context of sports will improve our understanding of how this technology can be used to support elite athletes' success.

Table 1.

Main studies used in this literature review

Authors/date	Main Purpose of Study	Population & Sample Size	Outcome measures	Main Findings
(IJsselstein et al., 2004)	Explore the effect of immersion athletes motivation	24 in active Philips employees	Motivation was measured using Intrinsic Motivation Inventory (IMI) Speed of biker	High levels of immersion resulted in higher motivation and faster cycling speed
(Hoffmann et al., 2014)	To measure if VR as a means to learn about energy management.	15 novice rowers	VO2 max incremental test, Race, ventilatory and energy variables, Race strategy	Rowers who used a virtual boat as a reference point for pace had better pace strategy, reduced race duration, and better performance compared to the control.
(Bideau et al., 2010)	To use VR to Isolate visual discrepancies and examining anticipatory behaviors	Two case studies		Two case studies using VR technology could inform a player's course of action in perception-action and deceptive tasks
(Stinson & Bowman, 2014)	To see if high fidelity VR environments could induce anxiety	28 university students	Anxiety levels in a VR system	An interaction between the athlete's trait anxiety and the stimulation level of the experience, suggesting a multifaceted relationship between competitive anxiety.
(Lagos et al., 2011)	To evaluate the effects of HRVBFB on physiological, psychological, and sport performance	21-year-old competitive golfer	A comparison of physiological, psychological, and sport performance data collected before and after the HRV BFB training.	The golfer was able to significantly lower her heart rate and increase performance on the VR golf simulation
(Bakit & Mohamed , 2011)	Could VR improve skill performance of hurdlers	12 young Track and field athletes	Skilled performance level	Hurdlers experienced an increase in their performance levels and decreased record levels.
(Edmonds et al., 2008)	how biofeedback training could be used to facilitate good psyc hophysiological regula tion skills so that athletes can enter an optimal performance z one	9 participants	Performance of the simulate driving task and affect-related performance zones for the pre- and post-test trials, the ability for the participants to stay within their optimal performance zones.	BFB training conditions were able to better utilize self-regulation techniques to sustain optimal performance zones and decrease the times spent in the poor performance zones
(Paul & Garg, 2012)	To test if heart rate variability (HRV) biofeedback (BFB) training could enhance the performance psychology of basketball players	30 basketball player who met inclusion criteria	Physiological Measures, Psychological Measures, Performance Measures	HRV BFB training were able to significantly reduce trait anxiety compared to the placebo and control groups and consequently improve on performance measures (shooting, dribbling, passing) even at a one-month follow-up

(Caird et al., 1999)	determine whether a psychophysiological intervention of biofeedback and rel axation could decrease the submaximal oxygen consumption and improve running economy for elite long-distance runners	seven sub-elite long-distance runners	heart rate, oxygen, and ventilation	Those who received biofeedback training improved their running economy and were able to lower their O2, HR, and ventilation lactate threshold by 7.3%, 2.5%, and 9.2%, respectively and improve running economy
(Harvey et al., 2011)	examined how biofeedback training could be used to increase the reaction time in the 2010 Vancouver Olympic short track speed skating team	Ten male athletes affiliated with Speedskating Canada	Reaction time	Biofeedback training can enhance (e.g., making faster) the reaction time performance of speedskaters
(Rijken et al., 2016)	To investigate the outcomes of various biofeedback modalities (HRV or EEG) on self-reported factors related to stress, performance, recovery and sleep quality in elite athletes.	Two groups of participants: Professional soccer player and Elite sprinters and hurdlers	Quantitative and subjective measures related to stress, recovery and sleep as well as HRV and EEG	Results indicated the most significant improvements were in the athletes' ability to regulate their EEG and HRV, however athletes using EEG modalities significantly increased their concentration and emotional scales, while athletes using HRV significantly increased their recovery index
(Morris, 2015)	To examine how an athlete's functional state of readiness could better guide an effective training program in university football players.	Control : 28 university foot player Experimental group : 31 university football player . Total participants 59	The athletes functional state as indicated by the Omegawave readiness output, and performance measures such as vertical jump, vertical power, broad jump, and aerobic efficiency	Omegawave assessments of the experimental group, athletes reduced the amount of time spent on resistance training. Consequently, performance measures such as vertical jump, vertical power, broad jump, and aerobic efficiency were significantly improved compared to the control group

(Heishman et al., 2018)	To assess the efficacy of external load and internal stress monitoring as assessment tools for examining a performance index of fatigue.	10 elite NCAA basketball players	Athletes' performance scores were assessed using a vertical jump test	higher functional state of readiness scores on the Omegawave test resulted in significantly better results on the vertical jump test. In contrast, higher player load as measured by the Catapult system resulted in lower jump scores on the performance test.

References

Akbaş, A., Marszałek, W., Kamieniarz, A., Polechoński, J., Słomka, K. J., & Juras, G. (2019). Application of Virtual Reality in Competitive Athletes – A Review. *Journal of Human Kinetics*, *69*(1), 5–16. https://doi.org/10.2478/hukin-2019-0023

Altukhov, S., & Nauright, J. (2018). The new sporting Cold War: Implications of the Russian doping allegations for international relations and sport. *Sport in Society*, *21*(8), 1120–1136. https://doi.org/10.1080/17430437.2018.1442194

Argelaguet Sanz, F., Multon, F., & Lécuyer, A. (2015). A Methodology for Introducing Competitive Anxiety and Pressure in VR Sports Training. *Frontiers in Robotics and AI*, *2*. https://doi.org/10.3389/frobt.2015.00010

Bakit, M. A., & Mohamed, M. S. E.-D. (2011). *THE EFFECTIVENESS OF IMMERSIVE VIRTUAL REALITY SYSTEMS IN IMPROVING THE SKILLED AND RECORD PERFORMANCE OF YOUNG HURDLERS*. 13.

Bar-Eli, M., & Blumenstein, B. (2004). Performance enhancement in swimming: The effect of mental training with biofeedback. *Journal of Science and Medicine in Sport*, *7*(4), 454–464. https://doi.org/10.1016/S1440-2440(04)80264-0

Bentley, F., Tollmar, K., Stephenson, P., Levy, L., Jones, B., Robertson, S., Price, E., Catrambone, R., & Wilson, J. (2013). Health Mashups: Presenting Statistical Patterns between Wellbeing Data and Context in Natural Language to Promote Behavior Change. *ACM Transactions on Computer-Human Interaction*, *20*(5), 1–27. https://doi.org/10.1145/2503823

Bideau, B., Kulpa, R., Vignais, N., Brault, S., Multon, F., & Craig, C. (2009). Virtual reality, a serious game for understanding performance and training players in sport. *IEEE Computer Graphics and Applications*, 5339124. https://doi.org/10.1109/MCG.2009.134

Bideau, B., Multon, F., Kulpa, R., Fradet, L., Arnaldi, B., & Delamarche, P. (2004). Using virtual reality to analyze links between handball thrower kinematics and goalkeeper's reactions. *Neuroscience Letters*, *372*(1–2), 119–122. https://doi.org/10.1016/j.neulet.2004.09.023

Blumenstein, B., & Orbach, I. (2014). *Biofeedback for Sport and Performance Enhancement*. Oxford University Press. https://doi.org/10.1093/oxfordhb/9780199935291.013.001

Bourdon, P. C., Cardinale, M., Murray, A., Gastin, P., Kellmann, M., Varley, M. C., Gabbett, T. J., Coutts, A. J., Burgess, D. J., Gregson, W., & Cable, N. T. (2017). Monitoring Athlete Training Loads: Consensus Statement. *International Journal of Sports Physiology and Performance*, *12*(s2), S2-161-S2-170. https://doi.org/10.1123/IJSPP.2017-0208

Burgess, D. J. (2017). The Research Doesn't Always Apply: Practical Solutions to Evidence-Based Training-Load Monitoring in Elite Team Sports. *International Journal of Sports Physiology and Performance*, *12*(s2), S2-136-S2-141. https://doi.org/10.1123/ijspp.2016-0608

Caird, S. J., McKENZIE, A. D., & Sleivert, G. G. (1999). Biofeedback and relaxation techniques improve running economy in sub-elite long distance runners: *Medicine & Science in Sports & Exercise*, *31*(5), 717–722. https://doi.org/10.1097/00005768-199905000-00015

Cardinale, M., & Varley, M. C. (2017). Wearable Training-Monitoring Technology: Applications, Challenges, and Opportunities. *International Journal of Sports Physiology and Performance*, *12*(s2), S2-55-S2-62. https://doi.org/10.1123/ijspp.2016-0423

Chen, K. Y., Janz, K. F., Zhu, W., & Brychta, R. J. (2012). Redefining the Roles of Sensors in Objective Physical Activity Monitoring: *Medicine & Science in Sports & Exercise*, *44*, S13–S23. https://doi.org/10.1249/MSS.0b013e3182399bc8

Covaci, A., Postelnicu, C.-C., Panfir, A. N., & Talaba, D. (2012). A Virtual Reality Simulator for Basketball Free-Throw Skills Development. In L. M. Camarinha-Matos, E. Shahamatnia, & G. Nunes (Eds.), *Technological Innovation for Value Creation* (Vol. 372, pp. 105–112). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-28255-3_12

Craig, C. (2013). Understanding perception and action in sport: How can virtual reality technology help? *Sports Technology*, *6*(4), 161–169. https://doi.org/10.1080/19346182.2013.855224

De Bosscher, V., De Knop, P., Van Bottenburg, M., & Shibli, S. (2006). A Conceptual Framework for Analysing Sports Policy Factors Leading to International Sporting Success. *European Sport Management Quarterly*, *6*(2), 185–215. https://doi.org/10.1080/16184740600955087

Dowrick, P. W. (2012). Self modeling: Expanding the theories of learning. *Psychology in the Schools*, *49*(1), 30–41. https://doi.org/10.1002/pits.20613

Edmonds, W. A., Tenenbaum, G., Mann, D. T. Y., Johnson, M., & Kamata, A. (2008). The effect of biofeedback training on affective regulation and simulated car-racing performance: A multiple case study analysis. *Journal of Sports Sciences*, *26*(7), 761–773. https://doi.org/10.1080/02640410701813068

Feltz, D. L., Lirgg, C. D., Singer, I. R. N., Hausenblas, H. A., & Janelle, C. (2001). *Self-efficacy Beliefs of Athletes, Teams, and Coaches*. 36.

Gould, D., & Maynard, I. (2009). Psychological preparation for the Olympic Games. *Journal of Sports Sciences*, *27*(13), 1393–1408. https://doi.org/10.1080/02640410903081845

Gray, R. (2017). Transfer of Training from Virtual to Real Baseball Batting. *Frontiers in Psychology*, *8*, 2183. https://doi.org/10.3389/fpsyg.2017.02183

Halson, S. L., Peake, J. M., & Sullivan, J. P. (2016). Wearable Technology for Athletes: Information Overload and Pseudoscience? *International Journal of Sports Physiology and Performance*, *11*(6), 705–706. https://doi.org/10.1123/IJSPP.2016-0486

Hamlin, M. J., Wilkes, D., Elliot, C. A., Lizamore, C. A., & Kathiravel, Y. (2019). Monitoring Training Loads and Perceived Stress in Young Elite University Athletes. *Frontiers in Physiology*, *10*, 34. https://doi.org/10.3389/fphys.2019.00034

Harvey, R. H., Beauchamp, M. K., Saab, M., & Beauchamp, P. (2011). Biofeedback Reaction-Time Training: Toward Olympic Gold. *Biofeedback*, *39*(1), 7–14. https://doi.org/10.5298/1081-5937-39.1.03

Haugen, T., Seiler, S., Sandbakk, Ø., & Tønnessen, E. (2019). The Training and Development of Elite Sprint Performance: An Integration of Scientific and Best Practice Literature. *Sports Medicine - Open*, *5*(1), 44. https://doi.org/10.1186/s40798-019-0221-0

Heishman, A. D., Curtis, M. A., Saliba, E., Hornett, R. J., Malin, S. K., & Weltman, A. L. (n.d.). *NONINVASIVE ASSESSMENT OF INTERNAL AND EXTERNAL PLAYER LOAD: IMPLICATIONS FOR OPTIMIZING ATHLETIC PERFORMANCE*. 8.

Hoffmann, C. P., Filippeschi, A., Ruffaldi, E., & Bardy, B. G. (2014). Energy management using virtual reality improves 2000-m rowing performance. *Journal of Sports Sciences*, *32*(6), 501–509. https://doi.org/10.1080/02640414.2013.835435

Humara, M. (n.d.). *The Relationship Between Anxiety and Performance: A Cognitive-Behavioral Perspective*. 14.

IJsselsteijn, W., de Kort, Y., Westerink, J., de Jager, M., & Bonants, R. (2004). Fun and Sports: Enhancing the Home Fitness Experience. In M. Rauterberg (Ed.), *Entertainment*

Computing – ICEC 2004 (Vol. 3166, pp. 46–56). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-28643-1_8

Jennings, C. T., Reaburn, P., & Rynne, S. B. (2013). The Effect of a Self-Modelling Video Intervention on Motor Skill Acquisition and Retention of a Novice Track Cyclist's Standing Start Performance. *International Journal of Sports Science & Coaching*, *8*(3), 467–480. https://doi.org/10.1260/1747-9541.8.3.467

Kiernan, D., Hawkins, D. A., Manoukian, M. A. C., McKallip, M., Oelsner, L., Caskey, C. F., & Coolbaugh, C. L. (2018). Accelerometer-based prediction of running injury in National Collegiate Athletic Association track athletes. *Journal of Biomechanics*, *73*, 201–209. https://doi.org/10.1016/j.jbiomech.2018.04.001

Kulpa, R., Bideau, B., & Brault, S. (2013). Displacements in Virtual Reality for Sports Performance Analysis. In F. Steinicke, Y. Visell, J. Campos, & A. Lécuyer (Eds.), *Human Walking in Virtual Environments* (pp. 299–318). Springer New York. https://doi.org/10.1007/978-1-4419-8432-6_13

Lagos, L., Vaschillo, E., Vaschillo, B., Lehrer, P., Bates, M., & Pandina, R. (2011). Virtual Reality–Assisted Heart Rate Variability Biofeedback as a Strategy to Improve Golf Performance: A Case Study. *Biofeedback*, *39*(1), 15–20. https://doi.org/10.5298/1081-5937-39.1.11

Lehrer, P. M., Woolfolk, R. L., & Sime, W. E. (Eds.). (2007). *Principles and practice of stress management* (3rd ed). Guilford Press.

Li, R. T., Kling, S. R., Salata, M. J., Cupp, S. A., Sheehan, J., & Voos, J. E. (2016). Wearable Performance Devices in Sports Medicine. *Sports Health: A Multidisciplinary Approach*, *8*(1), 74–78. https://doi.org/10.1177/1941738115616917

Lindsay Ross-Stewart, Jeffrey Price, Daniel Jackson, & Christopher Hawkins. (2018). A Preliminary Investigation into the Use of an Imagery Assisted Virtual Reality Intervention in Sport. *Journal of Sports Science*, *6*(1). https://doi.org/10.17265/2332-7839/2018.01.003

Loke, S.-K. (2015). How do virtual world experiences bring about learning? A critical review of theories. *Australasian Journal of Educational Technology*, *31*(1). https://doi.org/10.14742/ajet.2532

Lorenz, D. S., Reiman, M. P., Lehecka, B. J., & Naylor, A. (2013). What Performance Characteristics Determine Elite Versus Nonelite Athletes in the Same Sport? *Sports Health: A Multidisciplinary Approach*, *5*(6), 542–547. https://doi.org/10.1177/1941738113479763

Maddux, J. E. (Ed.). (1995). *Self-Efficacy, Adaptation, and Adjustment.* Springer US. https://doi.org/10.1007/978-1-4419-6868-5

Mahoney, M. J., & Avener, M. (1977). Psychology of the elite athlete: An exploratory study. *Cognitive Therapy and Research*, *1*(2), 135–141. https://doi.org/10.1007/BF01173634

McCann, J., Bryson, D., & Textile Institute (Manchester, England) (Eds.). (2009). *Smart clothes and wearable technology*. Woodhead Publishing : In association with the Textile Institute ; Published in North America by CRC Press.

Michalski, S. C., Szpak, A., & Loetscher, T. (2019). Using Virtual Environments to Improve Real-World Motor Skills in Sports: A Systematic Review. *Frontiers in Psychology*, *10*, 2159. https://doi.org/10.3389/fpsyg.2019.02159

Middlemas, S., & Harwood, C. (2019). A Pre-Match Video Self-Modeling Intervention in Elite Youth Football. *Journal of Applied Sport Psychology*, 1–26. https://doi.org/10.1080/10413200.2019.1590481

Morris, C. W. (n.d.). *The Effect of Fluid Periodization on Athletic Performance Outcomes in American Football Players*. 110.

Morris, T., Spittle, M., & Watt, A. P. (2005). *Imagery in sport*. Human Kinetics.

Murphy, A. P. (n.d.). *Load monitoring in high performance youth tennis players: Preparation for competition readiness*. 305.

Murray, E. G., Neumann, D. L., Moffitt, R. L., & Thomas, P. R. (2016). The effects of the presence of others during a rowing exercise in a virtual reality environment. *Psychology of Sport and Exercise*, *22*, 328–336. https://doi.org/10.1016/j.psychsport.2015.09.007

Nissim, Y., & Weissblueth, E. (2017). Virtual Reality (VR) as a Source for Self-Efficacy in Teacher Training. *International Education Studies*, *10*(8), 52. https://doi.org/10.5539/ies.v10n8p52

Oliver Farley, Kirsten Spencer, & Livvie Baudinet. (2019). Virtual reality in sports coaching, skill acquisition and application to surfing: A review. *Journal of Human Sport and Exercise*.

Paul, M., & Garg, K. (2012). The Effect of Heart Rate Variability Biofeedback on Performance Psychology of Basketball Players. *Applied Psychophysiology and Biofeedback*, *37*(2), 131–144. https://doi.org/10.1007/s10484-012-9185-2

Pop-Jordanova, N., & Demerdzieva, A. (2010). Biofeedback Training for Peak Performance in Sport—Case Study. *Macedonian Journal of Medical Sciences*, *3*(2), 113–118. https://doi.org/10.3889/MJMS.1857-5773.2010.0098

Rijken, N. H., Soer, R., de Maar, E., Prins, H., Teeuw, W. B., Peuscher, J., & Oosterveld, F. G. J. (2016). Increasing Performance of Professional Soccer Players and Elite Track and Field Athletes with Peak Performance Training and Biofeedback: A Pilot Study. *Applied Psychophysiology and Biofeedback*, *41*(4), 421–430. https://doi.org/10.1007/s10484-016-9344-y

Robertson, I. H. (2017). The stress test. In *Progress in Brain Research* (Vol. 232, pp. 155–158). Elsevier. https://doi.org/10.1016/bs.pbr.2016.12.003

Smith, D. J. (2003). A Framework for Understanding the Training Process Leading to Elite Performance: *Sports Medicine*, *33*(15), 1103–1126. https://doi.org/10.2165/00007256-200333150-00003

Snyder, A. L., Anderson-Hanley, C., & Arciero, P. J. (2012). Virtual and Live Social Facilitation While Exergaming: Competitiveness Moderates Exercise Intensity. *Journal of Sport and Exercise Psychology*, *34*(2), 252–259. https://doi.org/10.1123/jsep.34.2.252

Ste-Marie, D. M., Rymal, A., Vertes, K., & Martini, R. (2011). Self-Modeling and Competitive Beam Performance Enhancement Examined Within a Self-Regulation Perspective. *Journal of Applied Sport Psychology*, *23*(3), 292–307. https://doi.org/10.1080/10413200.2011.558049

Stinson, C., & Bowman, D. A. (2014). Feasibility of Training Athletes for High-Pressure Situations Using Virtual Reality. *IEEE Transactions on Visualization and Computer Graphics*, *20*(4), 606–615. https://doi.org/10.1109/TVCG.2014.23

Taylor, M. K., Gould, D., & Rolo, C. (2008). Performance strategies of US Olympians in practice and competition. *High Ability Studies*, *19*(1), 19–36. https://doi.org/10.1080/13598130801980281

Tholander, J., & Nylander, S. (2015). Snot, Sweat, Pain, Mud, and Snow: Performance and Experience in the Use of Sports Watches. *Proceedings of the 33rd Annual ACM Conference on Human Factors in Computing Systems - CHI '15*, 2913–2922. https://doi.org/10.1145/2702123.2702482

Tirp, J., Steingröver, C., Wattie, N., Baker, J., & Schorer, J. (n.d.). *Virtual realities as optimal learning environments in sport – A transfer study of virtual and real dart throwing*. 14.

van Rossum, J. H. A. (1996). Psychological Characteristics of Elite Athletes According to Top Level Coaches. *High Ability Studies*, *7*(1), 15–23. https://doi.org/10.1080/0937445960070103

Walter, N., Nikoleizig, L., & Alfermann, D. (2019). Effects of Self-Talk Training on Competitive Anxiety, Self-Efficacy, Volitional Skills, and Performance: An Intervention Study with Junior Sub-Elite Athletes. *Sports*, *7*(6), 148. https://doi.org/10.3390/sports7060148

Watson, L., Binks, E., & Kawycz, S. (2011). "In it for the long run": Sources of self-efficacy in adolescent female athletes. *British Journal of Sports Medicine*, *45*(2), e1–e1. https://doi.org/10.1136/bjsm.2010.081554.28

Weinberg, R. (2008). Does Imagery Work? Effects on Performance and Mental Skills. *Journal of Imagery Research in Sport and Physical Activity*, *3*(1). https://doi.org/10.2202/1932-0191.1025

Witmer, B. G., & Singer, M. J. (1998). Measuring Presence in Virtual Environments: A Presence Questionnaire. *Presence: Teleoperators and Virtual Environments*, *7*(3), 225–240. https://doi.org/10.1162/105474698565686

Zadeh, A., Taylor, D., Bertsos, M., Tillman, T., Nosoudi, N., & Bruce, S. (2020). Predicting Sports Injuries with Wearable Technology and Data Analysis. *Information Systems Frontiers*. https://doi.org/10.1007/s10796-020-10018-3