Review article

DIGITAL HEALTH

DIGITAL HEALTH
Volume 9: 1–19

DOI: 10.1177/20552076231177498
journals.sagepub.com/home/dhj
Sage

Wearable technology in the sports medicine clinic to guide the return-to-play and performance protocols of athletes following a COVID-19 diagnosis

Dhruv R Seshadri[1], Ethan R Harlow[1,2], Mitchell L Thom[1,2], Michael S Emery[3], Dermot M Phelan[4], Jeffrey J Hsu[5], Peter Düking[6], Kristof De Mey[7], Joseph Sheehan[8], Benjamin Geletka[1,2,9], Robert Flannery[1,2], Jacob G Calcei[1,2], Michael Karns[1,2], Michael J Salata[1,2], Tim J Gabbett[10,11,12] and James E Voos[1,2]

Abstract

The coronavirus disease 2019 (COVID-19) pandemic has enabled the adoption of digital health platforms for self-monitoring and diagnosis. Notably, the pandemic has had profound effects on athletes and their ability to train and compete. Sporting organizations worldwide have reported a significant increase in injuries manifesting from changes in training regimens and match schedules resulting from extended quarantines. While current literature focuses on the use of wearable technology to monitor athlete workloads to guide training, there is a lack of literature suggesting how such technology can mediate the return to sport processes of athletes infected with COVID-19. This paper bridges this gap by providing recommendations to guide team physicians and athletic trainers on the utility of wearable technology for improving the well-being of athletes who may be asymptomatic, symptomatic, or tested negative but have had to quarantine due to a close exposure. We start by describing the physiologic changes that occur in athletes infected with COVID-19 with extended deconditioning from a musculoskeletal, psychological, cardiopulmonary, and thermoregulatory standpoint and review the evidence on how these athletes may safely return to play. We highlight opportunities for wearable technology to aid in the return-to-play process by offering a list of key parameters pertinent to the athlete affected by COVID-19. This paper provides the athletic community with a greater understanding of how wearable technology can be implemented in the rehabilitation process of these athletes and spurs opportunities for further innovations in wearables, digital health, and sports medicine to reduce injury burden in athletes of all ages.

Keywords

Wearable technology, COVID-19, return to play, exercise physiology, reduce injury burden

Submission date: 11 June 2022; Acceptance date: 6 May 2023

[1]University Hospitals Sports Medicine Institute, Cleveland, OH, USA
[2]Department of Orthopaedic Surgery, University Hospitals Cleveland Medical Center, Cleveland, OH, USA
[3]Sports Cardiology Center, Heart, Vascular, and Thoracic Institute, Cleveland Clinic, Cleveland, OH, USA
[4]Sanger Heart and Vascular Institute, Atrium Health, Charlotte, NC, USA
[5]David Geffen School of Medicine, University of California Los Angeles, Los Angeles, CA, USA
[6]Integrative and Experimental Exercise Science, Department of Sport Science, University of Würzburg, Würzburg, Germany
[7]Ghent University, Ghent, Belgium
[8]Cleveland Browns Organization, Cleveland, OH, USA
[9]University Hospitals Rehabilitation Services and Sports Medicine, Cleveland, OH, USA
[10]Gabbett Performance Solutions, Brisbane, Australia
[11]Centre for Health Research, University of Southern Queensland, Ipswich, Australia
[12]School of Science, Psychology and Sport, Federation University, Ballarat, Australia

Corresponding author:
Dhruv R Seshadri, University Hospitals Sports Medicine Institute, 11100 Euclid Ave, Cleveland, OH, 44106, USA.
Email: dhruv.seshadri@gmail.com

Introduction

The global patient vital signs monitoring market is currently valued at around US$8.5 billion with an average compound annual growth rate (CAGR) of 8.9% from 2021 to 2028.[1] This growth, catapulted by the ongoing coronavirus disease 2019 (COVID-19) pandemic and use of wearables (i.e. wrist-worn, patches, and hearables) for self-tracking, has brought into sharp focus the need to harness and adopt a digital infrastructure for remote monitoring applications.[2] Wearable technology has been shown to play a pivotal role in predicting the likelihood of infections[3] based on changes in basic vitals such as respiratory rate (RR),[4] heart rate variability (HRV),[5] and heart rate (HR).[6] With one in five adults in the USA reportedly owning wearable fitness trackers,[7] there remains great potential for consumer wearable technology to help users monitor vital signs and detect early COVID-19 infection.[8]

While most of the literature surrounding the application of wearable technology and COVID-19 have focused on the general population and the use of sensors to predict[4] or monitor the incidence of COVID-19,[2,3,9–11] there is limited literature[12] detailing how athletes, athletic trainers, and team physicians can collectively and collaboratively use data from wearable sensors to guide and inform return-to-play (RTP) protocols following a COVID-19 infection. Following widespread administration of vaccines worldwide, recent variants have resulted in significant disruptions to professional and organized sports, with various leagues continuously adapting isolation and RTP screening protocols in response to waves of COVID-19 (Table 1).

There are expected changes in muscle physiology and deconditioning known to occur in athletes following prolonged absences to high acuity workouts and training environments.[18–21] There remains an unmet clinical need to understand the role of digital health to enable remote athlete monitoring platforms to ensure the RTP process is objective and comprehensive to mitigate injuries manifesting from rapid changes in biomechanical, physiological, and thermoregulatory stresses. Wearable technology has a unique role in mediating the RTP process in athletes who may be quarantined from teammates, coaches, trainers, and medical staff and subjected to extended time away from full competition. The ability to measure biomechanical parameters such as movement (e.g. tri-axial acceleration) along with physiological parameters such as HR, HRV, temperature (core body and skin), RR, and heart rhythm simultaneously via time synchronous algorithms enables real-time quantification of the external and internal loads expended by an athlete. The integration of high-fidelity, low-power machine learning (ML) algorithms enables the measurement of advanced digital biomarkers such as cuffless blood pressure (BP)[22,23] and a suite of biomarkers not currently possible by wearable technology towards understanding insights relevant to athlete health and performance.

With most of the studies focusing either on monitoring healthy athletes or on COVID-19 prediction, there is a gap in the literature detailing opportunities to apply wearable technology to guide the RTP and return to performance of athletes following a positive COVID-19 diagnosis. This review seeks to bridge and address this clinical gap. Given the interdisciplinary nature of this paper, we present a definition of key terms used throughout for recommended review by the reader (Table 2).

Deconditioning effects of COVID-19 on athletes

The musculoskeletal and cardiopulmonary systems of athletes are accustomed to a large volume and intensity of training, and any significant deviation in habitual stimuli will lead to a degree of physiological system and tissue deconditioning, in turn reducing physical performance, leading to increased risk of injury.[20] COVID-19 has led to a significant change in the organization and day-to-day processes for athletes and sports medicine practitioners.[25] Lockdowns saw marked reductions in training intensity, frequency, and duration among athletes from recreational to world-class level.[26] This likely leads to some effects of deconditioning.

There is limited evidence regarding detraining in athletic populations (elite, collegiate, or youth); however, it appears than in some populations and athletes, detraining as a result of a COVID-19 quarantine is even more detrimental than traditional off-season.[27] Principles of deconditioning can be translated from human laboratory studies using extreme experimental setups such as limb immobilization (local disuse), bed rest (whole body disuse), or reduced step count (moderate decreases in physical activity) in previously “healthy” individuals.[28] When considering the effect of the pandemic on athletic wellness, athletes are subjected to the downstream effects of physical and mental deconditioning, regardless of infection positivity. We categorize athletes into three groups: (a) those recovering from an acute symptomatic infection, (a) an asymptomatic infection, and (c) those requiring quarantine and cessation of a supervised training program without a positive test or symptom(s). The current literature has not substantiated an evidence-based protocol for RTP during the pandemic; however, we now have a better understanding of the physiologic effects of the virus on young and relatively healthy patients[29,30] and vast literature to describe the effect of disuse deconditioning on the athlete. Because of this work, trainers and physicians can better understand how each of the three “disease states” have affected the athlete and what training or other intervention is required prior to returning to sport. We elucidate the effects of

Table 1. Summary of COVID-19 protocols across major sporting organizations around the world. Sports with high cutting and pivoting movements with a high propensity for musculoskeletal injuries were included. Given the repeated changes in protocols given uncertainties and learnings over the course of the pandemic, protocols listed publicly around the end of 2021 are included. Data were gathered from publicly available databases. Table organized alphabetically.

League	Length of Isolation	RTP Screening Protocol
Australian Football League (AFL)	Lacks a league-wide protocol. Each club establishes its own protocols to guide RTP and testing.	Lacks a league-wide protocol. Each club establishes its own protocols to guide RTP and testing.
Bundesliga	Lacks a league-wide protocol. Each club establishes its own protocols to guide RTP and testing.	Lacks a league-wide protocol. Each club establishes its own protocols to guide RTP and testing.
English Premier League (EPL)	Lacks a league-wide protocol. Each club establishes its own protocols to guide RTP and testing.	Lacks a league-wide protocol. Each club establishes its own protocols to guide RTP and testing.
Major League Baseball (MLB)	10-day isolation following a positive test[13]	Depending on severity of illness during COVID-19, some athlete may require cardiac evaluation and testing with triad testing (hsTrop, ECG, and echo).[13]
Major League Soccer (MLS)	10 days following symptoms or positive test[14]	Depending on severity of illness during COVID-19, some athlete may require cardiac evaluation and testing with triad testing (hsTrop, ECG, and echo).[14]
National Basketball Association (NBA)	5 days, if PCR cycle threshold (CT) above 30[15]	Depending on severity of illness during COVID-19, some athlete may require cardiac evaluation and testing with triad testing (hsTrop, ECG, and echo). The player must rest and cannot exercise for at least 10 days from the first onset of symptoms. There is then an observation process for players to RTP.[16]
National Football League (NFL)	5 days and 24 hours since their last fever[17]	Depending on severity of illness during COVID-19, some athlete may require cardiac evaluation and testing with triad testing (hsTrop, ECG, and echo). Following evaluation, the athlete should undergo a workout at the facility under the supervision of the medical staff.
National Rugby League (NRL)	Lacks a league-wide protocol. Each club establishes its own protocols to guide RTP and testing.	Lacks a league-wide protocol. Each club establishes its own protocols to guide RTP and testing.

deconditioning below from a musculoskeletal, psychological, and cardiopulmonary systems standpoint.

Musculoskeletal health

Deconditioning results in a decrease in skeletal muscle mass, overall muscle strength, and flexibility with a predilection for the lower extremity muscles.[31–33] In general, physical inactivity causes muscle shortening or increased laxity with concomitant changes in tonicity depending on the muscle type, especially when inactivity exceeds 4 weeks.[18,34,35] Interestingly, athletes with greater baseline muscle mass may be affected more profoundly than others as a result of disuse deconditioning as measured by reduction in muscle size and change in tendon/muscle architecture.[36] There is also a known transition of fast-twitch into slow-twitch muscle fibers at 4 weeks of inactivity with a concomitant decrease in cross-sectional muscle area.[37] Changes at the microscopic level include decreases in collagen synthesis and turnover in lower extremity tendons between 10 and 21 days.[38] Sousa et al.[39] found that training-induced gains following a combination of aerobic and resistance training may be compromised with a short-term deconditioning period (2–4 weeks). The alterations in normal musculoskeletal physiology independent of disease status occur in addition to the described cardiorespiratory maladaptations later discussed.

Multiple studies have described an increase in injury rate for professional athletes in their preseason training compared to competition.[40] Following the 2011 National

Table 2. Definition of key terms involving the application of wearable technology and sports analytics to guide athlete rehabilitation.

Term	Definition
Acute workload	Workload of an athlete over a short duration (typically one session to 1 week). This value contains both training load and match load information over the set period and is analogous to "fatigue"
Chronic workload	Workload of an athlete over 3-week duration or longer. Chronic workload provides a clear indication of the training an athlete has done leading up to the present training or match day and provides an indication of an athlete's capacity (also analogous to an athlete's "fitness" level)
Acute-to-chronic workload ratio	Ratio of the acute workload to the chronic workload. The ratio provides an indication of the training an athlete has performed relative to their capacity. These data can then be fed into models to assess the likelihood the athlete may suffer an injury manifesting from repeated overuse (or underuse)
Digital biomarker	Defined characteristic that is measured as an indicator of normal biological processes, pathogenic processes, or biological responses to an exposure or intervention, including therapeutic interventions[24]
Digital health technologies	A system that uses computing platforms, connectivity, software, and sensors for healthcare applications[24]
External workload	Measure of the physical work done during training and/or competition
Internal workload	Individual physiological, psychological, or biomechanical response to an external load
Minimal clinically important difference	Smallest difference in score that patients can perceive as beneficial or harmful. It is a measure of a patient's experience of treatment outcomes
Remote athlete monitoring	Technology to enable monitoring of injured athletes to guide the return to play and return to performance processes
Return to play	Process of deciding when an injured or ill athlete may safely return to competition when the risk for reinjury is minimized
Return to performance	Athlete has returned to his or her sport and is performing at or better than preinjury level
Substantial clinical benefit	The threshold of outcome improvement that the patient perceives as considerable

Football League (NFL) bargaining lockout which resulted in players being barred from the training facility due to ongoing contractual discussions, Myer et al.[41] sought to track injury rates during the resulting accelerated transition from training camp to preseason competition. Ten Achilles tendon injuries occurred during the first 12 days of training camp with two additional injuries in the subsequent 17 days, which included the first 2 weeks of preseason competition. The authors noted a four-fold increase in Achilles injuries for the 2011 season compared to prior preseasons.[41] One result of the lockout could be an increase in relative reinjury risk during early sports reintegration, due to greater residual biomechanical and neuromuscular deficits from prior injuries or surgeries sustained in previous seasons. There is mixed evidence in the literature assessing whether injury risk increased following COVID-19–related lockdown periods (Table 3). During standard rehabilitation, the sports medicine team and strength and conditioning staff work collaboratively with the athlete to bridge the potential gap between the athletes' perceived versus actual sports readiness (often measured and compared using the rating of perceived exertion scale). This bridge is especially significant as subjective scores often do not correlate with quantified function and strength scores in athletes with severe injury, post-surgery, and potentially those returning from a viral illness such as COVID-19.

The literature that is currently available for sports medicine practitioners to understand these effects is studies conducted on athletes during "off-season" periods[53,54], which represents a reduction in the normal in-season training burden where training may be largely self-directed by the athlete. Most of our understanding is derived from short interval detraining experiments in previously trained athletes and individuals undergoing experimental bedrest.[34]

Table 3. Summary of published studies assessing injury profiles of athletes following a positive diagnosis of COVID-19 or the effect of the pandemic on injury rates in sporting leagues worldwide. Sports with high cutting and pivoting movements with a high propensity for musculoskeletal injuries were included in the analysis.

League	Findings
NFL	Platt et al.[42] • Proportion of players injured did not change before or after COVID-19 (IRR: 0.94, 95% CI: 0.9–1.0; $p > 0.999$) Baker et al.[43] • Players during weeks 1–4 of the canceled 2020–2021 preseason had significantly higher injury rates compared to weeks 1–4 of the 2016–2019 preseasons (RR by week: 1.82–4.09; $p < 0.001$) • Rates of injury in NFL players during weeks 1–4 of the 2020–2021 regular season had significantly higher injury rates compared to weeks 1–4 of the 2016–2019 seasons (RR by week: 1.31–1.88; $p < 0.01$)
NBA	Torres-Ronda et al.[44] • Players experienced an increased incidence of missed games ($p < 0.004$) and unique injury ratios ($p < 0.05$) during the 2020–2021 season compared to the 2019–2020. • Tendon/ligament injury groups had the highest ratio of missed games (1.16, 95% CI: 0.90–1.37) and unique injuries (0.21, 95% CI: 0.18–0.25)
EPL	Mannino et al.[45] • Players experienced an increased incidence of muscular/ligamentous injuries with decreased time to first injury during the 2020–2021 season compared to the 2018–2020 seasons • There were 6.8 days in-between games played during the 2020–2021 season compared to the previous years of 9.12 (2018–2019) and 7.12 (2019–2020) days
Italian Serie A	Marotta et al.[46] • Players experience no increase in incidence of musculoskeletal injuries per 1000 game-hours between post-COVID-19 lockdown (prelockdown: 16.9, post-lockdown 15.5; RR = 0.92; $p > 0.05$)
Bundesliga	Seshadri, Thom et al.[47] • Players during the 2020–2021 season had a 3.1× higher likelihood for injury following the COVID-19 lockdown (RR: 3.1; $p < 0.001$) • 17% of all athletes experienced injury (with muscle injuries being the most common) during their first competitive match following lockdown Krutsch et al.[48] • When examining injury rates for the 9 match days following the restart of the 2019–2020 season (4.9/1000 hours), rates were significantly lower compared to the previous season's final 9 match days (6.9/1000 hours, $p < 0.001$) and did not increase compared to the rates after summer (5.5/1000 hours, $p > 0.05$) or winter break (5.6/1000 hours, $p > 0.05$). Thron et al.[49] • There were no significant differences in injury occurrence when comparing the 25 match days before COVID-19 lockdown to the 9 match days post-lockdown ($p > 0.05$).
Belgian First Division A	Wezenbeek et al. (Wezenbeek E, Denolf S, Willems TM, et al. Br J Sports Med 2022;1–7. doi: bjsports-2021-104595) • Athletes from three Belgian professional male football were significantly more likely to develop muscle strain following SARS-CoV-2 infection (HR = 5.1, 95% CI: 1.1–23.1; $p < 0.037$)
MLB	Paul et al.[50] • Pitchers in the 2020–2021 season were significantly more likely to undergo ulnar collateral ligament repair (UCLR) per game played compared to the 2017–2019 seasons (RR: 2.88; $p < 0.001$)
Running	Toresdahl et al. (2021)[51] • Athletes who self-reported a diagnosis of COVID-19 had a higher incidence of injury compared to those without prior COVID-19 infection (OR: 1.66, 95% CI: 1.11–2.48; $p = 0.01$) Dejong et al. (2021)[52] • Athletes experienced an increased running-related injury (RRI) risk during the pandemic, compared to prior to COVID-19 lockdown (OR: 1.4, 95% CI: 1.18–1.61)

NFL: National Football League; NBA: National Basketball Association; EPL: English Premier League; MLB: Major League Baseball.

Table 4. Physiologic effects of deconditioning.[32,33,37]

Cardiovascular	Respiratory	Psychological	Musculoskeletal	Endocrine
Decreased stroke volume leading to a decrease in cardiac output	Reduction in maximal arterial–venous (mixed) oxygen difference	Social and training isolation	Decreased strength and endurance	Increased percentage body fat mass
Decreased plasma volume and total hemoglobin content	Impaired ventilatory efficiency	Variable access to support groups	Decreased flexibility	Decreased insulin sensitivity
Initial rapid decline $\dot{V}O_2$ max		Disruption in career goals	Decreased skeletal muscle capillarization	Altered temperature regulation
Increase in resting heart rate		Unpredictable schedules	Conversion of type 2 fast twitch to type 1 slow twitch	
		Increase in post-traumatic stress symptoms in public	Reduction in collagen synthesis in tendon tissue	

Although the effect of duration and severity of infection in these physiologic maladaptations have not been fully elucidated, we may have enough understanding of the short-term changes such that inferences on potential changes in the quarantined athlete are possible (Table 4). Thus, detailed and quantifiable rehabilitation processes are needed prior to resuming regular "premorbid" level of play. In short, the effects of detraining as it affects the musculoskeletal health of the athlete are summarized below.

Psychological health

Restrictions in training present several psychological considerations in the athlete. There is likely a significant impact of confinement and isolation on athlete psyche and eventual performance after returning from isolation.[55,56] Social isolation, disruption in career goals, and reduced access to training resources have been described as detrimental influences on athlete mental health during the pandemic. Data exist describing the effects of quarantine on the public, which shows that there are wide-ranging, substantial, and potentially long-lasting negative psychological maladaptations including exhaustion, depression, insomnia, and anxiety.[57] Clearly, the psychological impact is not unique to the athlete, but athletes do have unique stressors as it may pertain to disproportionate access to social and training resources depending on where they live, ability to cope with the disruption in their career, and learning to train alone without the potentially positive influence of social bonding on exercise performance.[37,58–60] A recent systematic review found that athletes reported worse mental and emotional health during the pandemic, but these effects were attenuated by home training programs and organized quarantine training.[56] Strategies have been employed to ensure teams are promoting mental health in their athletes during these periods of quarantine.[61]

Cardiopulmonary health

Short-term athlete deconditioning in as little as 4 weeks can lead to reduced plasma volume, total hemoglobin content, impaired ability to modulate blood volume, disruption of temperature regulation, and maladaptations in HR and BP control. These changes can instigate cardiac atrophy with resultant deleterious effects on stroke volume and cardiac output.[20,62] These changes manifest clinically as decreases in maximum oxygen delivery ($\dot{V}O_2$ max). A significant decrease in an athlete's $\dot{V}O_2$ max has been previously described following 2–4 weeks of deconditioning.[32] Following this period, deconditioning may lead to a return to baseline values regardless of prior training intensity.[39] Jukic et al.[61] recommended that sidelined athletes perform endurance training or resistance circuit-based training to promote both neuromuscular and metabolic adaptations, thus minimizing the effects of deconditioning on $\dot{V}O_2$ max and the neuromuscular system. It should be recognized that even without the added stress of infection, deconditioned athletes may be subjected to these changes and will require cardiac re-training to meet their basal level of function.

Regardless of deconditioning, cardiovascular abnormalities, such as arrhythmias[63] and myocarditis,[64,65] remain an important concern following COVID-19 infection. Myocarditis has been reported of particular concern to the sports clinician as it is exacerbated by exercise during recovery and an important cause of sudden cardiac death during exercise.[65,66] As a result, subsequent reports of athletes with suspected COVID-19–induced myocarditis raise concerns for the short- and long-term safety of athletes.[67,68]

Early in the pandemic, initial concerns about the very high incidence of myocardial involvement in hospitalized patients with COVID-19 resulted in sports cardiology leaders creating conservative RTP guidelines for athletes following an infection.[69] The American College of Cardiology's Sports & Exercise Cardiology Council (ACCSECC) initially recommended a 14-day rest period with self-isolation before gradual resumption of activity.[69] For all mildly and severely symptomatic athletes, abnormal triad testing results (high sensitivity troponins (hsTrop), 12-lead electrocardiogram (ECG), and echocardiogram) would determine the need for cardiac magnetic resonance (CMR) imaging, a tool validated in the diagnosis of myocarditis in the setting of high pretest probability.[69,70] As clinicians gained experience in RTP for high school, professional, and masters (>35 years old) athletes infected with COVID-19, updated ACCSECC guidelines evolved to (a) reflect Centers for Disease Control and Prevention (CDC) guidance by reducing self-isolation to a 10-day rest period and (b) solely require cardiac screening for athletes with significant symptoms, or those suggestive of either clinical myocarditis or multisystem inflammatory syndrome (MIS-C).[65] In contrast to prior recommendations, recent guidelines following the 2022 American College of Cardiology (ACC) expert consensus specify cardiac screening should no longer be performed unless there are cardiopulmonary symptoms that justify clinical concern for myocarditis.[71]

Using updated guidelines, Martinez et al.[64] performed cardiac screening on 789 professional athletes following COVID-19 infection. The authors found 0.6% of athletes developed inflammatory heart disease (myocarditis or pericarditis) by CMR imaging, with no adverse cardiac events reported. A separate study by Daniels et al.[72] employed CMR data from the Big Ten COVID-19 Cardiac Registry to illustrate that abnormal findings on CMR occurred in 2.3% (range 0–7.6%) of college athletes following a COVID-19 diagnosis. While CMR remains the non-invasive gold standard for myocarditis diagnosis without biopsy, the specificity of CMR for myocarditis diagnosis in an otherwise healthy population is unknown.[73] In hospitalized patients with suspected acute myocarditis, Lurz et al.[74] found CMR to have a 76% sensitivity and 54% specificity in the diagnosis of endomyocardial biopsy-confirmed myocarditis. The use of CMR in diagnosis of COVID-19–induced cardiac complications is limited in the absence of both clinical symptoms suspicious for myocarditis and abnormal cardiac screening tests.[75] Cardiac screening is time intensive and requires plentiful resources in addition to team personnel work hours; therefore, wearable technology may be employed to remotely and/or continuously cast a wide net in monitoring for changes in cardiac health (i.e. abnormal ECG and recording of arrhythmias/palpitations) of youth, collegiate, and professional athletes recovering from COVID-19 infection.[12]

There remains a gap in the literature for clinical studies using wearable devices to monitor athlete HR, rhythm, and structural changes following COVID-19 infection. Currently, wearable technology may allow us to study the cardiovascular effects of the changing public health landscape of the virus and its variants and complement present cardiac screening protocols as athletes gradually return to prior workload. More research is still required to inform how athletes can use resting HR (RHR) and HRV to inform their recovery following COVID-19 infection.

Integration of wearable technology into the return to play and performance workflow

Rehabilitation from COVID-19 has helped shine light on the potential for wearable technology to advance the field of sports medicine, specifically for monitoring the internal and external workload of athletes.[12,76–80] Our assessments of athletes and determination of when one is fit to RTP are very challenging. We believe it is important to think of the athlete as behaving as a dynamic system as described by Stern et al.[81]; in the setting of a major destabilizing input (quarantine and illness), the athlete is pushed toward the "injured state." Gabbett[82] described the internal and external workload paradigm and how perturbations in either can lead to an increased risk of injury. To better capture subtle changes in these systems, we recommend assessing variables describing external and/or internal load continuously, in real time, and analyzing them in context of the individual's environment. It is likely that a continuous measurement is better able to capture and understand the condition of the athlete than any one-time measurement. Collecting data in a continuous manner is best achieved through wearable technology as this provides a tool for assessing how the athlete's system behaves continuously over time. It also provides a medium to collect data from multiple inputs in a time synchronous manner.

The performance and injury determinants important from an external and internal workload and other associated wellness perspective include (a) movement (i.e. distance and acceleration), (b) muscle oxygen saturation (SmO_2), (c) sleep quality and stress monitoring and concomitant coping skills, (d) HR (and derivations of it), (e) RR, and (f) core body temperature (CBT). We build upon our discussion from the previous section to discuss each of these parameters and how wearable technology may be applied to optimize each system in the athlete rehabilitating from COVID-19 or extended quarantine.

Movement

For most athletes, external load can be captured through global positioning system (GPS) devices and microelectromechanical (MEMS) devices.[83–85] The utility and limitations of these measurements in monitoring the movement profiles of athletes are discussed in prior publications by our group.[12,77] Given the multitude of GPS sensors currently used by sports practitioners among teams and interchangeably between practices and matches, it is imperative for researchers to perform independent validation of this technology[85] prior to its use in guiding RTP programs. Several external workload parameters[86] may be considered which include (a) movement inertia measured as inertial measurement units, (b) acceleration efforts/distance as measured by GPS or accelerometer,[87] and (c) sport-specific performance tests of stability, power, and motor control.[20] In the deconditioned athlete, rehabilitation programs may be tailored to the athlete by monitoring trends in external workload parameters to prevent supra-therapeutic acute on chronic workloads.[82,88–92] Li et al.[83] studied workload profiles in healthy NFL athletes over a two-season period and found that athletes who had an acute-to-chronic workload ratio greater than 1.6 were 1.5× likely to have a soft-tissue injury relative to time- and position-matched controls. The data demonstrated the potential for wearable technology to monitor workloads and assess injury risk.[93] A systematic review by Andrade et al.[94] assessed 20 studies, totaling 2375 injuries from 1234 athletes in various sports, to investigate correlations between acute to chronic workload ratio (ACWR) and risk of injuries resulting in loss of playing time in elite team sport athletes. The authors found that athletes were at a greater risk of time-loss injuries with an elevated ACWR compared to a moderate or low ACWR using session rating of perceived exertion and movement parameters as a measure of external workload. Despite studies demonstrating the potential of the ACWR for injury modeling, there has been an emergence in literature questioning its efficacy as a surrogate for soft-tissue injury prediction.[12,95,96] While this discussion is out of scope for this narrative review, we refer the reader to other reviews juxtaposing this topic.[12,97–99] Application of a sport- and context-specific model is necessary and lacking to ensure a high positive predictive value as it relates to monitoring the health, performance, and wellness of athletes and we believe wearable technology provides the measurement of objective and continuous internal and external markers to complement and guide clinical decision-making.

There lack studies using wearable technology to guide the RTP of athletes following extended deconditioning.[12] Some argue that the workload of athletes should be increased ~10% each week with a RTP decision typically occurring about by the time the athlete has reached ~90% of the total external workload capacity prior to injury.[82] It remains to be seen how athlete external loads should be prescribed and progressed following a COVID-19 diagnosis. Initial evidence demonstrates that musculoskeletal injuries may increase after returning to sport following a COVID-19 diagnosis or quarantine, with severity and duration of illness as additional confounding variables (Table 3). In the post–COVID-19 athlete, assessment of internal workload becomes particularly relevant as the athlete may have changes in internal pathological cardiac (myocarditis), respiratory (reduced lung capacity and fibrosis), and thermoregulatory (febrile illness) function. Balancing sport-specific and local tissue

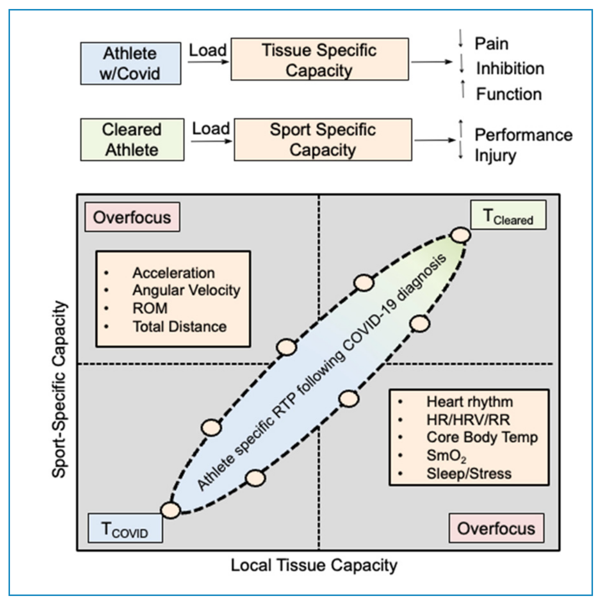

Figure 1. The balance between sport-specific and local tissue capacity in healthy athletes and those return to play and performance following a positive COVID-19 diagnosis. In healthy athletes, the prescription of training load prioritizes the development of sport-specific and local tissue capacity to improve performance and minimize injury risk. For athletes diagnosed with COVID-19 and seeking a return to training and subsequent competition, the prescription of training load in this population prioritizes the development of local tissue loading to decrease pain and inhibition and increase function to mitigate injuries that may manifest from inopportune modulations in workload. Maintaining a balance between local tissue loading and sport-specific loading via the measurement of biomarkers, physiological markers, or movement-based markers is critical to quantify and complement athlete-reported outcome measures recorded by athletic trainers and physical therapists. Modified with permission from BMJ Publishing Group Ltd.[100]

conditioning is imperative to optimize the RTP and return to performance processes (Figure 1).

Muscle oxygen saturation

A consensus statement recommends that post–COVID-19 rehabilitation should start with a week of low-level muscle stretching and light muscle strengthening activity.[101] Other than these guidelines, there is little guidance on how athletes should begin strength and conditioning training from a musculoskeletal standpoint. This becomes particularly relevant in athletes who have sustained more severe muscle atrophy because of hospitalized deconditioning. Near-infrared spectroscopy (NIRS) has been used to study SmO_2 which is a biomarker that decreases acutely in response to muscular strength exercise.[102] The muscular response of SmO_2 using NIRS is significantly associated with the maximum blood lactate concentration achieved during steady state and critical power exercise as well as utility in monitoring the physical response of athletes during endurance exercise.[103] Measurement of SmO_2 could make up for challenges with $\dot{V}O_2$ max and lactate measurements, when continuous and non-invasive monitoring is required. The literature involving SmO_2 measurement has solely focused on healthy athletes during workouts (e.g. squatting activities[104–106]); however, with athletes presenting with atrophy following extensive time away from sport, measurement of SmO_2 levels in this injured population could yield important data on changes in muscle physiology during rehabilitative periods.

Sleep and stress

The origins of the degradation of sleep quality induced during the COVID-19 pandemic are numerous, complex, and entangled. A systematic review detailed the impact of the pandemic on changes to physical activity, mental health, and quality of life in professional athletes.[107] Specifically, over the course of the pandemic, stress, fatigue, and depression were found to increase while sleep quality decreased.[108] A study by Silva et al.[109] found that elite male athletes had significantly higher sleep latency and wake after sleep onset than women ($p = 0.004$ and $p = 0.002$, respectively; $n = 146$ athletes). Altered mood (POMS scores) had a significant effect on sleep quality and hours.[110] Interestingly, the amount of training days per week was positively correlated with sleep quality.[111] Another study showed that there was a delay in falling asleep and an increase in daytime sleepiness compared to before the pandemic among athletes.[108] These changes were significantly associated with negative mental health outcomes. The authors highlighted the importance of considering individuals' circadian rhythms, as the evening chronotype subjects had worse mental health outcomes due to changes in sleep time. A large cross-sectional study ($n = 339$, median age: 20 years old (IQR, 19–21), 48.5% female, 47% individual sports) showed that sleep hygiene has been greatly perturbed due to the COVID pandemic.[112] Results showed a disrupted sleep quality in 63.7% of participants. One in five students had a total sleep time under 6.5 hours per night.[112] Poor sleep quality was significantly associated with nocturnal concerns related to the pandemic, female gender, caffeine consumption, and lack of sleep routine (all $p < 0.05$).[112] Sleep hygiene and stress management can be optimized to improve the restorative effect of sleep and reinforce its benefits on metabolic, immune, and cognitive functions that can improve the performance of athletes. Wearable technology can provide continuous and reliable assessment of sleep habits and hygiene without being entirely dependent on user input and can provide data on adherence to sleep hygiene protocols.[113] Applying ML to data sets collected from sleep detection technology will allow for development of more accurate monitoring of sleep hygiene.[114] Future studies determining the relationship between sleep quality and soft-tissue injuries are needed.[115]

Heart rate and heart rate variability

HR and HRV are established variables currently used in load management. Prior work has established that reductions in HRV during rapid increases in workload are associated with an increased risk of developing overuse injuries.[116] These results imply that larger changes in workload may be well tolerated when HRV trends remain "normal" or "high."[117] Therefore, HRV monitoring may be used by practitioners to adjust and individualize training load prescriptions to minimize the risk of overuse injury.

Viral infections are known to affect the cardiovascular system, leading to an increased RHR in the presence of fever.[118] According to Friman and Wesslén,[118] an increased RHR (>10 bpm higher than normal) is a contraindication for physical training in addition to fever (>38°C or 0.5°–1° higher than usual). A case study by Baumann et al.[119] showed that COVID-19–infected individuals exhibit decreases in resting HRV but no increase in RHR. Therefore, it is insufficient to solely examine RHR; further derivations of HR are required for a differential analysis.

HR and HRV are being described in individualizing training and detecting overtraining in athletes infected with COVID-19. A recent case report used HR and HRV to individualize training and monitor athlete health status in an elite athlete recovering from viral illness.[120] Viral infection had a direct influence on HR and HRV measurements due to cardiac autonomic regulation; thus, monitoring HRV levels is a validated tool for indicating cardiac autonomic responsiveness. Two studies have found a slower HR acceleration at the onset of exercise in athletes suffering from exercise-induced fatigue following overtraining.[121,122] A reduced performance capacity and altered cardiac autonomic control due to fatigue may also occur in athletes following the onset of a viral infection. With current technology available (i.e. wrist monitors, epidermal patches, or chest straps), graded progression of training with HR monitoring can be performed relatively routinely in collegiate and professional sporting environments.

Early detection of COVID-19 infection and signs of influenza-like illness may be possible using metrics related to cardiac function, such as RHR, HRV, and oxygen saturation (SpO_2).[2] Elevation in RHR due to physiological response to infection has been shown to accurately model influenza outbreaks at a population level.[123] Mishra et al.[124] and Alavi et al.[3] developed an algorithm that utilized data from commercial smartwatches (i.e. Fitbit, Apple Watches, and Garmin) to detect onset of COVID-19 based on changes in elevated RHR when controlling for daily activity (i.e. daily step count).[124] Furthermore, using the Apple Watch, HRV was found to be predictive of COVID-19 when measured on infected healthcare workers at Mount Sinai Health System.[125,126] Workers who reported COVID-19 symptoms and tested positive for COVID-19 via polymerase chain reaction (PCR) testing were found to have significantly decreased HRV at onset of symptoms ($p = 0.01$) and significantly different HRV levels relative to workers who were COVID-19 negative ($p = 0.006$).[126] While clinical trials are ongoing, the CovidDeep app by NeuTigers claims to use metrics including BP, HRV, and SpO_2 to identify users with COVID-19 infection with 90% accuracy.[127] The technology makes use of Empatica's E4 wristband and manual input of BP and SpO_2 measurements using external monitoring devices (i.e. non-wearables).[128] An all-encompassing wearable device measuring basic vitals and advanced digital biomarkers such as cuffless BP has not yet been shown to measure these variables simultaneously during ambulatory subjects (as is required for high-performance athletes). However, the studies suggest that sports clinicians may integrate available measurements of cardiac function through single or multiple wearable devices to both predict COVID-19 infection and monitor athlete recovery. Furthermore, asymptomatic athletes or those with mild symptoms may be monitored remotely by a team physician using wearable sensors as these individuals may gradually ramp up their exercise volume at home while completing their isolation. In this case, monitoring external or internal workload could provide athletic trainers an objective metric to ensure the return to sport processes are not ramped up in an expeditious manner, as to mitigate injuries from spikes in acute workloads.[92]

While the above variables remain important data for the sports cardiologist, wearable devices that can remotely monitor heart rhythm are necessary if this technology is to be implemented into current COVID-19 RTP protocols. Wearable sensors are capable of measuring physiological and pathological heart rhythm and volume changes using ECG and photoplethysmography (PPG), respectively.[12] Such devices remain an exciting avenue for the study of cardiac health in infected athletes. There is limited data on the use of such technologies to monitor heart rhythm in athletes; the evidence today is on patients with arrhythmias such as atrial fibrillation (AF).[129] Bumgarner et al.[129] investigated the ability of the wrist-worn KardiaBand (KB) to detect sinus rhythm and AF compared to 12-lead ECG recordings. The KB interpreted AF with 93% sensitivity, 84% specificity, and a κ coefficient equal to 0.77, compared to physician interpretation of KB recordings that demonstrated 99% sensitivity, 83% specificity, and a κ coefficient equal to 0.83. In short, the team concluded that the KB algorithm for AF detection, supported by physician review, can accurately differentiate AF from sinus rhythm. While AF is a concern following COVID-19 infection,[130] results such as from the study above suggest the potential for wrist-worn wearable devices to provide heart rhythm data in a non-invasive and unobtrusive manner. Currently, the Apple Respiratory Study is underway aiming to integrate ECG recordings from Apple Watches to detect physiological changes representing COVID-19 infection.[131]

Respiratory rate

Persistent cough and dyspnea following acute COVID-19 infection are anticipated to fully resolve in the 4-week period following most infections.[132] While this recovery should be progressive, it is reported to be exacerbated especially in the context of vigorous exercise.[132] Deviation from a pattern of improvement during rehabilitation, onset of new symptoms, or progressive early fatigability may be detected more readily through physiologic monitoring and should prompt further clinical workup and cessation of an athlete's RTP program. Athletes with symptomatic disease may experience chronic sequelae such as breathlessness on exertion, wheezing, and/or chest tightness that may or may not be related to exertion. In general, athletes have a high prevalence of underlying airway dysfunction; one in four endurance athletes is affected by airway dysfunction such as asthma and exercise-induced bronchoconstriction.[133] Chronic COVID-19 sequelae may alter normal trends and patterns in premorbid physiologic monitoring and should influence the decision on when to RTP.[134] The WHOOP strap has emerged as a popular wrist monitor for athletes to monitor HR, strain, RR, and sleep[135] and assess the onset of COVID-19.[136] Using the WHOOP 3.0 strap, Miller et al.[4] developed a model which identified 20% of COVID-19–positive individuals 2 days prior to symptom onset and 80% of COVID-19–positive cases by the third day of symptoms. A change in RR, increase in RHR, and decrease in HRV were found to correlate with a positive COVID-19 diagnosis.[4] Given the popularity and proven capability to predict COVID-19 symptoms, utilization of such a device may be a viable option for athletes to provide numerical data during the RTP process.[3,124]

Core body temperature

There is some literature[137,138] guiding clinicians on how to manage temperature aberrations in athletes; however, it remains unclear how the COVID-19 virus specifically affects the thermoregulatory system and overall health of athletes. There is some evidence that exists on the effects of fever (elevated CBT secondary to endogenous or exogenous pyrogens that reset the hypothalamic set point) on physiology and performance.[139] Specifically, normal body processes that cool the body such as vasodilation and sweating are altered during fever.[140] Furthermore, a 10% increase in metabolic rate has been observed for every 1°C increase in temperature.[140] Additionally, an increase in peripheral vascular resistance (blood shunted away from peripheral capillary beds) has been noted.[140] Fever has been correlated with a reduction in exercise tolerance, decreased endurance and muscle strength, and an increase in perceived fatigue.[141] The potential for dehydration has been known to occur via the production of antidiuretic hormone causing reductions in cardiac output and BP.[141] Decreases in speed and coordination have been observed after febrile illness and can be seen as early as 3- or 4-day post-infection which may increase the risk of additional injuries, including ankle sprains and dislocations.[118] When an athlete exercises with a fever, temperature-regulating mechanisms are altered and could result in potentially harmful increases in core temperature, especially if the febrile illness also causes some degree of dehydration. Thus, continuous temperature monitoring may provide insight into when an athlete is in danger of exertional heat illness[137,138] by training too soon after or during an acute febrile illness. However, it is unclear how routine CBT measurements can assist in rehabilitation other than ensuring the athlete has recovered from fever to safely increase physical activity and not threaten transmissibility.

The primary modalities for monitoring CBT in athletics involve the use of ingestible pills or rectal measurements.[142–144] The use of pills for CBT monitoring is not ideal for athletes, as pills pose a severe detriment if an athlete suffers an injury and requires an magnetic resonance imaging. Additionally, often, the athlete must wear or fasten a recorder around the waist or arm for data transmission, thereby hindering the athlete from sport-specific movements. The invasive nature of rectal thermometry is a significant hurdle for athlete monitoring as the recording is uncomfortable and data are acquired in a discrete manner.

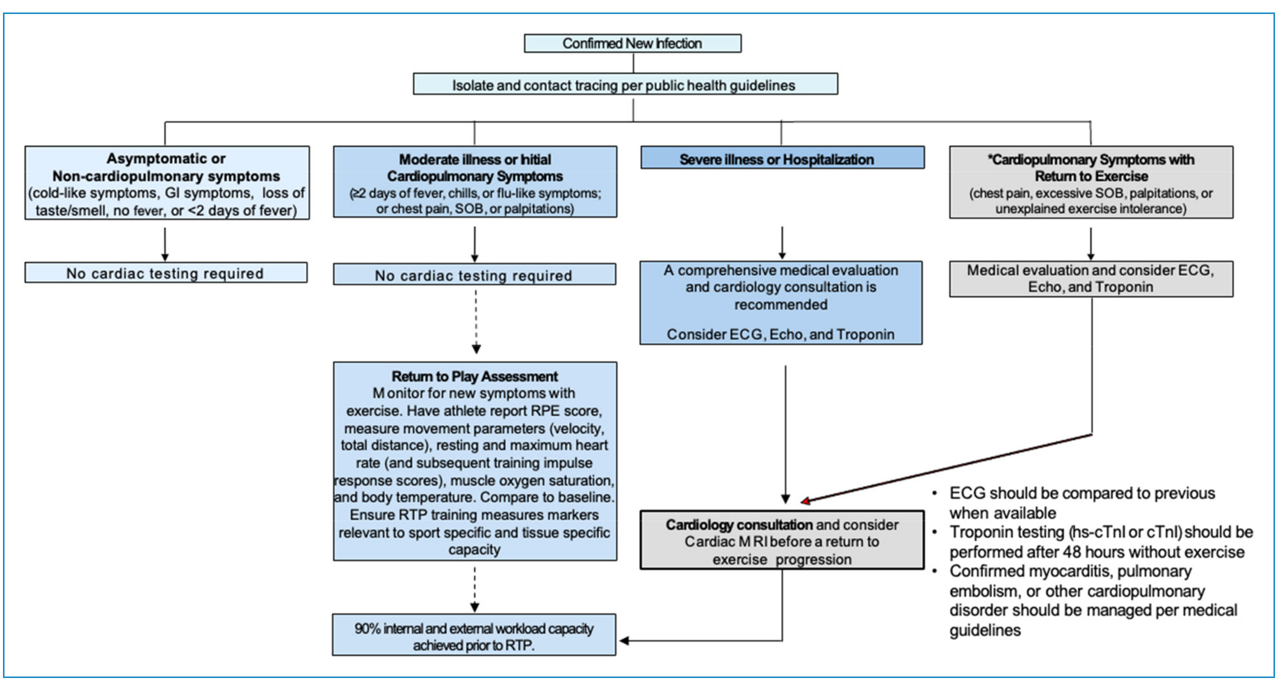

Figure 2. Implementation of wearable technology for cardiopulmonary and musculoskeletal monitoring for athletes following a positive COVID-19 infection. Return to play assessment is left to the discretion of the medical staff for athletes who have moderate illness or initial cardiopulmonary symptoms. Figure adapted and modified from Kim et al.,[65] Phelan et al.,[69] Writing Committee et al.,[71] Drezner et al.,[146] and Phelan et al.[147]

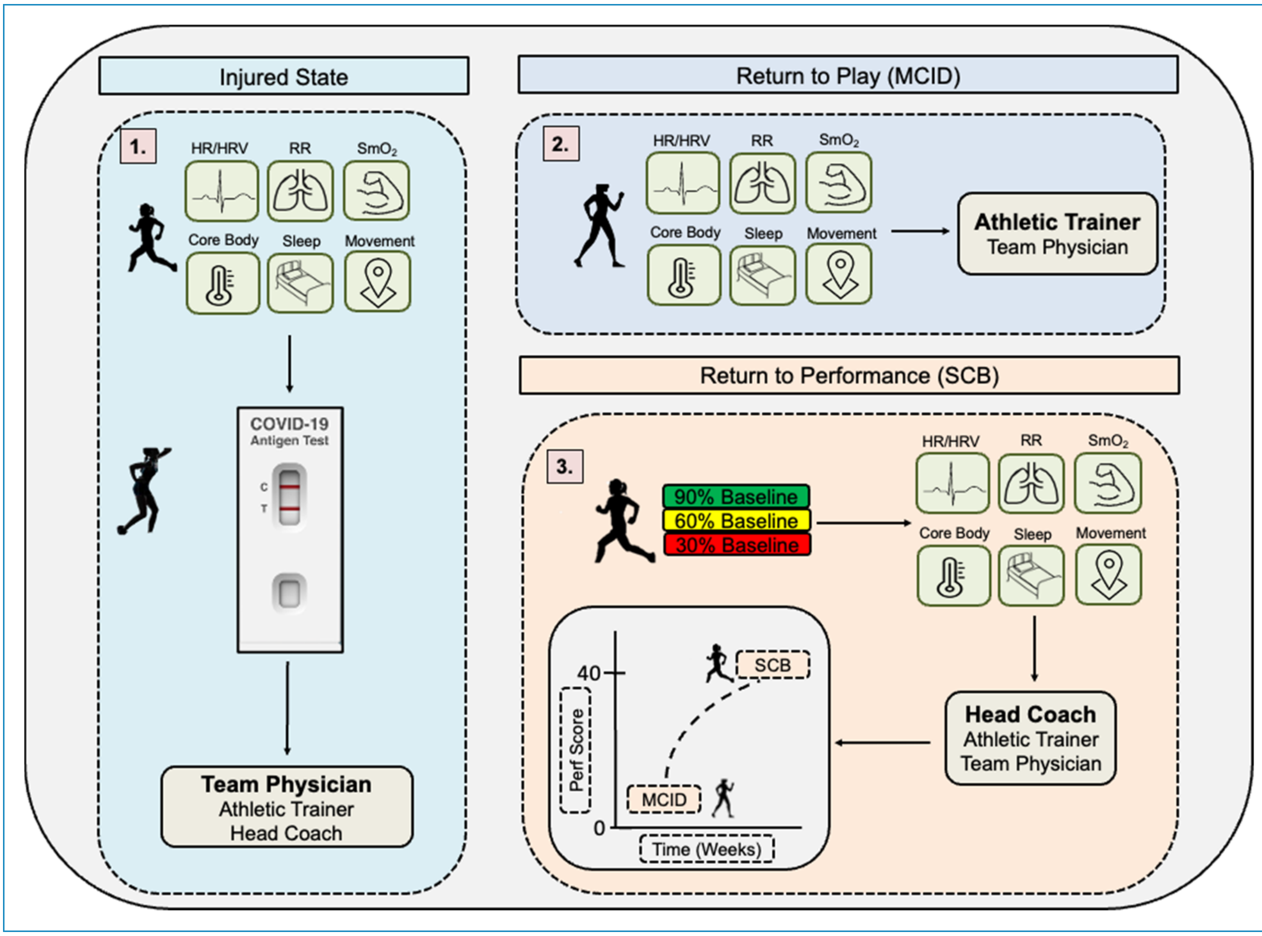

Figure 3. Operational workflow detailing the implementation of wearable sensors into the clinic to enable the transition from the return to play to return to performance level. (1) Changes in vitals measured from wearable technology necessitate the athlete to get tested for COVID-19. A positive test coupled with the athlete reporting symptoms are reported to the team physician. (2) Following an extended quarantine period, the athletic trainer monitors the athlete's response to the workouts using wearable sensors until the athlete is able to make a meaningful improvement in overall performance by meeting a minimal clinically important difference (MCID) score which factors in any pain, functionality, and movement deficits during the rehabilitation sessions. The athlete will then be monitored until they meet acceptable internal and external workload thresholds compatible with other age- and sport-matched healthy controls (analogous to patient acceptable symptom state). (3) As the athlete is cleared to return to play, the tests are repeated and the athlete is assessed comparing their current performance to their prior healthy and competitive level of performance, in part analogous to achieving a substantial clinical benefit (SCB). The metrics collected from wearable sensors are compared to baseline levels with a criterion > 90% (green) indicating a physiologic state compatible with return to performance. The head coach then integrates the athlete back into the team structure. Perf: performance.

Thus, the nature of CBT collection and lack of continuous data limit this method from being utilized for athlete monitoring. The development of wearable technology to measure CBT in a continuous, unobtrusive, and non-invasive manner would address this unmet clinical need. Verdel et al.[145] evaluated the efficacy of the CORE, greenTEG, wearable sensor against rectal measurements. The authors found that the temperature indicated by the CORE sensor did not agree well with rectal measurements, with ∼50% of all paired measurements differing by more than the predefined threshold for validity of ≤0.3°C. Given the poor correlation to rectal measurements, the measurement of CBT non-invasively is still not possible today. Future development efforts could potentially provide baseline data to translate physiological understandings into clinical insight.

Recommendations: wearable technology in the rehabilitation clinic to guide RTP

Our recommendations regarding detraining as it effects the musculoskeletal system, sleep quality, psychological state, cardiopulmonary health, and thermoregulatory system of the athlete are summarized below. We propose an algorithm building upon those from the ACC and ACSM that

Table 5. Sampling of commonly used wearable technology used by athletes today for monitoring musculoskeletal markers, sleep, stress, cardiopulmonary, or thermoregulatory parameters. Devices with multi-functionality are only listed once. Table is modified from Seshadri et al.[77]

Measurement	Company	Product Type	Product Functionality
Musculoskeletal	Catapult	Sensor unit	Movement, turn rates, orientation, and heart rate
	Cricflex	Sleeve	Measures arm angle and force during bowling
	Driveline[a]	Sleeve	Measures arm angle and force during throwing
	Moxy	Sensor unit	Measures muscle oxygen saturation levels
	Statsports	Sensor unit	Movement, turn rates, orientation, and strain
	Zebra	Sensor unit	Movement, turn rates, orientation, and player tracking
Sleep/stress	Moov	Wrist monitor	Heart rate, sleep quality, and activity
	WHOOP	Wrist monitor	Heart rate, strain, sleep, and respiration rate
	Oura Health	Ring	Heart rate, body temperature, and movement
Cardiopulmonary	Apple	Wrist monitor	Heart rate, heart rhythm, and blood oxygen levels
	Fitbit	Wrist monitor	Heart rate
	Medtronic[b]	Strap	Heart rate, respiration rate, and core body temperature
	Polar	Strap	Heart rate
Thermoregulatory	greenTEG	CORE	Core body temperature, heart rate, and skin temperature

N/A: lack of technology utilized by athletes today.
[a]Driveline acquired Motus.
[b]Medtronic acquired Covidien who acquired Zephyr, the developers of the BioHarness.

incorporates wearable technology into the COVID-19 RTP process to guide rehabilitation (Figure 2).

- Increased risk for musculoskeletal injury following RTP resulting from extended inactivity warrants careful monitoring and more comprehensive RTP evaluation than what is currently described in the literature.
- Athletic trainers should have athletes record their sleep duration and quality in electronic sleep logs during quarantine to prevent cases of insomnia and emotional fatigue.
- Teams should organize mental fatigue monitoring and mental training workshops via telecommunication platforms to assess the mental acuity of the athlete.
- Athletes while in quarantine should be provided the resources to perform body mass resistance circuit-based training to promote aerobic adaptation.
- Athletes of all levels should establish a baseline RHR, HRV, and heart rhythm analysis at the beginning of each season in the chances of future COVID-19 infection or exposure for comparison and return to baseline.
- Infected athletes with mild symptoms should use RHR and HRV to inform additional rest following the recommended time away from activity by their team physician.
- Infected athletes with cardiopulmonary symptoms during or following infection should be monitored in a continuous and remote manner to assess metrics such as RHR, HRV, and heart rhythm to screen for pathological rhythm changes in heart function. Per expert consensus recommendations, infected athletes with cardiopulmonary symptoms should seek cardiology consultation for triad testing.[71]

Limitations and opportunities

It is impossible to forecast far into the future with any degree of accuracy an athlete's risk for injury or specific RTP time. Rather, the objective should be on integrating measured variables and associating these with the perceived efforts of the athlete and recommendations and observations by medical team personnel (Figure 3). Minor changes during the rehabilitation process may result in profound differences over time which may ultimately improve RTP outcomes by minimizing injury risk and maximizing athlete performance. RTP outcomes can be improved by viewing injury risk as a regularly changing, non-linear, and dynamic system.[116] By honing-in on the more influential determinants, practitioners may prevent more athletes from tipping into the "injury trough" and having a poor result when returning from quarantine or COVID-19. We have provided a sampling of devices commonly used by athletes to help the sports medicine team to choosing and translating the data acquired from these devices (Supplementary Tables 1 and 2) to meet their clinical specifications (Table 5).

Prior to adoption, we strongly recommend independent validation of technologies to mitigate errors manifesting from inaccuracies in measurement and to meet user needs.[148,149] While the collection of continuous data is desirable (in most instances), from a practical perspective, data cleaning and interpretation can be time consuming depending on the device.[150] Athlete management systems, which often integrate questionnaires, rating of perceived exertion scores, and data from wearable sensors, need to be created with the end users in mind (often the athletic trainer and head coach) for efficient integration into the daily workflow to accurately inform the clinical decision-making process in an expeditious and accurate manner. As a result, issues around data privacy and interoperability of wearable sensors into existing data management systems used by the team need to be considered.[151,152] This can be accomplished by an interdisciplinary team and collaboration between engineers, sports medicine clinicians, and athletic trainers.[76]

Conclusion

The COVID-19 pandemic has galvanized our need to harness a digital infrastructure for remote monitoring. Wearable sensors are widely used in professional sporting leagues to measure biomechanical and physiological metrics and guide RTP decisions. However, the integration of these remote athlete monitoring technologies such as wearable sensors to guide the RTP and return to performance processes of athletes following a COVID-19 diagnosis has not been studied in the literature. This review provides guidelines for team physicians, athletic trainers, and sports scientists on the role of wearable technology in the RTP process. Our paper provides an objective method for sports medicine practitioners to quantify the RTP status of athletes following a COVID-19 diagnosis with broader implications to viral illnesses warranting extended confinement periods.

Acknowledgements: The authors acknowledge ongoing collaboration relating to the translation of wearable technology for athlete health and performance monitoring.

Author notes: Dhruv R Seshadri is currently affiliated with Department of Bioengineering, Lehigh University, Bethlehem, PA, USA.

Peter Duking is currently affiliated with Department of Sports Science and Movement Pedagogy, Technical University of Braunschweig, Braunschweig, Germany.

Contributorship: DRS, ERH, and MLT conceived the ideas presented in the manuscript and drafted and edited the manuscript. MSE, DMP, JJH, PD, KDM, JS, BG, RF, JGC, MK, MJS, TJG, and JEV contributed to the editing of the manuscript.

Declaration of conflicting interests: The author(s) declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: JEV serves as an education consultant for Arthrex. TJG works as a consultant to several high-performance organizations, including sporting teams, industry, military, and higher education institutions.

Ethical approval: Not applicable.

Funding: The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: D.R.S acknowledges funding from the American Orthopedic Society for Sports Medicine (grant #2022PM2). The project described was supported by a grant (#2022PM2) from the American Orthopedic Society for Sports Medicine. The content is solely the responsibility of the authors and does not necessarily represent the official views of the American Orthopedic Society for Sports Medicine.

Guarantor: DRS

Informed consent: Patient consent and thus IRB approval were not necessary given that this is a narrative (literature) review.

ORCID iDs: Dhruv R Seshadri https://orcid.org/0000-0002-2426-8795
Ethan R Harlow https://orcid.org/0000-0001-9995-5701
Michael S Emery https://orcid.org/0000-0003-2926-5371

Supplemental material: Supplemental material for this article is available online.

References

1. Vital signs monitoring devices market size report, 2021–2028, https://www.grandviewresearch.com/industry-analysis/vital-signs-monitoring-market (accessed 17 March 2022).
2. Frontiers | Wearable sensors for COVID-19: a call to action to harness our digital infrastructure for remote patient monitoring and virtual assessments | Digital health, https://www.frontiersin.org/articles/10.3389/fdgth.2020.00008/full (accessed 5 November 2020).

3. Alavi A, Bogu GK, Wang M, et al. Real-time alerting system for COVID-19 and other stress events using wearable data. *Nat Med* 2022; 28: 175–184.
4. Miller DJ, Capodilupo JV, Lastella M, et al. Analyzing changes in respiratory rate to predict the risk of COVID-19 infection. *PLOS ONE* 2020; 15: e0243693.
5. Mol MBA, Strous MTA, van Osch FHM, et al. Heart-rate-variability (HRV), predicts outcomes in COVID-19. *PLOS ONE* 2021; 16: e0258841.
6. Assessment of prolonged physiological and behavioral changes associated with COVID-19 infection | Infectious Diseases | JAMA Network Open | JAMA Network, https://jamanetwork.com/journals/jamanetworkopen/fullarticle/2781687?resultClick=3 (accessed 17 March 2022).
7. Vogels EA. About one-in-five Americans use a smart watch or fitness tracker. Pew Research Center, https://www.pewresearch.org/fact-tank/2020/01/09/about-one-in-five-americans-use-a-smart-watch-or-fitness-tracker/ (accessed 24 March 2022).
8. Inc G. One in five U.S. adults use health apps, wearable trackers. *Gallup.com*, https://news.gallup.com/poll/269096/one-five-adults-health-apps-wearable-trackers.aspx (2019, accessed 17 March 2022).
9. Walter JR, Kim D, Myers D, et al. Pilot and feasibility deployment of an advanced remote monitoring platform for COVID-19 in long-term care facilities. *J Am Geriatr Soc* 2022; 70: 968–971.
10. Ni X, Ouyang W, Jeong H, et al. Automated, multiparametric monitoring of respiratory biomarkers and vital signs in clinical and home settings for COVID-19 patients. *Proc Natl Acad Sci* 2021; 118: e2026610118.
11. Scripps Translational Science Institute. *The DETECT (Digital Engagement & Tracking for Early Control, & Treatment) study*. Clinical Trial Registration NCT04336020, clinicaltrials.gov, https://clinicaltrials.gov/ct2/show/NCT04336020 (2021, accessed 17 March 2022).
12. Seshadri DR, Thom ML, Harlow ER, et al. Wearable technology and analytics as a complementary toolkit to optimize workload and to reduce injury burden. *Front Sports Act Living* 2021; 2. https://www.frontiersin.org/article/10.3389/fspor.2020.630576. accessed 18 March 2022.
13. Health and safety protocols for 2021 season. *MLB.com*, https://www.mlb.com/news/health-and-safety-protocols-for-2021-mlb-season (accessed 19 March 2022).
14. mlssoccer. Health and safety protocols for 2021 MLS season | MLSSoccer.com. *mlssoccer*, https://www.mlssoccer.com/news/health-and-safety-protocols-for-2021-mls-season (accessed 18 March 2022).
15. NBA, NBPA agree to new COVID protocols that would shorten isolation periods in certain situations, per report. *CBSSports.com*, https://www.cbssports.com/nba/news/nba-nbpa-agree-to-new-covid-protocols-that-would-shorten-isolation-periods-in-certain-situations-per-report/ (accessed 18 March 2022).
16. Here's all you need to know on the NBA's health and safety protocols. *RSN*, https://www.nbcsports.com/chicago/bulls/heres-all-you-need-know-nbas-health-and-safety-protocols-0 (accessed 18 March 2022).
17. Salvador J. Report: NFL, NFLPA agree to major change to COVID-19 protocols. *Sports Illustrated*, https://www.si.com/nfl/2021/12/28/nfl-covid-19-protocols-shortening-quarantine-from-10-to-five-days (accessed 18 March 2022).
18. Bogdanis GC. Effects of physical activity and inactivity on muscle fatigue. *Front Physiol* 2012; 3: 42.
19. Fitts RH. Cellular mechanisms of muscle fatigue. *Physiol Rev* 1994; 74: 49–94.
20. Stokes KA, Jones B, Bennett M, et al. Returning to play after prolonged training restrictions in professional collision sports. *Int J Sports Med* 2020; 41: 895–911.
21. Richmond PA. Return to sports after a COVID-19 diagnosis. Pediatric Associates of Richmond, https://parpeds.com/return-to-sports-after-a-covid-19-diagnosis/ (2021, accessed 25 March 2022).
22. Sola J, Vybornova A, Fallet S, et al. Validation of the optical Aktiia bracelet in different body positions for the persistent monitoring of blood pressure. *Sci Rep* 2021; 11: 20644.
23. Liu C, Kim J-T, Kwak SS, et al. Wireless, skin-interfaced devices for pediatric critical care: application to continuous, noninvasive blood pressure monitoring. *Adv Healthc Mater* 2021; 10: 2100383.
24. Vasudevan S, Saha A, Tarver ME, et al. Digital biomarkers: convergence of digital health technologies and biomarkers. *Npj Digit Med* 2022; 5: –3.
25. Mack CD. Implementation and evolution of mitigation measures, testing, and contact tracing in the national football league, August 9–November 21, 2020. *MMWR Morb Mortal Wkly Rep* 2021; 70: 130–135.
26. Washif JA, Farooq A, Krug I, et al. Training during the COVID-19 lockdown: knowledge, beliefs, and practices of 12,526 athletes from 142 countries and six continents. *Sports Med Auckl NZ* 2022; 52: 933–948.
27. Grazioli R, Loturco I, Baroni BM, et al. Coronavirus disease-19 quarantine is more detrimental than traditional off-season on physical conditioning of professional soccer players. *J Strength Cond Res* 2020; 34: 3316–3320.
28. Wall BT, Morton JP and van Loon LJC. Strategies to maintain skeletal muscle mass in the injured athlete: nutritional considerations and exercise mimetics. *Eur J Sport Sci* 2015; 15: 53–62.
29. Nalbandian A, Sehgal K, Gupta A, et al. Post-acute COVID-19 syndrome. *Nat Med* 2021; 27: 601–615.
30. CDC. Coronavirus disease 2019 (COVID-19). Centers for Disease Control and Prevention, https://www.cdc.gov/coronavirus/2019-ncov/lab/guidelines-clinical-specimens.html (2020, accessed 13 April 2020).
31. de Hoyo M, Pozzo M, Sañudo B, et al. Effects of a 10-week in-season eccentric-overload training program on muscle-injury prevention and performance in junior elite soccer players. *Int J Sports Physiol Perform* 2015; 10: 46–52.
32. Eirale C, Bisciotti G, Corsini A, et al. Medical recommendations for home-confined footballers' training during the COVID-19 pandemic: from evidence to practical application. *Biol Sport* 2020; 37: 203–207.
33. Effect of reduced training on muscular strength and endurance in competitive swimmers – Google Search, https://www.google.com/search?q=Effect+of+reduced+training+on+muscular+strength+and+endurance+in+competitive+swimmers&oq=Effect+of+reduced+training+on+muscular+strength+and+endurance+in+competitive+swimmers&

aqs=chrome.69i57.227j0j4&sourceid=chrome&ie=UTF-8 (accessed 18 March 2022).
34. Kramer A, Gollhofer A, Armbrecht G, et al. How to prevent the detrimental effects of two months of bed-rest on muscle, bone and cardiovascular system: an RCT. *Sci Rep* 2017; 7: 13177.
35. Ferrari R, Di Pasquale G and Rapezzi C. Commentary: what is the relationship between COVID-19 and cardiovascular disease? *Int J Cardiol* 2020; 310: 167–168.
36. Sport preparation system in team sports: synergy of…*moam.info*, https://moam.info/sport-preparation-system-in-team-sports-synergy-of-_5b7ec589097c4773218b4636.html (accessed 17 March 2022).
37. Mulcahey MK, Gianakos AL, Mercurio A, et al. Sports medicine considerations during the COVID-19 pandemic. https://journals.sagepub.com/doi/full/10.1177/0363546520975186 (2021, accessed 18 March 2022).
38. de Boer MD, Selby A, Atherton P, et al. The temporal responses of protein synthesis, gene expression and cell signalling in human quadriceps muscle and patellar tendon to disuse. *J Physiol* 2007; 585: 241–251.
39. Sousa AC, Neiva HP, Izquierdo M, et al. Concurrent training and detraining: brief review on the effect of exercise intensities. *Int J Sports Med* 2019; 40: 747–755.
40. Effects of detraining on the risk of injury in athletes. *Barça Innovation Hub*, https://barcainnovationhub.com/effects-of-detraining-on-the-risk-of-injury-in-athletes/ (2021, accessed 31 March 2022).
41. Myer GD, Faigenbaum AD, Cherny CE, et al. Did the NFL lockout expose the Achilles heel of competitive sports? *J Orthop Sports Phys Ther* 2011; 41: 702–705.
42. Platt BN, Collofello B, Stockwell N, et al. Injury rates in the National Football League during the 2020 COVID-19 season. *Phys Sportsmed* 2021: 1–6.
43. Baker HP, Pirkle S, Cahill M, et al. The injury rate in national football league players increased following cancellation of preseason games because of COVID-19. *Arthrosc Sports Med Rehabil* 2021; 3: e1147–e1154.
44. Torres-Ronda L, Gámez I, Robertson S, et al. Epidemiology and injury trends in the National Basketball Association: pre- and per-COVID-19 (2017–2021). *PLOS ONE* 2022; 17: e0263354.
45. Mannino BJ, Yedikian T, Mojica ES, et al. The COVID lockdown and its effects on soft tissue injuries in Premier League Athletes. *Phys Sportsmed* 2021; 0: 1–5.
46. Marotta N, de Sire A, Gimigliano A, et al. Impact of COVID-19 lockdown on the epidemiology of soccer muscle injuries in Italian Serie A professional football players. *J Sports Med Phys Fitness* 2022; 62: 356–360.
47. Frontiers | Case report: return to sport following the COVID-19 lockdown and its impact on injury rates in the German Soccer League | Sports and Active Living, https://www.frontiersin.org/articles/10.3389/fspor.2021.604226/full (accessed 19 March 2022).
48. Krutsch W, Hadji A, Tröß T, et al. No increased injury incidence in the German Bundesliga after the SARS-CoV-2 virus lockdown. *Arch Orthop Trauma Surg* 2022; 142: 1571–1578.
49. Thron M, Härtel S, Woll A, et al. Physical match performance and injuries in professional soccer before and after the COVID-19 break. *Sci Med Footb* 2021; 5: 31–34.
50. Paul RW, Omari A, Fliegel B, et al. Effect of COVID-19 on ulnar collateral ligament reconstruction in Major League Baseball pitchers. *Orthop J Sports Med* 2021; 9: 23259671211041360.
51. Toresdahl BG, Robinson JN, Kliethermes SA, et al. Increased incidence of injury among runners with COVID-19. *Sports Health* 2021: 19417381211061144.
52. DeJong AF, Fish PN and Hertel J. Running behaviors, motivations, and injury risk during the COVID-19 pandemic: a survey of 1147 runners. *PLOS ONE* 2021; 16: e0246300.
53. Kildow AR, Wright G, Reh RM, et al. Can monitoring training load deter performance drop-off during off-season training in division III American football players? *J Strength Cond Res* 2019; 33: 1745–1754.
54. Gabbett T. Reductions in pre-season training loads reduce training injury rates in rugby league players. *Bri J Sports Med* 2004; 38:743–749. https://bjsm.bmj.com/content/38/6/743 (accessed 28 March 2022).
55. Mehrsafar AH, Moghadam Zadeh A, Gazerani P, et al. Mental health status, life satisfaction, and mood state of elite athletes during the COVID-19 pandemic: a follow-up study in the phases of home confinement, reopening, and semi-lockdown condition. *Front Psychol* 2021; 12. https://www.frontiersin.org/article/10.3389/fpsyg.2021.630414 (accessed 28 March 2022).
56. Jia L, Carter MV, Cusano A, et al. The effect of the COVID-19 pandemic on the mental and emotional health of athletes: a systematic review. *Am J Sports Med* 2022: 3635465221087473.
57. The psychological impact of quarantine and how to reduce it: rapid review of the evidence - The Lancet, https://www.thelancet.com/journals/lancet/article/PIIS0140-6736(20)30460-8/fulltext (accessed 18 March 2022).
58. Schinke R, Papaioannou A, Henriksen K, et al. Sport psychology services to high performance athletes during COVID-19. *Int J Sport Exerc Psychol* 2020; 18: 269–272.
59. BMJ. Anxiety and insomnia in athletes during the COVID era: part 1—foundation and facts. *BJSM blog - social media's leading SEM voice*, https://blogs.bmj.com/bjsm/2020/04/27/anxiety-and-insomnia-in-athletes-during-the-covid-era-part-1-foundation-and-facts/ (2020, accessed 31 March 2022).
60. Gouttebarge V, Castaldelli-Maia JM, Gorczynski P, et al. Occurrence of mental health symptoms and disorders in current and former elite athletes: a systematic review and meta-analysis. *Br J Sports Med* 2019; 53: 700–706.
61. Jukic I, Calleja-González J, Cos F, et al. Strategies and solutions for team sports athletes in isolation due to COVID-19. *Sports* 2020; 8: 56.
62. Levine BD, Zuckerman JH and Pawelczyk JA. Cardiac atrophy after bed-rest deconditioning. *Circulation* 1997; 96: 517–525.
63. Lavelle MP, Desai AD and Wan EY. Arrhythmias in the COVID-19 patient. *Heart Rhythm O2* 2022; 3: 8–14.
64. Martinez MW, Tucker AM, Bloom OJ, et al. Prevalence of inflammatory heart disease among professional athletes with prior COVID-19 infection who received systematic return-to-play cardiac screening. *JAMA Cardiol* 2021; 6: 745–752.

65. Kim JH, Levine BD, Phelan D, et al. Coronavirus disease 2019 and the athletic heart: emerging perspectives on pathology, risks, and return to play. *JAMA Cardiol* 2021; 6: 219–227.
66. Bohm P, Scharhag J, Egger F, et al. Sports-related sudden cardiac arrest in Germany. *Can J Cardiol* 2021; 37: 105–112.
67. Heart issue linked to virus drives Power 5 concern. *ESPN.com*, https://www.espn.com/college-football/story/_/id/29633697/heart-condition-linked-covid-19-fuels-power-5-concern-season-viability (2020, accessed 19 March 2022).
68. Heart issue ends season for Red Sox's Rodriguez. *ESPN.com*, https://www.espn.com/mlb/story/_/id/29579222/boston-red-sox-pitcher-eduardo-rodriguez-done-season-due-heart-issue (2020, accessed 19 March 2022).
69. Phelan D, Kim JH and Chung EH. A game plan for the resumption of sport and exercise after coronavirus disease 2019 (COVID-19) infection. *JAMA Cardiol* 2020; 5: 1085–1086.
70. Caforio ALP, Pankuweit S, Arbustini E, et al. Current state of knowledge on aetiology, diagnosis, management, and therapy of myocarditis: a position statement of the European Society of Cardiology Working Group on Myocardial and Pericardial Diseases. *Eur Heart J* 2013; 34: 2636–2648, 2648a–2648d.
71. Writing Committee, Gluckman TJ and Bhave NM, et al. 2022 ACC expert consensus decision pathway on cardiovascular sequelae of COVID-19 in adults: myocarditis and other myocardial involvement, post-acute sequelae of SARS-CoV-2 infection, and return to play. *J Am Coll Cardiol* 2022; 79: 1717–1756.
72. Daniels CJ, Rajpal S, Greenshields JT, et al. Prevalence of clinical and subclinical myocarditis in competitive athletes with recent SARS-CoV-2 infection: results from the big ten COVID-19 cardiac registry. *JAMA Cardiol* 2021; 6: 1078–1087.
73. Ferreira VM, Schulz-Menger J, Holmvang G, et al. Cardiovascular magnetic resonance in nonischemic myocardial inflammation: expert recommendations. *J Am Coll Cardiol* 2018; 72: 3158–3176.
74. Lurz P, Eitel I, Adam J, et al. Diagnostic performance of CMR imaging compared with EMB in patients with suspected myocarditis. *JACC Cardiovasc Imaging* 2012; 5: 513–524.
75. Phelan D, Kim JH, Drezner JA, et al. When to consider cardiac MRI in the evaluation of the competitive athlete after SARS-CoV-2 infection. *Br J Sports Med* 2022; 56: 425–426.
76. Seshadri DR, Drummond C, Craker J, et al. Wearable devices for sports: new integrated technologies allow coaches, physicians, and trainers to better understand the physical demands of athletes in real time. *IEEE Pulse* 2017; 8: 38–43.
77. Seshadri DR, Li RT, Voos JE, et al. Wearable sensors for monitoring the internal and external workload of the athlete. *Npj Digit Med* 2019; 2: 1–18.
78. Seshadri DR, Li RT, Voos JE, et al. Wearable sensors for monitoring the physiological and biochemical profile of the athlete. *Npj Digit Med* 2019; 2: 72.
79. Seshadri DR, Rowbottom JR, Drummond C, et al. A review of wearable technology: moving beyond the hype: from need through sensor implementation. In: 2016 8th Cairo International Biomedical Engineering Conference (CIBEC), 2016, pp. 52–55.
80. Seshadri DR, Magliato S, Voos JE, et al. Clinical translation of biomedical sensors for sports medicine. *J Med Eng Technol* 2019; 43: 66–81.
81. Stern BD, Hegedus EJ and Lai Y-C. Injury prediction as a non-linear system. *Phys Ther Sport Off J Assoc Chart Physiother Sports Med* 2020; 41: 43–48.
82. Gabbett TJ. The training—injury prevention paradox: should athletes be training smarter and harder? *Br J Sports Med* 2016; 50: 273–280.
83. Li RT, Salata MJ, Rambhia S, et al. Does overexertion correlate with increased injury? The relationship between player workload and soft tissue injury in professional American football players using wearable technology. *Sports Health* 2019: 1941738119868477.
84. Brosnan RJ, Watson G, Stuart W, et al. The validity, reliability, and agreement of global positioning system units-can we compare research and applied data? *J Strength Cond Res* 2022; 36: 3330–3338.
85. Nicolella DP, Torres-Ronda L, Saylor KJ, et al. Validity and reliability of an accelerometer-based player tracking device. *PloS One* 2018; 13: e0191823.
86. Düking P, Achtzehn S, Holmberg H-C, et al. Integrated framework of load monitoring by a combination of smartphone applications, wearables and point-of-care testing provides feedback that allows individual responsive adjustments to activities of daily living. *Sensors* 2018; 18: 1632.
87. Data scientists are predicting sports injuries with an algorithm, https://www.nature.com/articles/d41586-021-00818-1 (accessed 19 March 2022).
88. Blanch P and Gabbett TJ. Has the athlete trained enough to return to play safely? The acute:chronic workload ratio permits clinicians to quantify a player's risk of subsequent injury. *Br J Sports Med* 2016; 50: 471–475.
89. Gabbett TJ, Hulin B, Blanch P, et al. To couple or not to couple? For acute:chronic workload ratios and injury risk, does it really matter? *Int J Sports Med* 2019; 40: 597–600.
90. Gabbett TJ, Nassis GP, Oetter E, et al. The athlete monitoring cycle: a practical guide to interpreting and applying training monitoring data. *Br J Sports Med* 2017; 51: 1451–1452.
91. Hulin BT, Gabbett TJ, Caputi P, et al. Low chronic workload and the acute:chronic workload ratio are more predictive of injury than between-match recovery time: a two-season prospective cohort study in elite rugby league players. *Br J Sports Med* 2016; 50: 1008–1012.
92. Hulin BT, Gabbett TJ, Blanch P, et al. Spikes in acute workload are associated with increased injury risk in elite cricket fast bowlers. *Br J Sports Med* 2014; 48: 708–712.
93. Kim T, Park J-C, Park J-M, et al. Optimal relative workload for managing low-injury risk in lower extremities of female field hockey players: a retrospective observational study. *Medicine (Baltimore)* 2021; 100: e27643.
94. Andrade R, Wik EH, Rebelo-Marques A, et al. Is the acute: chronic workload ratio (ACWR) associated with risk of time-loss injury in professional team sports? A systematic review of methodology, variables and injury risk in practical situations. *Sports Med Auckl NZ* 2020; 50: 1613–1635.

95. Impellizzeri F, Wookcock S, McCall A, et al. The acute-chronic workload ratio-injury figure and its 'sweet spot' are flawed. Epub ahead of print 2 June 2019. DOI: 10.31236/osf.io/gs8yu.
96. Impellizzeri FM, Woodcock S, Coutts AJ, et al. What role do chronic workloads play in the acute to chronic workload ratio? Time to dismiss ACWR and its underlying theory. *Sports Med Auckl NZ* 2021; 51: 581–592.
97. Dalen-Lorentsen T, Bjørneboe J, Clarsen B, et al. Does load management using the acute:chronic workload ratio prevent health problems? A cluster randomised trial of 482 elite youth footballers of both sexes. *Br J Sports Med* 2021; 55: 108–114.
98. Carbone L, Sampietro M, Cicognini A, et al. Is the relationship between acute and chronic workload a valid predictive injury tool? A Bayesian analysis. *J Clin Med* 2022; 11: 5945.
99. Clubb J. The debate on the acute: chronic workload ratio. *Global Perf Insights*, https://www.globalperformanceinsights.com/post/the-debate-on-the-acute-chronic-workload-ratio (2016, accessed 28 March 2023).
100. Gabbett T, Sancho I, Dingenen B, et al. When progressing training loads, what are the considerations for healthy and injured athletes? *Br J Sports Med* 2021; 55: 947–948.
101. Barker-Davies RM, O'Sullivan O and Senaratne KPP. The Stanford Hall consensus statement for post-COVID-19 rehabilitation. *Br J Sports Med* 2020; 54: 949–959. https://bjsm.bmj.com/content/54/16/949 (accessed 22 March 2022).
102. Farzam P, Starkweather Z and Franceschini MA. Validation of a novel wearable, wireless technology to estimate oxygen levels and lactate threshold power in the exercising muscle. *Physiol Rep* 2018; 6: e13664.
103. Belardinelli R, Barstow TJ, Porszasz J, et al. Changes in skeletal muscle oxygenation during incremental exercise measured with near infrared spectroscopy. *Eur J Appl Physiol* 1995; 70: 487–492.
104. Miranda-Fuentes C, Chirosa-Ríos LJ, Guisado-Requena IM, et al. Changes in muscle oxygen saturation measured using wireless near-infrared spectroscopy in resistance training: a systematic review. *Int J Environ Res Public Health* 2021; 18: 4293.
105. Davis PR, Yakel JP and Anderson DJF. Muscle oxygen demands of the vastus lateralis in back and front squats. *Int J Exerc Sci* 2020; 13: 734–743.
106. Gómez-Carmona CD, Bastida-Castillo A, Rojas-Valverde D, et al. Lower-limb dynamics of muscle oxygen saturation during the back-squat exercise: effects of training load and effort level. *J Strength Cond Res* 2020; 34: 1227–1236.
107. Jurecka A, Skucińska P and Gądek A. Impact of the SARS-CoV-2 coronavirus pandemic on physical activity, mental health and quality of life in professional athletes—a systematic review. *Int J Environ Res Public Health* 2021; 18: 9423.
108. Facer-Childs ER, Hoffman D, Tran JN, et al. Sleep and mental health in athletes during COVID-19 lockdown. *Sleep* 2021; 44: zsaa261.
109. Silva A, Narciso FV, Rosa JP, et al. Gender differences in sleep patterns and sleep complaints of elite athletes. *Sleep Sci* 2019; 12: 242–248.
110. Lu J, An Y and Qiu J. Relationship between sleep quality, mood state, and performance of elite air-rifle shooters. *BMC Sports Sci Med Rehabil* 2022; 14: 32.
111. Mon-López D, García-Aliaga A, Ginés Bartolomé A, et al. How has COVID-19 modified training and mood in professional and non-professional football players? *Physiol Behav* 2020; 227: 113148.
112. Melone M-A, Tourny C, Gehlbach BK, et al. Prevalence and risk factors of poor sleep quality in collegiate athletes during COVID-19 pandemic: a cross-sectional study. *Int J Environ Res Public Health* 2022; 19: 3098.
113. Altini M and Kinnunen H. The promise of sleep: a multi-sensor approach for accurate sleep stage detection using the oura ring. *Sensors* 2021; 21: 4302.
114. Ghorbani S, Golkashani HA, Chee NIYN, et al. Multi-night at-home evaluation of improved sleep detection and classification with a memory-enhanced consumer sleep tracker. *Nat Sci Sleep* 2022; 14: 645–660.
115. von Rosen P, Frohm A, Kottorp A, et al. Multiple factors explain injury risk in adolescent elite athletes: applying a biopsychosocial perspective. *Scand J Med Sci Sports* 2017; 27: 2059–2069.
116. Williams S, Booton T, Watson M, et al. Heart rate variability is a moderating factor in the workload-injury relationship of competitive CrossFit^{TM} athletes. *J Sports Sci Med* 2017; 16: 443–449.
117. Plews DJ, Laursen PB, Kilding AE, et al. Heart rate variability in elite triathletes, is variation in variability the key to effective training? A case comparison. *Eur J Appl Physiol* 2012; 112: 3729–3741.
118. Friman G and Wesslén L. Special feature for the Olympics: effects of exercise on the immune system: infections and exercise in high-performance athletes. *Immunol Cell Biol* 2000; 78: 510–522.
119. Baumann C, Buchhorn R and Willaschek C. Heart rate variability in a patient with coronavirus disease 2019. Epub ahead of print 12 May 2020. DOI: 10.20944/preprints202005.0209.v1.
120. Hottenrott L, Gronwald T, Hottenrott K, et al. Utilizing heart rate variability for coaching athletes during and after viral infection: a case report in an elite endurance athlete. *Front Sports Act Living* 2021; 3. https://www.frontiersin.org/article/10.3389/fspor.2021.612782. accessed 22 March 2022.
121. Malik M, Hnatkova K, Huikuri HV, et al. Crosstalk proposal: heart rate variability is a valid measure of cardiac autonomic responsiveness. *J Physiol* 2019; 597: 2595–2598.
122. Bellenger CR, Thomson RL, Howe PRC, et al. Monitoring athletic training status using the maximal rate of heart rate increase. *J Sci Med Sport* 2016; 19: 590–595.
123. Radin JM, Wineinger NE, Topol EJ, et al. Harnessing wearable device data to improve state-level real-time surveillance of influenza-like illness in the USA: a population-based study. *Lancet Digit Health* 2020; 2: e85–e93.
124. Mishra T, Wang M, Metwally AA, et al. Pre-symptomatic detection of COVID-19 from smartwatch data. *Nat Biomed Eng* 2020; 4: 1208–1220.
125. Mount Sinai study finds wearable devices can detect COVID-19 symptoms and predict diagnosis | Mount Sinai – New York. *Mount Sinai Health System*, https://www.mountsinai.org/about/newsroom/2021/mount-sinai-study-finds-wearable-devices-can-detect-covid19-symptoms-and-predict-diagnosis-pr (accessed 19 March 2022).

126. Hirten RP, Danieletto M and Tomalin L. Use of physiological data from a wearable device to identify SARS-CoV-2 infection and symptoms and predict COVID-19 diagnosis: observational study. *J Med Internet Res* 2021; 23:e26107. https://www.jmir.org/2021/2/e26107/ (accessed 19 March 2022). doi:10.2196/26107
127. NeuTigers Launches CovidDeep, a rapid screening app using wearable sensor data to detect COVID-19 infection. *Hospitality Technology*, https://hospitalitytech.com/neutigers-launches-coviddeep-rapid-screening-app-using-wearable-sensor-data-detect-covid-19 (accessed 19 March 2022).
128. CovidDeep app 90% accurate at predicting coronavirus infection, https://www.medicaldevice-network.com/news/coviddeep/ (accessed 19 March 2022).
129. Bumgarner JM, Lambert CT, Hussein AA, et al. Smartwatch algorithm for automated detection of atrial fibrillation. *J Am Coll Cardiol* 2018; 71: 2381–2388.
130. Gawałko M, Kapłon-Cieślicka A, Hohl M, et al. COVID-19 associated atrial fibrillation: incidence, putative mechanisms and potential clinical implications. *Int J Cardiol Heart Vasc* 2020; 30: 100631.
131. Apple Inc. Apple respiratory study: a prospective study of Apple watch-based detection of respiratory viral illness in Greater Seattle, WA. Clinical Trial Registration NCT04912180, clinicaltrials.gov, https://clinicaltrials.gov/ct2/show/NCT04912180 (12 July 2021, accessed 17 March 2022).
132. How long does COVID-19 last?, https://covid.joinzoe.com/post/covid-long-term (accessed 22 March 2022).
133. Bussotti M, Di Marco S and Marchese G. Respiratory disorders in endurance athletes—how much do they really have to endure? *Open Access J Sports Med* 2014; 5: 47–63.
134. Wilson MG, Hull JH, Rogers J, et al. Cardiorespiratory considerations for return-to-play in elite athletes after COVID-19 infection: a practical guide for sport and exercise medicine physicians. *Br J Sports Med* 2020; 54: 1157–1161.
135. Labs DI. NFLPA provides WHOOP to all active NFL players. *WHOOP*, https://www.whoop.com/thelocker/nflpa-provides-whoop-to-players/ (accessed 22 March 2022).
136. The PGA tour leans on whoop for early COVID-19 detection, https://www.sporttechie.com/pga-tour-whoop-covid-19-detection (accessed 22 March 2022).
137. Belval L. Heat stroke risk factors | Korey Stringer Institute, https://ksi.uconn.edu/emergency-conditions/heat-illnesses/exertional-heat-stroke/heat-stroke-risk-factors/ (2015, accessed 20 August 2019).
138. Heatstroke | NEJM, https://www.nejm.org/doi/full/10.1056/NEJMra1810762 (accessed 23 October 2019).
139. Balli S and Sharan S. Physiology, fever. In: *StatPearls*. Treasure Island (FL): StatPearls Publishing, http://www.ncbi.nlm.nih.gov/books/NBK562334/ (2022, accessed 1 April 2022).
140. Dick NA and Diehl JJ. Febrile illness in the athlete. *Sports Health* 2014; 6: 225–231.
141. Purcell L. Canadian Paediatric Society, Paediatric Sports and Exercise Medicine Section. Exercise and febrile illnesses. *Paediatr Child Health* 2007; 12: 885–887.
142. Casa DJ, Becker SM, Ganio MS, et al. Validity of devices that assess body temperature during outdoor exercise in the heat. *J Athl Train* 2007; 42: 333–342.
143. Ganio MS, Brown CM, Casa DJ, et al. Validity and reliability of devices that assess body temperature during indoor exercise in the heat. *J Athl Train* 2009; 44: 124–135.
144. Muniz-Pardos B, Sutehall S, Angeloudis K, et al. The use of technology to protect the health of athletes during sporting competitions in the heat. *Front Sports Act Living* 1. https://www.frontiersin.org/article/10.3389/fspor.2019.00038 (2019, accessed 1 April 2022).
145. Verdel N, Podlogar T, Ciuha U, et al. Reliability and validity of the CORE sensor to assess core body temperature during cycling exercise. *Sensors* 2021; 21: 5932.
146. Drezner JA, Heinz WM, Asif IM, et al. Cardiopulmonary considerations for high school student-athletes during the COVID-19 pandemic: NFHS-AMSSM guidance statement. *Sports Health Multidiscip Approach* 2020; 12: 459–461.
147. Phelan D, Kim JH, Elliott MD, et al. Screening of potential cardiac involvement in competitive athletes recovering from COVID-19. *Jacc Cardiovasc Imaging* 2020; 13: 2635–2652.
148. Düking P, Hotho A, Holmberg H-C, et al. Comparison of non-invasive individual monitoring of the training and health of athletes with commercially available wearable technologies. *Front Physiol* 2016; 7. https://www.frontiersin.org/article/10.3389/fphys.2016.00071 (accessed 2 April 2022).
149. Düking P, Fuss FK, Holmberg H-C, et al. Recommendations for assessment of the reliability, sensitivity, and validity of data provided by wearable sensors designed for monitoring physical activity. *JMIR MHealth UHealth* 2018; 6: e9341.
150. Windt J, MacDonald K, Taylor D, et al. To tech or not to tech? A critical decision-making framework for implementing technology in sport. *J Athl Train* 2020; 55: 902–910.
151. Austen K. The trouble with wearables. *Nature* 2015; 525: 22–24.
152. Muniz-Pardos B, Angeloudis K, Guppy FM, et al. Ethical dilemmas and validity issues related to the use of new cooling technologies and early recognition of exertional heat illness in sport. *BMJ Open Sport Exerc Med* 2021; 7: e001041.