

1. Why technology in sport?

1.1 Introduction to Sport Technology

1.1.1 Origins of sport technology

Throughout the course of human history, technology has largely been developed for the purpose of providing people and groups with material comforts. Thus, most technologies were developed through necessity and sometimes even by accident. However, more recent advancements in technology have largely emphasised assisting humans through augmenting our intelligence. These include the development of artefacts that we now consider fundamental to the human experience, such as reading, writing and computing. Even more recently, these advancements have become increasingly strategic in nature; structured innovation and long-term planned development of technology by multinational organisations are now commonplace. Perhaps the most appropriate contemporary definition of technology thus reads as “material devices designed and manufactured to make human activities easier or to make possible activities which people have dreamt of engaging in but to which they are not biologically adapted” (Tiles & Oberdieck, 1995, p. 4). Pursuits relating to improving human performance have been at the forefront of many of these innovations as well as an increased utility of technology – whether it is through military, space travel or, of course, sport.

Most of the recent advancements in human intelligence have not been achieved through improving mental capacity (or biological adaptation, as described above), but through the appropriate utility of external aides and technologies (Norman, 2014). Many of these technologies exhibit value by providing more accurate information, enhancing communication, or generating insights into phenomena not observable or measurable without them. Our contemporary lives would be unrecognisable without the internet, for example.

From a sports perspective, it is unimaginable to contemplate contemporary professional leagues without video and the accompanying television coverage, replay and analysis that are pervasive all over the globe. Sometimes technology improves humans’ lives not just through augmenting intelligence, but through increasing efficiency. For instance, the modern computer has revolutionised the way in which data can be processed, analysed and accessed, thus leading to massive enhancements in individual and workplace efficiency. The success of these enhancements has shifted the skillsets required of those working in sport; a working understanding of technology is no longer an option – it is a necessity.

However, a dichotomy exists with respect to the influence of technology on both humans as individuals and humans as collectives. Technology can have the effect of

actually making humans less intelligent; they can become complacent, lazy or potentially even more stupid. For all its potential ability to educate, most of us would agree that television, for example, has not on the whole made people smarter. This complacency or overreliance on technology by humans also means that, in many cases, there is no back-up plan if technology fails. As humans increasingly both utilise existing technology and develop new devices altogether, this reliance becomes greater.

The sheer volume and variety of types available also means that it has become more difficult to maintain a thorough understanding of the inner workings of all of the technologies that surround human environment. This is not an altogether new concern. In the early 1990's, Carl Sagan wrote "We live in a society exquisitely dependent on science and technology, in which hardly anyone knows anything about science and technology. This is a clear prescription for disaster" (Sagan, 1990, p. 264).

Another complacency can emerge with respect to the ease of technology. For instance, a relationship often exists between the ease in which information can be obtained from a technology and the reduced willingness of humans to question it. How many times do we check a digital watch, or observe values outputted from a set of electronic scales and stop to question their accuracy? Or do we just accept the number on face value, utilise the information accordingly and then get on with our day? Such questions are equally relevant to sport. Many technologies have now been entrenched in sport for many decades; however, both the quality and value of some are rarely, if ever, questioned.

Another reason for the lack of human literacy in technology is that once upon a time, technology was largely explainable based on *surface* representations; that is, the workings of a device or artefact were clearly visible to the user. For instance, how a pencil functions is obvious to us just by watching someone use it, as is a hammer and a nail. In sport, even a child or a beginner can pick up a bat and a ball and have some implicit understanding about how both devices function. However, nowadays, humans are increasingly exposed to technology containing also *internal* representations; that is, there is a component of the device or equipment that is not immediately visible to the user. In such cases, surface representations also have importance for the physical design of technology. Humans require a working understanding of tens of thousands of different objects across their lives. If the intended function of the object is not apparent from visual inspection, then it will require new training or upskilling on behalf of the individual, which requires time and resources. In fact, even following considerable training, some devices may not be interpretable by the user at all. This can lead to a lack of integration of the technology into an organisation or a lack of ongoing utility. Sometimes inappropriate surface representations can lead to 'human error' when using technology. Appropriately, it has been proposed that this could be rephrased as 'technology error' – given that technology should be designed with human limitations in mind and thus aim to account for their limitations (Norman, 2014). Despite these potential problems, for most technologies containing internal representations, a surface representation is still required. For instance, a global positioning system (GPS) tracking device without some kind of computer software to display the outputted numbers

would be of limited use to sporting teams who typically use the data shortly after collection to monitor athlete workloads, evaluate training designs and assess performance.

This course discusses the important impact that technology has on sport, and vice versa, particularly with respect to furthering human performance. In particular, it provides a range of different tools and practical frameworks that can be used to apply various technologies for the purpose of improving departmental or organisational decision-making. The importance of theoretical underpinnings for the use of technology is discussed, as is the crucialness in being able to evaluate the quality of different technology. In doing so, the course addresses technology from a point of scepticism, but also one of optimism.

1.1.2 The benefits of technologies to sport

The benefits of technology to sport can be categorized in innumerable ways, using various theoretical or operational frameworks. However, fundamentally the majority of new technologies, including computing, can be considered under at least one of the three categories below:

- 1) Technology that derives **new** insights into important concepts or constructs that are not currently being measured. This type represents technological advancement at its finest – whereby development of the technology in and of itself leads to the discovery of previously unknown information about a given phenomenon. An example of this could be the discovery of the genome and its subsequent applications since. Importantly, as more and more phenomena become measurable, developing technology that truly provides new insights will become rarer. Those phenomena that remain outstanding and unmeasured tend to be those that are hardest to measure, and/or the most complex, abstract and difficult to understand. In many cases, these are also the most important or influential with respect to the problem on hand. In team sport, for instance, even though there is a general acknowledgement that characteristics such as communication, leadership and decision-making are inherent in many good players, tools and technologies that can specifically measure such qualities remain scant.
- 2) Technology that leads to **improved** insights into existing phenomena. These technologies are more commonplace than the former and tend to provide incremental improvements to existing practice. Examples are replete in both the literature and practice. Such is the case of the use of electronic timing gates for improved accuracy over a stopwatch in evaluating running velocity, or the development of swim suits to reduce drag in swimming. In some cases, the technology improves insights by either supplementing a human evaluation (i.e., coach evaluation of an athlete) or by replacing it altogether (i.e., tracking systems to track running workloads that may previously have been confined to measuring time). Sometimes, the effect of such technologies on athlete performance is clearly measurable (i.e., the systematic decrease in 100m swimming times).

due to the development of swim suits), while other times, in more complex sports, determining the influence is more challenging. Advancement of these types of technologies (along with the next category) is moving at an incredibly rapid rate.

3) Technology that generates **faster** insights. Whilst computing is a large contributor to these types of technologies, their benefits represent more than just faster data processing or analysis. Faster insights can also be achieved through improved technology design being more efficient for the end user, or through enhanced visualisations facilitating more rapid decision-making. Automation (or semi-automation) of processes, this increasing efficiency is another method. These types of technologies can often be overlooked with respect to their importance compared to the first two, due to them sometimes not being observable by many users. However, they are increasingly important. Like many scientific disciplines, sport has not had to worry about data volume for the majority of its existence; but it does now. Global data volume is growing at roughly 50% per year, equating to a 40-fold increase in the next decade (Manyika, et al., 2011). It is typically extremely varied and complex. A variety of frameworks have been proposed to summarise the development of these types of technologies; one such example is the cross-industry process for data mining (CRISP-DM) (IBM, 2012). This methodology provides a structure by which data mining projects can be planned, executed and evaluated more effectively and efficiently, through leveraging the power of data management, analytical tools and computing (discussed further in Theme 3.1.2).

1.1.3 Stakeholders in sport technology

This course focuses predominantly on a performance perspective to technology in sport. However, other stakeholders within sports organisations are clearly also major users of technology, be it those working in communications, marketing or in sponsorship departments. Technology is, of course, pervasive with almost no component of sport left untouched. Implications for the fans, media and franchise owners bear some overlap with those listed below. However, the list is delimited to those with direct implications for performance of the athlete. The information below summarises these key stakeholders, although it is by no means exhaustive.

- *Coaching:* Coaches may utilize learning technology with respect to providing feedback on the athlete. Examples could include interactive audiovisual technology to review training or competition (as popularized by Marcelo Bielsa) (Figure 1), or headsets and earpieces to communicate with athletes and other staff during training and competition.

Figure 1. Current Leeds United coach, Marcelo Bielsa, pictured alongside his famed Bielsamobile, which could be used to provide rapid feedback to footballers during training.



[Online photograph]. <https://trivela.com.br/conheca-o-bielsamovel-o-carrinho-tecnologico-inventado-por-bielsa-para-melhorar-os-treinos/>.

- *Athletic development:* Stakeholders involved in athlete development tend to utilize technology for the purposes of improving the performance of the athlete. This includes not only improving their fitness qualities, but also their skill and mental performance. Examples could include lightweight wearable resistance garments for the athlete to wear whilst training, or dual-energy X-ray absorptiometry (DXA) scanning to determine the body composition status of the athlete.
- *Healthcare:* These applications relate to the prevention and management of injury and illness and athletes, along with facilitating their safe return to competition. Such practitioners may use diagnostic tools, augment recovery, psychological wellness, improvement of nutritional status of the athlete. Examples include magnetic resonance imaging (MRI) to assess muscle strain or water-based treatments to enhance recovery.

- *Management:* These stakeholders are responsible for management of the schedules of athletes. They may also manage staff, information databases and re-contracting of an existing athlete list. Technology utilized might include smartphone applications to help facilitate travel schedule for a team, or computer-based systems to manage staff and player contracts.
- *Recruitment:* Individuals and teams involved in recruitment may use technology for the purpose of talent identification, pro-scouting, talent transfer (identify athletes talented in a sport that may be capable in another sport) or draft selection information. An example could include the collection of physical testing data from lower level competitions to inform dynamic predictive models utilized during a live draft.
- *Sport administration:* The responsibilities of governing bodies as they pertain to athletes include ensuring appropriate pay conditions, providing access to safe facilities and equipment, as well as ensuring that competition integrity and rules are both suitable and upheld. Examples of their interaction with technology could be through external engagement of third parties, such as universities, to assist with validation of new equipment prior to using in competition or incorporating video replay into competition refereeing to improve adjudication outcomes.
- *Participation:* Stakeholders in this area seek to maximise participation in the sport across all levels of the pathway, from junior recreational to the elite. Examples of technology application may include data mining of governing body databases to obtain national or international profiles of participants, to recommending alterations to existing equipment to help make the sport more user-friendly to younger athletes.
- *Strategy & Innovation:* This area is perhaps the most exciting area of all, as these stakeholders have the ability to transform sport as we know it, as well as take a futuristic view of technology. An example may be to develop a new kind of turf that reduces athlete soreness, which means that players can play more games. This may result in a league being able to play twice as many games in a season, thus also transforming it commercially. The relationship between technology and innovation is discussed further in Theme 4.1.2.

1.1.4 Contexts and examples of sports technologies

Categorizing the various contexts and purposes in which sport technologies can be utilized can be undertaken in a number of different ways. Many of the categories below will be utilized by multiple stakeholders mentioned in Theme 1.1.3, and some of the example technology examples provided may belong in more than one category. As per

the above, given the performance focus of this course, categories are delimited to those that directly influence the athlete:

- *Profiling and benchmarking the characteristics of elite performers:* These types of technologies serve to provide an evidence-base of what is required in order to be an elite athlete in a particular sport. Examples may include from the collection of maximum velocity data on an athlete in competition collected from a GPS system to video capture of the number of head scans undertaken by a professional footballer throughout a match.
- *Identifying potential talent:* These assessments, though similar to the one presented just above, may often relate to more general capabilities of an athlete that may be transferable to a number of sports. Examples may include measurement of movement kinematics using 3D motion capture, VO2 maximum testing or maximal strength tests using linear position transducers and force plates.
- *Insights:* They refer to technology that serves to provide feedback with the intention of improving performance. Both extrinsic and intrinsic versions of feedback exist. The former relates to external feedback provided to the athlete following a performance, whereas the latter is received directly by the athlete during the movement. This could be either haptic, auditory, visual or some combination of the three:
 - o *Extrinsic:* Examples include review screens or tablets to review plays in-game or radar guns in tennis to measure serve speed, which were first introduced in the early 1990's.
 - o *Intrinsic:* Examples include biofeedback (auditory and haptic) devices in golf providing vibration feedback or a noise cue to the player when their swing moves outside a 'desirable' range of movement.
- *Adjudication:* This refers to technology that is used for the purpose of refereeing or umpiring a sport. It may include live and in-competition applications, or those implemented in post-competition review. Refereeing examples include goal-line technology, which was first introduced to football in the early 2010's, along with video assistant refereeing. In tennis and cricket respectively, Hawkeye and the decision referral system (DRS) were early pioneers into the area of ball-tracking for the purposes of reviewing adjudication decisions whilst competition was in-play. Other technologies can be used to inform the development of new rules or in fact help find ways to circumvent them. Drug testing has consisted of a collection of technologies since the early 2000's, coming together under various

governing bodies (i.e., the World Anti Doping Agency) to more effectively detect and deter drug cheats.

- *Athlete-tracking:* Athlete tracking for position (either relative XY location or latitude and longitude) and displacement (and associated derivatives) has largely been implemented using three main types of technologies: global positioning systems (GPS), local positioning systems (LPS), or through optical (camera-based) systems; some of these systems originated in the early 2000's. In some team sports, the ball is also tracked. Other types of sensors, such as inertial measurement units, are also used to track the acceleration and orientation of athletes. Power meters in cycling represent a similar utility of a sensor in an individual sport.
- *Safety:* The ethical considerations relating to technology adoption and development are discussed in greater detail later in Theme 1.2.4. However, many of the major theories support the notion of 'do no harm'. Nevertheless, sometimes technologies are not only developed with this mantra in mind, but with the sole intention of actually reducing harm, indeed. Some of the best technologies not only achieve this aim but concomitantly also improve performance. Examples include smart helmets and mouthguards capable of detecting concussion, improvements to injury diagnosis through medical imaging and ice vests to enhance cooling in-competition for team sport athletes.
- *Training:* Training technologies represent those used to improve the effectiveness of the training process for the athlete and/or determine the response of the athlete to the applied stimulus. The former may include developing an athlete's mental skills or decision-making through electroencephalogram (EEG) or virtual reality (VR) based technologies respectively. The latter may include devices that can measure the hormonal response of the athlete following periods of heavy training to assist with monitoring the progression of a rehabilitation program, detect fatigue and potentially even prevent injury.
- *Athlete equipment:* Equipment is an incredibly broad area of sport technology with respect to the way in which it can benefit the athlete. The various sub-categories are described below:
 - o *Clothing:* Specialised shoes have been developed in almost every major sport in order to optimize comfort, speed and friction (grip), depending on requirements of the sport. Clothing has also been designed to reduce friction (i.e., swimming and sprinting), increase comfort, or even include smart-sensors that measure physiological functions and kinematics within the fabric.

- o *Design*: Most sports utilizing racquets or bats have seen fundamental changes to both their design and physical properties over time. For instance, tennis racquets and golf clubs moved from being wooden in nature to becoming steel and eventually graphite. Kevlar fibre is now used in all sorts of equipment from sails to body armour to cycling tyres.
- o *Scaling*: Relating to design, scaling consists of the use of analytical models to recommend different sizes and masses of racquets and bats to suit athletes of different ages, sexes and ability levels. It has shown to both improve participation rates and increase enjoyment in users.
- o *Feedback*: In-built sensors are now available in many bat or racquet sports capable of recording kinematic and kinetic data. This can provide feedback in either real-time or record it for later consideration and analysis.

o *Aerodynamics and hydrodynamics*: These technologies represent innovations in and of themselves. However, they have also been used to test the efficacy (i.e., reduction of drag) of design of new equipment such as in cycling or motor racing. One famous example is the 1989 Tour de France, whereby Greg LeMond's use of aerodynamic handlebars and helmet was shown through later testing to be responsible for him gaining an advantage over Laurent Fignon and going on to win the event.

- *Timing*: Many sports require extreme precision in timing for both their adjudication and simply awarding a winner. In the 1960's, automated timing of sprinters became commonplace, thus replacing hand-held methods. By the 1980's, radio frequency identification was used through locating tags on runners that were detected at various stages of a race. In the late 2000's, video had progressed to a sufficient quality to become a viable alternative. Force platforms are also used to detect when a runner leaves the starting blocks, based on meaningful changes in pressure recordings.
- *Data management and analytics*: Many of the above technologies rely on computing hardware or software in order to function or provide insights to the end user in a timely fashion. Examples include decision support systems used to improve organizational decision-making (discussed in detail in Module 3).
- *Communication*: These types of technologies include the various ways of enhancing communication both in-competition and around daily schedules. For the former, this includes the use of headsets, earpieces and walkie-talkies between coaches and athletes during competition. For the latter, this could include smartphone applications to keep an athlete informed of their upcoming schedule and commitments.

1.2 Technology & Complex Systems in Sport

1.2.1 Complex systems in sport

Even to the untrained observer, it is apparent that sporting competition is complex. In many team sports, for example, no situation occurring in a match will ever be repeated in the exact same manner. Complex systems have many features, but can be broadly defined as open systems containing many structurally and functionally heterogeneous parts which interact with one another (Balague, et al., 2013; Bertalanffy, 1969). They consist of dynamic, non-linear and recursive interactions between these parts and agents, which organise themselves to generate emerging and new properties, thus leading to self-organisation (Bittencourt, et al., 2016). These systems are unpredictable in that both the scale and timing of these interactions between parts are either unknown or unmeasurable. Importantly under these definitions, a system could relate to a single organ within the human body, a human themselves, a human and technology interaction, a group of individuals (such as a team) or groups of individuals (sometimes with competing interests such as two opposing teams) (Balague, et al., 2013).

According to Boehnert, et al. (2018), characteristics of complex systems include the following:

- *Feedback*: Outputs or outcomes relating to a process in a sport serve to influence system inputs, be it directly or indirectly. As many of these inputs are themselves dynamic, this feedback can accelerate or decelerate existing activity of a system. For example, after going behind in 1-0 in a match, a team may play more aggressively in response to the goal in order to facilitate scoring opportunities.
- *Emergence*: Unexpected processes or outputs arise based on interactions between components of the system. Such properties can be considered as emergent if no clear prior-stated 'cause and effect' relationship exists. For example, an athlete may develop a different movement pattern or varied technique in response to suffering an injury.
- *Self-organisation*: Higher level patterns arise due to the interaction of lower level components. For example, a team may play with greater width in order to combat a

specific defensive strategy from an opposing team, even without explicit instruction by a coach to do so.

- *Levers & hubs:* It refers to components of a system which exert a disproportionate influence. This influence can be positive or negative in that the component can not only help to catalyse change, but also to leave the system vulnerable if it is disrupted. For example, an outstanding player in a team when man-marked may substantially adversely affect the overall performance of the team.
- *Non-linearity:* The influence of the system's various inputs on its outputs is not proportional. This may manifest itself in the exhibition of exponential changes (i.e., a small change in one output may equate to a large change elsewhere) or a change in direction altogether. For instance, a team may exhibit such a change in one area that it ends up adversely affecting an output due to its negative influence elsewhere.
- *Domains of stability:* Systems gravitate towards certain states unless otherwise perturbed. An example could refer to the serve technique of a seasoned professional tennis player, which includes well-entrenched sections of movement that are incredibly stable, unless injury or something similar causes the movement to require changing.
- *Adaptation:* It refers to the ability of components within a system to learn or adapt. For example, exposing an athlete or a team in training to scenarios that they are yet to experience in competition may prepare them with tools they can use to behave strategically to respond in future.
- *Path dependency:* It refers to those situations when current states exhibit a dependency on the nature and timing of certain states that preceded them. For example, a golfer may only be able to play their pitching wedge as a second shot on a short par-4 if they use the driver club for their first shot from the tee.
- *Tipping points:* It refers to the point beyond which a sudden dramatic change occurs to the system. One such example in sport relates to the onset of a muscle strain due to a slow build-up of multiple factors, such as local muscular fatigue, changes in physiology and technique degradation.
- *Change over time:* Complex systems are always changing. As an example, a practitioner team working in a sport will continually be in a state of flux as staff

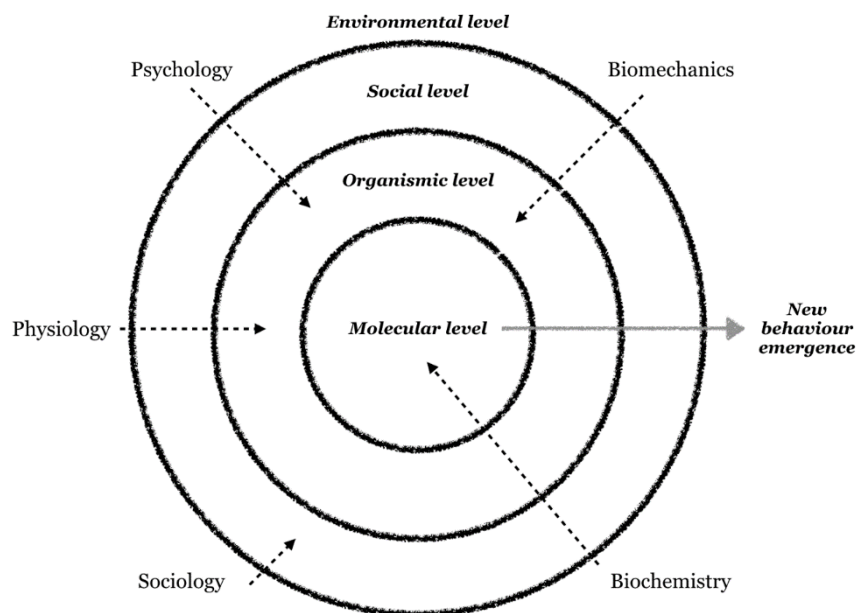
within it develops their skills and philosophies, but also as staff come and go from the team.

- *Open systems:* It refers to systems that have some interaction with components which are external to it. For example, teams may need to alter their game style in response to rule changes imparted by a league governing body.
- *Unpredictability:* Because so many components of the system exist (both unknown and known – see Theme 1.2.2. below) it is difficult to predict a future outcome. Such is the case of, for example, selecting the World Cup winner 5 years in advance, or the onset of a serious knee injury to an athlete.
- *Unknowns:* Many factors can influence a system of which humans are not currently aware (again, see Theme 1.2.2. below for further expansion on this). Thus, unforeseen changes following interventions should not be unexpected. An example of this is the lack of weight loss in an athlete in response to a prescribed eating plan.
- *Distributed control:* It refers to systems that do not have a single central control point, but rather multiple points. Various agents within the system may not have access to all of the information required. This is a good description of what is observed in most team sports during competition, whereby all participants exert some input into the nature and outcome of the outcome.
- *Nested systems:* 'Systems within systems'. An example that can illustrate this is the case of an athlete's cardiovascular system affected by the athlete as a system themselves (i.e., whether they are too fatigued to chase a ball passed to them) which, in turn, is affected by the match as a system (i.e., whether a team mate is afforded an opportunity to pass the ball in the first place).
- *Multiple scales and levels:* Components and interactions within systems can occur across multiple levels; therefore, it must be studied and considered accordingly. For instance, investigation into why an athlete's performance is suffering may require investigation not only into their physiology but also into their interactions within their organisation and other social-cultural influences.

Unfortunately, for the majority of its existence, sport science has not either acknowledged or assessed sporting pursuits with all of these features of complexity in mind. Thus, much of sport science research has continued to emphasize specialisation and mechanisms that are

independent from one another (Hristovski, et al., 2016). Sport science disciplines have also been criticized for being reductionist and favouring specialisation (Balagué, et al., 2016).

Figure 2. Arranged levels of organised content matter by sport science discipline. Although there are interactions across levels of matter, sport science disciplines predominantly focus on a single level, emphasising the discovery of mechanisms independent from the context.



(Adapted from Balagué et al., 2016)

So, why is there a lack of progress in sport science? Multiple reasons for these ongoing problems likely exist; from the structure of university sport science courses to the human difficulties associated with both understanding and practically utilising complexity as an area. One clear issue that has been noted pervasively in the literature for decades relates to a lack of collaboration across individuals from a range of disciplines:

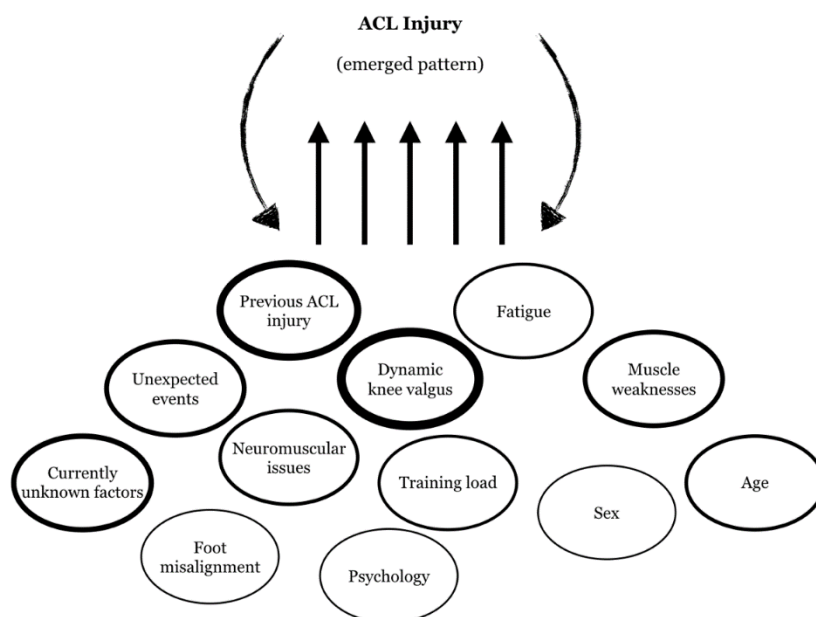
There is a major weakness in sport science, and this deficiency stems from the lack of integration of ideas and problem solving both within various disciplines and among areas. Thus, I believe that until a concerted effort is made to form interdisciplinary teams, the field of sports science will stagnate and not produce effective solutions to many problems. (Dillman, 1985, p. 107)

“Seldom is a complex question answered by research based in a single science discipline. Hence, the biomechanist must combine with the exercise physiologist and biochemist, the sport psychologist and the motor development specialist to structure appropriate research design” (Elliot, 1999, p. 307).

Fortunately, there is a growing realisation of complexity by many in sport. This has helped to increase progress into many of sports more challenging problems and questions which has otherwise been slow. For instance, acknowledgement of injury in sport as a complex event has arguably moved the industry closer to discovering underlying aetiology (Figure 3) (Bittencourt et al., 2016). Consider the quote below with respect to a team sport setting:

coordination processes in team sports lead to the emergence of functional, spatiotemporal, patterned relations between performers, as they adapt to the movements of teammates and opponents during performance. Analysis of the dynamics of coordination between performers can characterise the emergent couplings between different parts of the complex adaptive system. (Silva, et al., 2016, p. 2)

Figure 3. Example of risk factors for anterior cruciate ligament injury in an athlete using a complex systems approach. The darker solid borders around each risk factor indicate a greater influence.



(Adapted from Bittencourt et al., 2016)

So what does this complexity mean for both the development and utility of technology? As acknowledgement of complex systems become more popular in the literature, so have the limitations for its direct application in the field been highlighted, too. Similarly to practitioners and researchers, many technologies in sport have been designed for use with single sport science disciplines. Ensuring that measurement by technologies is of an appropriately detailed resolution has been emphasised as an area in need of further development (Glazier, 2017). For instance, in highly competitive and resource-rich sports, pressure will be imparted onto manufacturers to continually improve their product or device in order to ensure that the information received by key stakeholders is sufficient for the intended use. From a data resolution perspective, this will mean that the quality of new technologies will need to be further enhanced in order to ensure high precision and reliability. Technologies such as wearable sensors and computer vision are constantly making improvements in the area. Analysis of the data is another important consideration:

Complex adaptive systems are difficult to analyze and their behavior is difficult to predict. It is hoped that intricate computer simulations will provide useful tools for accurately forecasting the behavior of systems governed by the interactions of hundreds, or possibly thousands, of purposive agents acting to achieve goals in chaotic, dynamic environments. (Fogel, et al., 1999, p. 192)

The widespread increase in the use of powerful analytical tools, such as machine learning, has helped to make incursions into this area. In Module 3 we will discuss the role of decision support systems in harnessing this complexity for decision-making. Returning to the commencement of this theme, technologies that facilitate interdisciplinary collaboration will be some of the most valuable moving forwards. If these types can be achieved, then technology will be a key driver in furthering the understanding of sport as a complex system both now and into the future.

1.2.2 Augmenting human cognition through technology

Earlier in 1.1.2, the growth of data in sport as a function of increased application of technology was discussed. This growth in turn should result in a concomitant increase in the understanding of many of sports most pervasive problems, thus converting this data into 'information'. When analysed and interpreted appropriately, this information becomes 'actionable intelligence'. However, this process does not always occur successfully. Many reasons can contribute to the breakdown of this process: sometimes the quality of data is simply of an insufficient resolution for a given problem, or it may just be poor altogether. Often, when many different data types are collected and limited, or the time or resources to consider them is not enough, the relative importance of each comparatively is not clear.

The theory of bounded rationality provides a useful basis for understanding some of these problems from the perspective of human cognition and decision-making. It also provides a useful framework for understanding the position of technology within the type of complex systems discussed above in Theme 1.2.1. Bounded rationality states that in problems relating to decision-making in complex systems, individuals are bound to make satisfactory decisions rather than 'optimal ones' (Gama, 2013; Gigerenzer & Selten, 2002). This is because of the various cognitive and environment constraints that they experience on an ongoing basis (Simon, 1956). These cognitive constraints can include the limitations of the individual's own knowledge, their biases and preferences, or level of information processing capacity. Environmental constraints may include the amount of time afforded, cost and resources available by which to contemplate the decision at hand. Thus, as the human decision-maker will always experience the influence of constraints, they have no option but to settle for making satisfactory decisions rather than the potentially unachievable 'optimal' ones (a process referred to as 'satisficing').

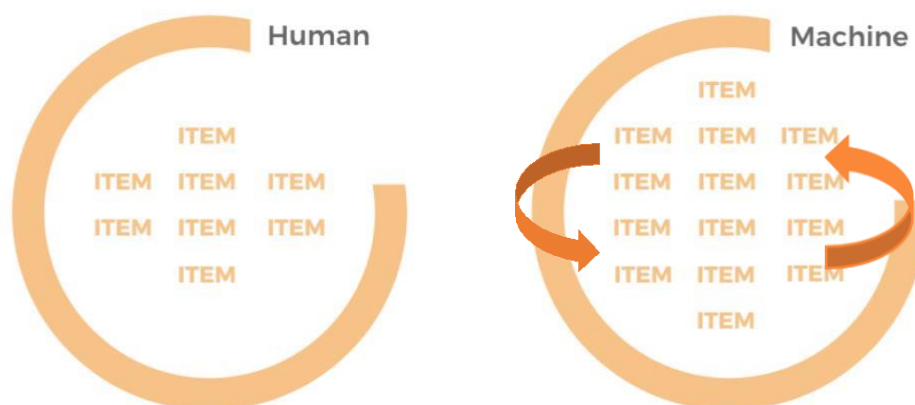
To this point of the course, we know that technology can provide a means to alter the influence of these constraints by performing as an external aide to the human decision-maker, or even as a replacement for the human altogether. Perhaps, the way to illustrate bounded rationality in sporting practice is through an example. For this purpose, we can consider the process of undertaking an evaluation of the quality of a footballer (see Robertson & Joyce, 2019 for a more detailed example). In order to undertake their evaluation, a good coach will likely call on a variety of information on which to make the assessment. Some of this information will be consciously collected and considered (i.e., the player's match statistics), whereas other parts of the evaluation may be subconsciously influenced (i.e., does the coach like the player?, do they especially value certain qualities that they possess, or did the player perform particularly well the week before the coach provided the assessment?).

Technology assists with this process in a number of ways. It can be used to collect enhanced information on the player that the coach may find of use in making the assessment. For instance, prior to video becoming available in sport, football coaches or

analysts were confined to using the pencil, paper and a stopwatch in order to record both timing and patterns of running, passing and dribbling by players participating in training or competition. Modern electronic performance tracking systems (EPTS), such as those offered by GPS, LPS or video, far increase the accuracy of such methods. However, technologies such as computers and decision support systems (discussed in greater detail in Module 3) can also serve to objectively consider a greater number of data types. In fact, they can process, store and analyse much larger data sets, as well as identify meaningful and potentially non-linear interactions between different data types.

The limitations of humans in undertaking such tasks are well-established (Grove, et al., 2000; Meehl, 1954). For instance, the seminal work of George Miller's, 'Magical number 7', refers to the approximate number of pieces of information that a human can consider when evaluating a problem before their limitations render any additional information redundant (Miller, 1956). In fact, the vast differences in handling large volumes of information coupled with the manner in which they can consider many of sports most complex problems means that it is probably unfair to compare human performance with that of a machine (Figure 4). Returning to our example, practically this means that the way in which the coach may rate the quality of the player will likely be quite different to the way the computer or machine does due to fundamental differences in the way it addresses the question. In fact, a similar example can be found in the literature in Italian football, whereby evaluations of player performance made by media experts were compared with those from computer models (Pappalardo, et al., 2017). Findings revealed that the experts utilised only a small sub-sample of 150 available metrics on which to base their evaluation. They also revealed a particular emphasis of the experts to favour particular data types (for instance, strikers were rated almost exclusively on the number of goals they scored).

Figure 4. Representation of the differences between machines and humans in information access and processing. Machines can both consider a greater volume of information and objectively identify non-linear interactions between different data.

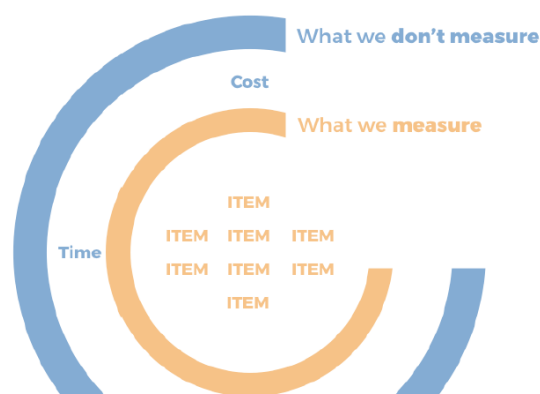


(Robertson & Joyce, 2019)

This presents a difficult problem for humans. Assuming the computer has ‘sufficient’ high quality data on which to make its evaluation, not only will the human be outperformed with respect to the volume of data they consider, but they are also liable to become prone to availability bias. Specifically, the human will overemphasise whatever information that they happen to have access to. This is doubly problematic, as often some technologies that are utilised in the field are simply done so because they are easy to use or gain access to (as introduced in Theme 1.1.2). If one reflects on components of sport that are the most important (i.e., motivation, teamwork, communication), one also acknowledges that they are the most difficult to measure. This also helps to explain why technology is yet to make meaningful incursions into progressing human performance via these means.

Returning to the example, Figure 5 adds a second layer to the problem. As more technology is developed, additional information can be accessed and utilized for the purpose of evaluating the player. To not reaching widespread consensus on which data should be used across the industry, this in turn means that there will likely be greater variability across individuals, clubs, and organisations with respect to how they view the same problem. Figure 5 shows the outer layer, which includes other types of data collected from technology that is not currently utilized by the coach in making their evaluation. Items could be located within this layer due to multiple environmental (i.e., insufficient resources, time or interest to consider the item) or cognitive reasons (i.e., non-comprehension by the user) (Gigerenzer & Selten, 2002). In the example, these might include items such as the leadership qualities displayed by the player during a game (not considered due to the lack of an appropriate measurement tool) or certain metrics derived from a player’s tracking data (not considered due to the time taken to analyse the data or a lack of interpretability by key stakeholders). This helps to explain why if we ask a fan or a coach from a different club to make an assessment on the same player, they may provide a different response. This does not necessarily mean that one evaluation is more or less correct than the other; rather, the evaluation will be based on the information they have at their disposal and the way that they interpret it.

Figure 5. Environmental and cognitive constraints.



(Robertson & Joyce, 2019)

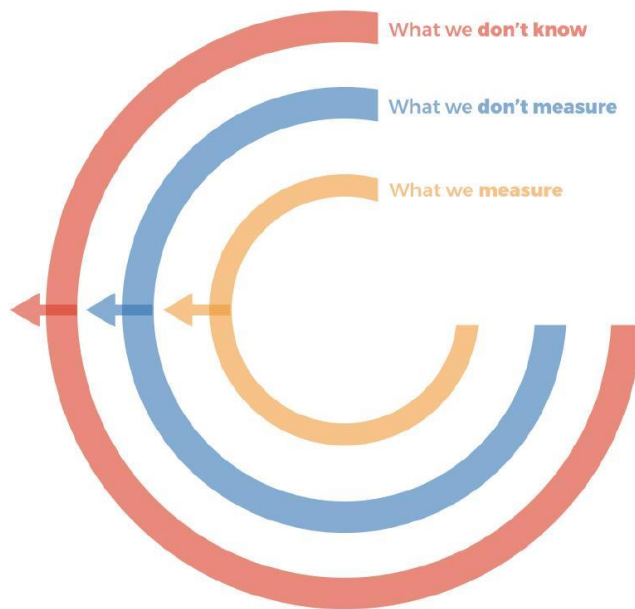
Environmental and cognitive constraints serve to limit the volume and type of information that can be used by humans when making judgments and evaluations. Certain items, whilst acknowledged as important, may not be considered because of low time, insufficient resources or a lack of expertise in interpreting the data

Figure 6 adds a final outer red layer to the schematic. This represents new types of technology which will lead to the creation of new types of data that currently do not exist. Newly developed technologies will serve to increase the dimensions of the red layer, whereas improvements to existing technologies (see 1.1.2) will serve to reduce the influence of environmental and cognitive constraints, thus expanding the inner two layers. Further, technologies and measurements currently located within the outer layers should shift into the inner layer as technology improves, becomes cheaper and ultimately, more accessible.

Returning to our example, this ostensibly has two ramifications. First, assuming the data generated by these technologies is of sufficient quality, the evaluation of the player should be more accurate in future because a more comprehensive representation of the complete player will be available. Second, philosophically this creates an interesting question – how much data is enough? Is a perfect evaluation of the player even attainable? If we accept that technology will continue to develop, then the answer must be ‘no’ and the problem must be viewed as inductive (Arthur, 1994). That is, that the manner in which we continue to evaluate the player over time will always continue to evolve.

Another challenge will be that, unless all of these data are accessible to all of the people that require it, disagreement will continue to exist as individuals and organisations choose (or are forced) to consider incomplete datasets in different ways. Depending on which way you look at it, this could of course be considered as a good thing and is also a hallmark of the complex systems discussed in the Theme above.

Figure 6. Visual representation of bounded rationality.



(Robertson & Joyce, 2019)

Over time, relaxation of environment and cognitive constraints increase the circumference of each layer. Uptake of new technologies as well as the search for competitive advantage will drive these expansions

1.2.3 Implications for the individual and the organisation

So what does this all mean in practice for the individual? The benefits of technologies that can both create data as well as harness its value should be clear by this stage of the module. One of the major dilemmas that arises from increased technology used centres on the implications this has for jobs. In some situations, there is in fact no real dilemma – the human is ostensibly replaceable. This is particularly the case in roles and positions that

consist of a large amount of repetition and that are capable of being automated (or at least semi-automated). Examples of machine-driven automation are all around us in society. In sport, computer vision-derived detection and classification of match events has reduced the burden on performance analysts, yet in some sports the benefit of their very existence has also been called into question. Nevertheless, signs of the impending shift are anything but new. As early as the 1950's, the psychologist Paul Meehl observed that "A considerable fraction of (human) clinical time is being irrationally expended in the attempt to do (...) prognostic jobs that could be done more efficiently...through the systematic cultivation of complex statistical methods" (Meehl, 1954, p. 4)". There is also strong evidence that matters of decision-making (particularly in complex environments) are also best left to computers or machines. For instance, a seminal meta-analysis of 136 scientific studies showed that humans outperformed machines across a range of tasks in just 6-16% of cases (Grove, et al., 2000). Similar findings have been observed in sporting contexts. For example, Maymin (2017) revealed machine recommendations outperformed that of general managers in player selections in National Basketball Association drafting and trading, whilst Pretorius & Parry (2017) investigated machine vs. human prediction of match outcome at the Rugby World Cup.

Consequently, a predominant question arises with respect to how much an individual should decide to redirect their training and expertise to developed technology-specific skills, as opposed to emphasise development of their more 'human' attributes. If the former is to be emphasised, which skills should be learnt, and which should be left to automation by technology or computing? For instance, is spending the time to learn a computer programming language going to be more advantageous for the performance analyst than becoming a better manager? Many successful sport coaches would, quite rightly, point out that their success has in part been due to their human qualities (i.e., empathy, relationships, communication). Dedicating already scant time to tasks relating to data or development of an understanding of underlying technology would seem impossible. Yet, this dilemma will not go away and will probably continue to become more difficult to solve.

Computational thinking represents one of the ways in which an individual can maintain pace with the changing landscape of sport, without diverting an excessive amount of their time and energy away from their core function and training. Because it consists of a way of thinking rather than a new skill to be taught, computational thinking can be rapidly integrated into the workflow and everyday process of individuals and teams. Computational thinking refers to the thought processes involved in formulating a problem and expressing its solution(s) in such a way that a computer can effectively carry out (Wing, 2014). It is worth noting that this process could result in action being undertaken by an actual computer, by a human themselves displaying relevant characteristics, or by a hybrid approach of computer and human. The five elements of computational thinking are typically categorised in the following way:

- *Decomposition:* Much of computational thinking is grounded in logic. Decomposition not only involves breaking down problems into smaller parts, but it also includes doing so in a logical manner in order to make it manageable for an individual or team to address. This especially helps with large, complex problems whereby certain parts may need to be allocated to multiple, different stakeholders.
- *Pattern recognition:* Once decomposition has occurred, the parts can be closer evaluated with respect to the level of similarity they bear to other decisions or processes undertaken within the organisation. This can allow for actions such as the identification of key stakeholders within an organization that may be useful to involve in the process, or to identify learnings from similar problems that have been faced elsewhere. Thus, this helps to improve efficiency from the outset.
- *Abstraction:* This process emphasises simplification, or removal of detail, of a problem as well as search of redundancies. It has groundings in other computational concepts such as parsimony (discussed in greater detail in Module 3), which refers to achieving an appropriate balance between collecting enough information to sufficiently inform a given process or decision, contrasted against collecting too many pieces of information that provide only incremental improvements.
- *Algorithms:* This can refer to a specific equation to follow in which to address a problem, or it can be as simple as a sequence of basic rules or flowcharts. Even a basic awareness of how different statistical techniques or machine learning algorithms form differing outputs and, thus, recommendations to the user can be of value with respect to developing flexibility in problem solving approaches. Specific analytical techniques are discussed in greater detail in Module 3.
- *Generalisation:* This centres on considering the extent to which solutions will work on the same problem in future, as well as be successful on different problems altogether. Thus, it tends to also incorporate some evaluation, or if the solution takes the form of a model, it may also consist of formal validation. It has similarities to abstraction in that parsimony may also be of relevance here, particularly as it pertains to overfitting. This concept refers to the notion that most generalisable solutions will often be simpler in nature. Overly specific solutions to problems may not generalise well to new scenarios, given the circumstances and conditions are constantly changing (Overfitting is also discussed in greater detail in Module 3). Thus

the volume of information considered in addressing a problem should also be considered.

With respect to the organisation, the abovementioned considerations have implications for the skillsets that are being hired for both now and into the future. With 'computation' having joined 'theory' and 'experimentation' as the recognised third pillar of science (United States President's Information Technology Advisory Committee, 2005), a key challenge for organisations is to recruit individuals and teams of individuals skilled in computational thinking, irrespective of whether they possess formally training in computer-related disciplines. The sport industry is not a unique case in this; almost all industries are experiencing similar challenges. In some cases, organisations may need to make the decision to outsource expertise in developing or harnessing technology. Consultancy is nothing new; however, partnerships are shaping now as a viable alternative. These can take the form of third party agreements with manufacturers, or ongoing relationships with universities.

Organisations with the necessary means and maturity may choose to invest time or advice into technology companies in return for equity, or become involved through venture capital. University partnerships are increasingly manifested as transdisciplinary collaborations. This form of partnership refers to different disciplines working jointly to create new conceptual, theoretical, methodological and translational innovations that integrate and move beyond discipline specific approaches to address a common problem. The main benefit of such partnerships is to address the big picture questions that require attention. For organisations, these are numerous and most, if not all, are not addressable without the involvement of technology. Examples include the following:

- Improvement of both the measurement and evaluation of the structure, communication practices and overall performance of practitioner, staff and coaching teams.
- Longitudinal inter-organisation and inter-sport investigations into complex phenomena such as talent identification and development, skill learning, decision-making and injury.
- Development of new methods to enhance communication and trust between coaches, practitioners and athletes.
- Improvement of human-computer interaction to improve practitioner efficiency and organisational decision-making.
- Various applications of data mining and analytics as a conduit and stimulus for interdisciplinary collaboration.

1.2.4 Ethical considerations, ceiling points & limitations

Because sport is a complex system, small changes can exert large influences on different components of the system, as well as its outcomes. When the entire system is not considered when making decisions relating to the governance, organisation and future of a sport, often any changes implemented can have unintended consequences. The history of sport is littered with examples of technology implementations and rule changes that have resulted in exactly this occurring. Sometimes these have been positive, but overwhelmingly they have been negative.

One consideration relating to the implementation of technology in sport relates to the level in which they augment the participant in such a way that the sport becomes meaningfully different, or perhaps even unrecognizable to what it was in the past. We have already discussed the varied ways in which technology can improve sport, but with respect to performance enhancement, there has often been an uneasy line which has been drawn between performance enhancement and 'cheating'. Tales of drug use and abuse come to mind initially; however, examples are often more nuanced than that. Advantage through means such as increasing the dimensions of a cricket bat or Oscar Pistorious using carbon fibre blades on his prosthetic legs has to lead to discussions on to what extent both standardisation and equal access for all participants are required.

Thus, a question arises with respect to how much a sport can change as a consequence of technology. When do historical records change so much that it becomes something different altogether? The fans and broader public has often been a good indicator for determining this balance. Sometimes a sport changes so much that a new product emerges, such as futsal, 3 vs. 3 basketball or 20/20 cricket all emerging as variants on existing sports. Other times technology has been rolled back post-implementation, such as engine limitations in Formula 1 racing to reduce speed and noise, restrictions on golf ball design to limit driving distance, or the banning of full-body suits in swimming as a response to wholesale systematic decreases in racing times. One point worthy of recognition in this discussion is that technology is constitutive with sport (Lolland, 2002). Without equipment, most sports would not exist.

Sometimes these technologies are not all that they seem. At the most basic level, in the 1960's Dick Fosbury altering his body movements to perform the high jump had fundamental implications for the sport, so much so that now his technique is utilised by all competitors. In today's environment, it is unlikely that such an augmentation would be considered as unfair.

Another consideration with respect to the ethical influence of technology relates to what the goals of sport actually are. This is a deeply philosophical question with many potential supporting theories. The non-theory of sport performance would state that sport is simply a

means towards the achievement of external goals. Thus, the aim is to win by any means necessary and there is no acceptable or unacceptable implementation of technology. For most, this is an unreasonable representation of how technology should be used; it evokes images of de-regulation and widespread illicit drug use. However, in keeping with the optimistic nature of this course, it is worth asking whether there are ceiling points to human performance that can be overcome through technology. This question more closely aligns with the thin theory of sport performance, which concerns itself with pushing the boundaries of human performance, thus emphasising record setting and viewing technology as a positive influence (Loland, 2001). Here, growth in technology and human performance are considered as evolutionary progress and something to be encouraged. Of course, the success of this theory assumes technology producing data of a sufficient quality to measure and record this progress.

The thick theory builds upon the thin theory by adding considerations relating to morality, societal norms and equality. Here, although technology is still regarded as positive for sport, it should be considered with respect to providing equal treatment and opportunity for its participants. Thus, technology that contravenes this position, or goes against the 'spirit of a sport' should not be encouraged even if it enhances human performance. By maintaining an emphasis on social norms, the thick theory also forces consideration of ethical dilemmas that may not have even been an issue in decades past. For instance, the use of genetic testing for talent identification provides an incorrect impression that success in sport is predictable in athletes from a young age. This leads to a whole range of problems; such as parents spending time, effort and money on early specialisation. This in turn can create a 'race to the bottom', whereby issues are experienced by all of the children involved in a sport. Those children achieving success also experience a lost childhood and potentially early burnout. Those that do not achieve success can suffer mental health issues and may be lost to participation in the sport altogether. In summary of the thick theory, the principle of 'do no harm' should be maintained when considering implementation of technology. This is typically the case with alterations to technique or body movements. With respect to equipment, emphasis should be focused on whether the technology is accessible by all participants and considered 'fair' with respect to the goals of the sport.

Another ethical consideration relating to sport relates to the nature and conduct of the industry itself. Quite simply, the broader sport industry is now massive and unrecognisable to itself from years past. Like many fast-growing, potentially lucrative and competitive industries, this can create and attract both unscrupulous types and practices. To those working and competing in sport, there needs to be an awareness of 'snake oil salesmen' and hype over substance. Given the speed in which enhanced and new types of technologies are being developed and marketed, it is a difficult pursuit to stay up to date with and undertake due diligence on new offerings. Many readers will have their own stories of being sold a product after being told it has certain capabilities, only to find out

later that the technology did no such thing. Analytics represents one great example of this. There is a great unattributed quote relating to the analytics start-up community, which says something like the following:

“When we raise... it’s artificial intelligence” (No author)

“When we hire... it’s machine learning” (No author)

“When we do the work... it’s logistic regression” (No author)

Neural networks and many (but not all) machine learning algorithms are often ‘black boxes’, with the underlying reasoning behind predictions or recommendations not interpretable by lay users. Utilisation of the term ‘artificial intelligence’ in the quote evokes a positive response in investors and may work well as a sales pitch, whereas in reality a potentially simple, linear, statistical model may actually be all that is required to undertake the work. The sports technology industry is replete with such examples. Thus, important skills and characteristics of staff working with sport technology should include critical appraisal, scientific rigour, scepticism and attention to detail.

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