A review of virtual environments for training in ball sports

Helen C. Miles a,*, Serban R. Pop a, Simon J. Watt b, Gavin P. Lawrence c, Nigel W. John a

a School of Computer Science, Bangor University, Dean Street, Bangor, Gwynedd LL57 1UT, UK
b School of Psychology, Bangor University, A deleid Brigantia, Gwynedd LL57 2AS, UK
c School of Computer Science, Bangor University, Dean Street, Bangor, Gwynedd LL57 1UT, UK

ABSTRACT

There is growing interest in utilising virtual environments (VEs) in the context of sports. In particular there is a desire to be able to improve sensorimotor skills rather than just using a VE as a tool for strategy analysis, or entertainment. The range of skills required across all different sports is very large and varied. This review of the state-of-the-art, therefore focuses on just ball sports, and was carried out as part of a current project developing training tools for rugby. A VE needs to provide realistic rendering of the sports scene to achieve good perceptual fidelity. More important for a sport-themed VE is high functional fidelity, which requires an accurate physics model of a complex environment, real time response, and a natural user interface. The goal is to provide multiple scenarios to players at different levels of difficulty, providing them with improved skills that can be applied directly to the real sports arena. The typical hardware and software components needed are identified in the paper, and important psychological factors that should be considered are discussed. The challenges that need to be overcome are identified and illustrated with examples from recent projects in this area.

1. Introduction

The way people learn and execute effective motor skills poses a diverse and challenging set of questions that have been the attention of researchers since the 19th century [1]. However, despite over 100 years of research on skill acquisition the fundamentals of effective coaching have still not been fully illuminated. What is clear is that in order to develop expert performance, individuals must invest considerable periods of practice time (e.g., a 10 year period [2,3]), and that this practice should be specific to the skills required for the to-be-learned task/sport (i.e., sports-specific or deliberate practice [4]; for a review see [5]). The body of research has identified that both coaching and skill acquisition normally involve three distinct processes: conveying information (i.e., observational learning), structuring practice (i.e., contextual interference) and the nature and administration of feedback (i.e., feedback frequency, timing and precision) [6]. Additionally, the time constraints placed on both coaches and performers require the teaching and learning of more than one skill in a single session. Consequently, most training sessions demand that learners practise a wide range and number of skills. Indeed the skill acquisition literature suggests that learning is typically maximised when performers are forced to learn a variety of skills in a single training session and where these skills are practised in a random fashion (i.e., the practice environment is very diverse and challenging, similar to the demands of a competition or game) [7–12]. This complexity and variety of training is difficult to achieve in conventional training sessions. Moreover, it can be very inefficient because the participation of many players is often required simply to simulate the competitive context being taught, even though only one player might benefit directly from the training.

There are many potential advantages to a sports training VE. For example, a VE allows standardised scenarios to be created by coaches; extra information can be given to players to enrich the environment and guide their performance; and it is possible to quickly and randomly change the environment to match any competitive situation (including simulating the presence of other players). All of these have the potential to revolutionise current training practices. The vast range of skills, environments, and levels of training encountered across all sports is beyond the scope of a single paper. We focus here on ball sports, because this area is most relevant to our current goal of producing a training VE for aspects of rugby. Specifically, we focus on motor-skill learning, but it should be noted that VEs also have the potential to provide a sophisticated tool for training in strategy and tactics [13]. The review aims to illustrate the current state-of-the-art technologies and research problems involved in improving functional fidelity for the trainee, where functional fidelity pertains to the similarity of the athlete's behaviour in the simulated
and real environments. A background section on VEs follows, including a brief overview of the contribution of sports-themed video games (many innovations stem from this sector). Clearly, the utility of a VE for sports training is dependent on the capabilities of the available technology components. Thus, a summary of the hardware and software technologies required to build a high functional fidelity sports-themed VE is then presented. These are explored in more detail in the context of the challenges that must be overcome to build an effective training environment for ball sports, and the advantages that can be achieved are highlighted. Examples from current multi-disciplinary research are used to demonstrate each point. The paper concludes with suggestions for future research directions.

2. Background

2.1. Virtual environments

A VE can be considered as a collection of technologies that allow people to interact efficiently with 3D computer generated models in real time using their natural senses and skills [14,15]. As such, a VE can be used in a variety of ways, including: to provide the end user with an immersive experience for entertainment purposes; to design a new concept or product; to explore and gain insight from data in an intuitive manner; and to train people at complex (and perhaps dangerous) tasks in a safe, convenient, and/or effective environment. Early adopters of VEs include the aeronautics industry (flight simulators), the entertainment industry (simulator rides, video games, and movies), medical-procedures training, oil and gas exploration, and automotive design. As the available hardware gets more powerful, and often less expensive, more and more application areas are taking advantage of VEs. Sport performance is one area where there has recently been great interest in obtaining added value from a VE. The effectiveness of any VE used for training can reasonably be measured against three criteria: it must be realistic enough, it must be affordable, and it must be validated to show that it works as designed. We suggest that it is only by satisfying all of these criteria that a VE built for training skills in sport will become an accepted tool.

2.2. Sports-themed computer games

At first thought, computer gaming might seem unlikely to inform VEs for professional sports training. Such games can be considered as a low functional fidelity VE, however, and although designed primarily for entertainment, many useful tools and techniques have been developed in this domain that can be deployed in training applications. These range from hardware peripherals, to physics engines, to computer-graphics rendering algorithms.

For example, a significant evolution within the computer games market followed the introduction in 2006 of the Nintendo (Kyoto, Japan) Wii, which uses a wireless remote interaction device – the Wii Remote – with built-in accelerometers and infrared sensors to detect three-dimensional movements. It allows users to play and control games using physical gestures combined with traditional button presses. Accuracy is increased with the Wii MotionPlus [16] add-on, which captures rotational motions using two gyroscopes and an angular rate sensor, helping to disambiguate complex movements. The Wii Balance Board is also available, which can measure the weight of the player and his or her centre of gravity, and is specifically aimed at fitness activities. Game players can therefore now improve their general fitness as they engage in the game activity. The popular Wii Sports package provides simplified versions of tennis, baseball, bowling, golf, and boxing, and evidence is emerging that the Wii platform is contributing to the acquisition of skills in some real sports (e.g., 10-pin bowling [17]).

Another recent innovation in games hardware is the Microsoft (Redmond, USA) Kinect for Xbox 360 and Windows, which employs camera-based marker-less tracking to encode the user’s movements. The images from an RGB camera inside the Kinect’s sensor bar are used to detect moving people against background objects and, together with the integrated depth sensor, can support human-feature recognition. The Kinect can build a reasonably accurate motion analysis map, and can track up to 20 separate points of articulation for each person in its range. The potential of this hardware is demonstrated by the Kinect Sports package that includes beach volleyball, boxing, bowling, soccer, table tennis and athletics. The user remains in the same place but mimics the actions and gestures of a real athlete using arm and leg movements. The Kinect may require calibration at the start of a session, but the accuracy achieved in play is good (considered better than on the Wii). However, independent reviews also report problems with the responsiveness of the device and general game play [18].

Video games continue to provide innovative technology at an affordable price. They can also excel at recreating the actual environment of a sport, from a high-quality reproduction of the stadium to the realistic scale of all the elements in play (balls, bats, gymnastic apparatus, etc.). Some games are designed as a first-person experience, to enhance the feeling of immersion, but others effectively re-enact a television broadcast by featuring realistic play-to-play audio commentary and television-specific camera-angles, giving the player a third-person experience. The drawback of this latter approach is that often the event flow is suspended whilst the user makes several choices about how he or she wants to continue. This would not be appropriate in a VE designed to provide skills training that would transfer to the real environment.

2.3. Components required for a sports VE

There are a number of basic technological elements required to construct a sports VE. The main technologies typically deployed are:

- Display technologies, often using stereoscopy. Examples range from Head Mounted Displays (HMDs) to large-screen Power Walls;
- Tracking technologies, such as optical, magnetic, and inertial systems. Motion capture is a particular example;
- Haptic technologies for force and tactile feedback. These range from hand-held joystick devices, to large-scale pneumatic motion platforms;
- Software algorithms for efficient rendering of 3D computer graphics and multi-user synchronisation;
- Many custom built devices will also be fabricated depending on the application area.

These components are mainly used in academic projects although there are also a few sports-related commercial systems. Visual Sports (Ontario, Canada), for example, offer relatively advanced simulators that cover golf, soccer, baseball, and other sports. Golf simulators are also available from VirtuGolf (Alabama, USA) and Indoor Golf & Racing (Washington, USA). Their main market is the entertainment industry but the difference from a video game is that the product is built to be life size and uses the above display and tracking technologies. Sports training is of interest to the commercial sports simulator manufacturer, but currently the majority of VEs available for sports training have been developed by
Fig. 1 summarises the hardware components that are typically used as identified from a survey of 25 academic papers relating to sports VEs. Many different technologies are used, some clearly favoured more than others, and they are described in the following section. The software options most used are also summarised. Key issues and challenges in delivering a ball sports VE are then identified and examples from published work are used to illustrate each point. Finally, possible research directions in the field are discussed.

3. Hardware used for sports VEs

3.1. Input devices

Suitable input devices are required to allow the user to interact and engage with the virtual world in a natural manner. Typically that means that input data need to be processed in real time. Joysticks, keyboards and game pads have all been commonly used in this capacity [19,20]. For many sports-training applications, and motor-skill learning in particular, however, the VE would ideally encode more complex aspects of movements.

One approach is to use motion capture: the practice of dynamically recording the positions in 3D space of various pre-defined points on the body or an object. There are various mature technologies employed to do this. Optical tracking devices use multiple infrared-sensitive cameras to track the positions of ‘markers’ attached to the target (to joints on the body, for example). ‘Passive’ systems illuminate the scene with infrared light and detect the positions of retro-reflective markers. ‘Active’ systems use infrared light-emitting diodes as markers, but are otherwise similar. Provided the positions of the cameras in the space are known (i.e., the system is calibrated) the 3D location of each marker can be recovered by analysing its position in each camera’s image (at least two are required to recover 3D position of a marker). A quite diverse array of systems is available from different optical motion-capture companies, including Vicon (Los Angeles, USA), OptiTrack (NaturalPoint, Corvallis, USA), PhaseSpace (San Leandro, USA), Qualisys AB (Gothenburg, Sweden), and Northern Digital Inc. (Waterloo, Canada). Other companies have developed electromagnetic motion capture systems (e.g., Polhemus, Colchester, USA) and some companies use several technologies (e.g., Ascension Technology Corporation, Burlington, USA).

Real-time motion capture is used with VEs to capture the user’s position and movement, and has two main purposes. First, with stereoscopic displays in particular (see Section 5.4), and any type of HMD, it allows the 3D graphics to be rendered correctly, taking into account the current position of the player’s head. Second, it allows the player to interact with the virtual world in an intuitive fashion, using natural movements. This could include using her body to control an avatar ‘double’ that is visible in the VE. This may be necessary when using a head-mounted display (HMD), for example (see Section 3.2), in which case the player’s actual body will not be visible to her. Or it could provide the player with alternative views of her actions. Alternatively, a more natural approach in many sports, particularly in situations where an athlete’s movement is confined within a given space (goal-keeping, for example), is to use motion capture just to measure the player’s movements, and use the VE only to present other players, objects etc.

In addition to capturing motion of a player’s body, it is often necessary to capture motion of sports equipment such as a tennis racket, or ball, in order to evaluate a player’s action (e.g., in situations where movement technique or outcome is dependent on the trajectory of the racket or flight of the ball). Indeed, there may be applications for which capturing only the motion of the equipment will be sufficient. This can be advantageous because markers can be permanently attached to the equipment, minimising setup time for new users.

Another potentially important use of motion capture in sports-training VEs is as a tool for analysing the movement of the player in great detail, either in real time, or post hoc. The standard method analysing athletes’ movements is video playback [21]. However, this has significant shortcomings, in that it relies entirely on the quality of the footage, and that it was filmed from the relevant angles. In contrast, after a player’s 3D motion has been captured, it can be played back at any speed and viewed from any angle, allowing sports practitioners to study the athlete intricately in order to understand how they can improve performance. Bideau et al. [21], for example, were able to observe previously undocumented evidence of how a goalkeeper is able to
determine the destination of a thrown ball. Motion capture is not perfect in this regard; one problem is the possibility of markers being obscured, for instance, resulting in lost data, or interpolated data that is not entirely representative of the actual motion. However, these problems can be minimised by using additional capture cameras.

A further potential use of motion capture in sports VEs is to provide data for animation of virtual figures or objects. Pre-recorded motion capture is used in this way in films and games to animate computer-generated characters, because it is both faster and more realistic than manually animating a character. It is possible to edit the motion captured to produce many variations of the same attacking or defensive moves that would otherwise be very time consuming to create if manually animating the characters. It is also potentially possible to create models of typical behaviour into which random variability in performance is introduced. These movement variations are essential when using VE for skill acquisition since all human motion contains inherent variability.

There are other techniques that could potentially be substituted for motion capture in the above roles, and that could be easier to administer. For example, photogrammetry can be used to recover 3D structure by mathematical analysis of several photographs of an object taken from different angles. Both commercial and public-domain photogrammetry software packages are available (e.g., Eos Systems (Vancouver, Canada) PhotoModeler, Carnegie Mellon's Automatic Photo Pop-up [22] project). Although equipment is needed to take high-quality photographs, it is a significantly less expensive method that can produce results comparable to full motion capture suites [23]. A ‘depth-relief map’ can also be recovered using structured-light scanning, which analyses the effects of projecting structured light into 3D surfaces [24]. A more general class of computer vision solutions have also been developed, which can analyse still or moving images to perform a task; this could be waiting for an event to occur, gathering information or controlling hardware [25].

In addition to technologies that capture human and object motion, technology for eye and gaze tracking can also be used in the context of sports training. Gaze behaviour can differ significantly between experts and novices, e.g., when tracking a ball and aiming [26,27]. Bad habits and unconscious actions that can affect performance can also be identified by tracking an athlete’s eyes during play. We are not aware of any examples of this in sports training VE at present.

3.2. Output devices

Feedback to the user must occur in real time. Of the human senses, it is vision and touch that are the most commonly used in the current generation of VEs, and so we explore these display modalities here. The visual display technologies in use today are:

- PC monitors,
- Data projectors, often with large display walls,
- HMDs (Head-Mounted Displays),
- CAVE (Cave Automatic Virtual Environment).

There are many examples of each of these four visual display methods being used as part of a sports-based VE. The ‘My Second Bike’ [28] project was designed as a social television application to be used at home, making a television or PC monitor a vital part of the setup. Data projectors are the most common display type in our survey (Fig. 1), because they offer a larger field-of-view than a desktop monitor, and so give a more immersive experience. V-Pong [29] offers a good example of a large (4 × 3 m) rear-projected screen, used to allow the user space for movement while only being required to wear a pair of lightweight polarisation glasses to view the environment stereoscopically. HMDs are less prominent in sports VEs, primarily because they can be cumbersome to wear and can cause difficulties for users performing active tasks. They have been used in VEs in which they will not detract from the user’s performance; for example a rugby VE [19] which only requires analysis of deceptive movement, or a virtual swimming experience [30] in which the HMD is suspended with the user as part of a system of pulleys and bungees to simulate buoyancy. CAVEs are rare in sports VEs; this is most likely to be because they are both expensive to set up and very space-consuming, requiring rear-projection for 4, 5 or 6 walls (including floor and ceiling). In our survey, the only project that used a CAVE was Tennis Space [31], which used a partial CAVE of 2 walls due to space restrictions.

All of these devices – monitors, projectors, HMDs and CAVEs – can be used to present stereoscopic images, with a variety of methods for separating the left and right eye’s image when viewing the scene, including separate displays for each eye (in HMDs), red-cyan anaglyph glasses, ‘comb’ wavelength interference filters, polarisation glasses, and liquid-crystal shutter glasses. There are also a number of glasses-free autostereoscopic computer monitors and televisions. Examples include Chong and Croft [32] who used a data projector to show anaglyph stereoscopic video in their rugby lineout VE because they believed the glasses to have better comfort, contrast, and a larger angle of head movement than polarised glasses. Xu et al. [31] used Infitec (Interference filter technology by Infitec GmbH, Ulm, Germany) comb wavelength filters, with simultaneous projection of the two eye’s images, for their tennis VE because it eliminates the problem of ghosting even for fast movements, which is important for fast-paced sports. Simultaneous left- and right-eye projection also eliminates depth distortions in moving stimuli that can be caused by field-sequential stereo presentation (discussed in Section 5.4). None of the papers reviewed directly addressed this issue.

Haptic technology provides various forms of sensing movement and providing force and tactile feedback to a user, providing them with a means of interacting with their environment in terms of touch and to enhance their immersion into the VE. The majority of haptic devices currently available on the market use a stylus grip to deliver a maximum force of between 3 N and 15 N (for example the PHANTOM product line (SensAble, Wilmington, USA), and the Omega range (Force Dimensions, Nyon, Switzerland)). Such devices have been used in a sports VE (for example, in a ping pong simulator [31]), but in general these types of device do not lend themselves to simulating sports equipment because they are generally anchored to a point in space, have a small range of movement, and cannot easily be adapted to particular requirements of different sports. Thus, a haptic device would most likely need to be custom built to allow the VE and haptic device to truly complement each other. One example is the HapStick, a virtual game of billiards with a custom haptic cue [34]. Also of note is the Safe Large Workspace Haptic device [35], which was designed to provide a large workspace for sports training and rehabilitation. The end effectors of this device accommodate a variety of components and objects to grip sports equipment and support the user’s body. It provides a spherical workspace of three metres diameter and delivers a maximum force of 500 N and has been used for training throwing techniques for the javelin and shot put. Support for large workspaces is an essential requirement for most ball sports training.

Vibrotactile feedback devices are a sub-category of haptic technology that involves the use of many small vibrating transducers that can be felt by the person; Alahakone et al. [36] identify rehabilitation, sport and motor learning, and information display and gaming as relevant applications for vibrotactile
technology. The use of vibrotactile feedback devices in sport is unusual, and very different to the use of general haptic devices, because they are typically not used to present naturalistic information but to signal to the user in other ways. Examples include: a motion feedback system intended to replace the auditory feedback from a coach with vibrotactile feedback cues [37]; a system that applies vibrotactile feedback to correct movement in snowboarding [38]; and a vibrotactile vest which allows the coach to direct players during football practice [39]. Vibrotactile devices hold great potential, due to their portability and flexibility. As such they can provide additional cues in a sport VE where the need for concentrating one's attention to the environment prevents the efficient use of auditory and visual outputs. In the training process they can be used for providing both guidance stimuli and attentional stimuli.

It is also important to consider devices that do not necessarily require any electronic components. For example, the virtual archery simulator by Göbel et al. [40] provides the user with a real bow as part of the VE and this too, is a tactile feedback device. For sport VEs, real, physical haptic items could be of great benefit, as many sports revolve around a physical object (football, tennis ball, rugby ball, shuttlecock, etc.) that could be used to maintain links to reality.

Audio output is another possibility. It is noted by Matsuura et al. [41] that the sounds a system produces directly impact upon the feeling of presence experienced by a user, and sound may provide important information for tasks such as judging how hard a ball has been hit with a bat. Using DirectSound 3D (part of the Microsoft DirectX library) to manipulate the sounds of a game of virtual hockey, Matsuura et al. achieved sound effects such as the Doppler Effect across the two networked computers being used to play the game. The senses of smell and taste are not yet a common component of a VE and have not been used in sports applications to our knowledge.

4. Software tools

Software is needed for 3D modelling, interfacing with the hardware devices, managing the VE in real time, and providing feedback and validation. There is no specialised software for sports applications and typically VEs are built using a variety of open-source and commercial software packages. Custom software is also needed so that the full multimodal experience can be provided for the particular sports scenario. For 3D modelling, companies such as Adobe (San Jose, USA) and Autodesk (San Rafael, USA) provide software specifically designed for rapid development. Such packages include Autodesk Maya and Adobe Director, and provide the user with a broad range of robust tools. A problem with commercial packages is that they are often expensive and the user is confined to the specific toolset given to them, whereas open-source software is not only free, but allows developers to modify the software for their particular project. For this reason, universities and research groups often use open-source software or develop their own. Examples include toolkits such as VR Juggler [42], a suite of APIs that allow portability between different hardware solutions; XVR [43] (extreme Virtual Reality — VR Media S.r.l, Pisa, Italy), a development environment for virtual and augmented reality applications; CAVELib [44] (Mechdyne Corporation, Marshalltown, USA), the original API designed for use with the CAVE, which has since been commercialised; and low level interfaces such as OpenGL (Khronos Group, Oregon, USA) and MATLAB (Mathworks, Massachusetts, USA). Companies that develop specific programs for building virtual reality applications and VEs include Dassault Systemes’ (Vélizy-Villacoublay, France) 3DVIA product line (including Virtuools); WorldViz (Santa Barbara, USA) Vizard – complete VE solutions – and extension libraries such as character creation and position tracking; EON Reality’s (Irvine, USA) family of interactive 3D software packages; and Manageable Kinematic Motion, MKM (Golaem S.A., France).

Software for motion capture systems is usually supplied with the product. Vicon, for example, offer different software packages not just for their different hardware solutions but for different uses of motion capture. Vicon Nexus is designed for Life Sciences, Vicon Motus allows markerless capture from pre-recorded media, Vicon Blade is for film or games actors, and Vicon Polygon can generate interactive media reports for use by surgeons, researchers and physical therapists; these programs are expensive, and aimed largely at professional companies.

Haptics software usually requires an API supplied by the hardware manufacturer, such as SensAble’s OpenHaptics. There are also popular open-source haptic APIs such as Chai3D [45].

To conclude, there are a large variety of software packages available for VE creation and development, but more importantly, there are few systems using one package alone. Each package or suite has different benefits, and most systems use the best available package for the specific section of a project.

5. Challenges of creating an effective VE for ball sports

As well as reviewing the common hardware and software components used in creating a ball sports VE, we have identified several challenges that need to be overcome in delivering a high fidelity training environment. We discuss each challenge in turn and the extent to which it has been overcome with reference to relevant published work.

5.1. Do sports skills reliably transfer from VE training conditions to real-world scenarios?

Despite recent technological advances in VEs and support for their use in training a variety of skills (e.g., surgery, [46]; aviation flying and landing [47]; navigation [48]), it is still not clear how skills developed through practising in a VE transfer to real-world situations. In surgical training, for example, Waxberg et al. [49] found that whilst VE-based training can enhance skill learning above that of no training at all, it does not necessarily emulate that of actual practice. Henry [50] proposed that the best learning experiences are those that most closely approximate the movements of the target skill and the environmental conditions of the target context (i.e., specificity of practice). For example, when participants practise under specific sensory conditions during skill acquisition, a change in these conditions during transfer to other environments causes a significant decrement in performance both early and late in practice [51–54]. It has been proposed that participants develop a movement plan to optimise the sensory information present during skill acquisition and that this movement plan is specific to the information that is available during practice [55–58]. Hence, if the practice conditions are changed, the movement plan previously developed is no longer appropriate for successful performance. These findings point to the importance of matching the VE as closely as possible with that of the real-world setting if transfer of learning is to be maximised. Furthermore, learning is proposed to be centred on the development of successful generalised motor programs and movement schemas [59]. These schemas are developed through exposure to four essential pieces of movement related information: (i) the movement parameters assigned to action (i.e., the force and timing of neural impulses); (ii) the initial conditions of the action (i.e., the body position, the size and weight of any object being interacted with, the environmental conditions etc.); (iii) the
outcome of the action (i.e., did the action meet the intended goal); and (iv) the sensory consequences of the action (i.e., visual, auditory, proprioceptive afferent information) [60]. Thus, if VE learning is to be successful – as measured by retention and transfer in real-world situations – the VE environment should provide opportunities to obtain all essential information required for schema development, and to a level that is as close to the real-world context as possible. To achieve this, the VE should (i) require the learner to produce actual movements identical to those required in the real-world setting, (ii) ensure that this movement is performed with a variety of initial conditions, (iii) guarantee that the outcomes of these movements are available to learners, and (iv) attempt to provide the sensory consequences of these actions. If one or more of these classes of information is omitted, or the VE does not adequately approximate the information in the real-world setting, transfer will be unlikely to occur.

Some ball-sport simulators have undergone comprehensive validation studies but this is not always the case. Where validation results are available the evidence for skills transfer is inconclusive, and varies according to the issues discussed above. This is highlighted by two baseball case studies. Zaal and Bootsma [61] have considered several different VE setups for the ‘outfielder’ problem in which a baseball fielder must run to catch fly balls before the ball hits the ground. The movement of the ball, and how the outfielder might reach the right location in time, has been extensively studied both in the real world using video recordings, and in the virtual world using simulated virtual balls.

Another baseball simulator that has undergone several studies into the nature of batting tactics, motor control and behaviour of baseball players is described by Gray [62]. The players stand 3.5 m away from a large SVGA monitor holding a baseball bat that has a Polhemus FASTRAK sensor attached to the end. A virtual baseball travels horizontally towards the user from 18.5 m away (normal release location of a pitcher) but air resistance and ball rotation are ignored, leaving gravity as the only force affecting the flight path. The player swings the real bat to intercept the virtual ball. Visual feedback is given to the user to give them an indication of how well they are performing. Their results indicate that the a VE can be a useful tool for not only researching and comparing the skills of the batters themselves but also for looking into the nature of expertise.

5.2. What types of skills appear to be best suited to training in VEs?

A common goal is to improve motor control skills. Better accuracy through repeatability in performing a particular task is the most addressed skill, for example by allowing practice at aiming and throwing a ball. Anticipation and decision making skills are also well suited for training in a VE, and the level of difficulty of the task can be increased over time.

A typical example for improving ball throwing skills has been demonstrated in a rugby lineout simulator [23,32,63]. The rugby player sees a life-sized projected anaglyptic video of a real player jumping and the task is simply to throw the rugby ball to the recorded player. A device called ‘throw accuracy measurement’ (TAM) was created, comprising of 28 lasers forming two grids. When the lasers are intersected, the data is sent to an application running in MATLAB, which determines the parabolic flight of the ball. The researchers used photogrammetry to determine whether the movement is performed with a variety of initial conditions, (iii) guarantee that the outcomes of these movements are available to learners, and (iv) attempt to provide the sensory consequences of these actions. If one or more of these classes of information is omitted, or the VE does not adequately approximate the information in the real-world setting, transfer will be unlikely to occur.

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The technology deployed does influence performance measurements such as the success rates of completing a task, e.g., catching a ball. Currently the choice of visualisation technology is the dominant factor, and the necessity to wear glasses, HMDs and/or tracking equipment invariably provides an unwanted constraint on the user. Utilisation of other technologies such as haptics is also starting to appear and will likely have a growing influence on performance measures.

A system to investigate the techniques of catching fly balls [65] uses a HMD (Cybermind Visette-Pro, by Cybermind, Maastricht, The Netherlands) and a baseball glove worn on the left hand, both tracked using the IS-900 hybrid inertial–ultrasonic tracker by InterSense (Billericia, USA). There is a 12 m² area in which the users can freely move. The user can see a basic virtual scene of the ground and sky, and are tasked with catching virtual baseballs, which are fired into the air from 36 m away. The balls then follow either a parabolic path according to normal gravity conditions and no air resistance, or a perturbed path where after reaching the highest point, the ball drops vertically at a constant velocity into one of the four quadrants surrounding the player. The authors
decided that as they were not studying the actual catching of the ball but the act of moving to the correct location, participants needed only to move their head or glove within 1 m of the ball to 'catch' it. Results of a study of 8 male and 4 female experienced college baseball and softball players showed that participants caught between 44–55% of the balls (depending on the conditions of the path), which is much lower than might be expected in the same situation in the real world. The authors suggest that the lower percentage of successful catches may be due to the weight and limited field-of-view of the HMD. The CAVE-based study for fly-ball catching [66] also presented problems as the available space was too small for any tasks requiring movement; the system also lacked ceiling projection (and so lessened the sense of immersion), and suffered from a time delay (latency).

A CAVE was also used for Tennis Space [31] where attempts were made to overcome space restrictions without requiring the user to wear a HMD. It was decided that one side wall was necessary but that using front, left, and right walls would be too restrictive, and that a floor would be more immersive than a ceiling panel. It was not possible to rear-project onto the walls, or to raise the floor to project from below. The solution to this was that the front and right wall were projected from above the player, casting a shadow behind them rather than in front, and the floor was simply covered with carpet, carefully matched to the colour of the grass projected onto the screens. A virtual tennis court and virtual opponent (VO) were created using OpenGL Performer and CAVElib; the VO was animated using motion-captured data of a real tennis player. A hybrid tracking system was created, which used both an ultrasonic tracking device to track sensors on the stereoscopic glasses (Infitec) and on the tennis racket and four cameras to track the body of the player. The authors concluded that the projectors were not bright enough at 12,000 ANSI lumens, and the size of the room in which the system was constructed interfered with the design: in a larger room a floor projector would have been used instead of a carpet and the two wall panels would have been made taller to cover as much of the peripheral vision of the player as possible.

A VE does offer a flexible environment for gathering and analysing performance data. This is demonstrated, for example, by the handball skills training environment [67]. The system consists of the motion-captured participant viewing the stereoscopic VE through shutter glasses; the handball goalkeepers see a VO running at them with a virtual ball, and they have to prevent the VO from throwing the ball into the net and scoring. The project initially involved observing how goalkeepers reacted to the VO compared with how they reacted to human opponents; it was found that the use of motion captured attack moves applied by the VO provided a realistic enough opponent to provoke real defensive movement from the goalkeeper [68]. The visual information the handball goalkeepers use [69] was also analysed, and it was found that the use of a VE allowed the modifying of specific individual parameters, producing an excellent testing environment. Follow on work examined the participating goalkeeper’s behaviour in judgement and motor tasks [70], differences in their performance for different qualities of graphical detail [71,72] and visual conditions [73]. As well as handball, the research group investigated deceptive movement in ‘sporting duels’ between rugby players [19,20]. Here the user wears a HMD (Cybermind Visette Pro with dual LCDs); the users’ avatar was controlled using the left and right arrow buttons on a Microsoft Sidewinder gamepad. The VO appears in front of the user, running towards them with a rugby ball. The user has to decide which direction they believed the VO is going to go, while the VO used deceptive motions to trick the user by deliberately shifting their centre of mass to confuse and disorient them.

Apart from vibrotactile effects found in devices such as the Wii Remote, haptic feedback has also been used successfully in sports-themed VEs. One of the first examples to successfully exploit haptics is in a ping-pong game described by Knörlein et al. [33] where virtual bats were co-located with two SensAble PHANToM 1.5 three-degrees-of-freedom force-feedback devices so that players could feel the impact of the simulated ball on the bat. Although this improved hand–eye coordination, the limited workspace of the PHANToM and lack of six-degrees-of-freedom force feedback were limiting constraints. The potential use of haptic guidance (i.e., non-natural feedback about performance, as discussed earlier) in training a dynamic motor skill (including in sports) has been studied in more detail by Huegel and O’Malley [74]. Their findings show that haptic guidance is useful to trainees when beginning to understand the task but should be ‘progressively removed to avoid possible negative dependence’, and allow the trainee to become reliant on their own skills. When all force is disabled, the haptics device can still be used for tracking and evaluation of the player’s performance.

5.4. Should stereoscopic displays be used?

On first inspection, it may seem obvious that VEs for ball sports should present stereoscopic depth information because binocular disparity is available in natural viewing, and results in a vivid sense of three-dimensional structure. The majority of the projects identified in this survey do indeed use stereoscopy. There are, however, practical, perceptual and ergonomic drawbacks of stereoscopic presentation, and these can be particularly acute in environments like sports VEs, which frequently need to present rapid motion, and large ranges of depicted depth.

First, stereoscopic VEs are generally significantly more expensive and complex than otherwise equivalent non-stereo systems, because of the specialised technology required. Clearly these extra ‘costs’ must confer sufficient benefit in terms of the system’s effectiveness to be worthwhile.

Second, although in entertainment applications the terms ‘stereoscopic’ and ‘3D’ are used interchangeably, our perception of depth in fact relies on a number of depth ‘cues’, the majority of which are monocural [75]. Depending on the task, perfectly adequate 3D percepts may be evoked by non-stereo displays. Psychophysical research suggests that for perception and for visuo-motor control the brain combines signals from all available cues (visual cues such as binocular cues, texture/perspective, motion) weighted according to their relative reliabilities [75,76–80]. Because the reliability of depth from binocular disparity falls off rapidly with viewing distance, even at near distances depth information from monocular texture/perspective cues can sometimes be as reliable (or more) than binocular cues [76,78]. Motion parallax (which requires head tracking) can itself provide a powerful percept of depth, and is likely to be important in many sporting situations, where the player typically moves. The importance of presenting stereo depth cues is therefore likely to depend on the specific details of the environment being simulated.

Third, viewing conventional stereoscopic displays often results in fatigue and discomfort, difficulty fusing stereo image pairs, and poor perception of stereo depth [81–89] all of which are particularly unwanted in a sports trainer or simulator. These undesirable effects have all been shown to result, at least in part, from the unnatural stimulus to the eyes’ focusing response in stereo displays. Because the two eyes’ images are presented on a fixed screen, the observer must converge his or her eyes at the portrayed depth, while focusing (accommodating) to the screen surface, resulting in a vergence–accommodation conflict. The required ‘decoupling’ of accommodation and vergence responses is effortful, and sometimes impossible, because the systems are synergistically linked [90,91]. Successful solutions to this problem
have been developed [81, 92–94], but most require the head to be fixed relative to the display (as in an HMD) and even then are not yet practical for a wearable display (with the exception of Love et al. [93]). Moreover, none are yet commercially available. At present, therefore, it is important to ensure that stereoscopic content remains inside a 'comfort zone' around the screen distance [95], and that the distance to the screen is as closely matched as possible to the depth in the portrayed scene. This may be difficult to achieve for stimuli such as balls flying out of the screen towards the viewer.

Fourth, stereoscopic images appear very distorted when viewed from the wrong place, and appear to move if the graphics rendering is not updated to reflect the current eye position. Although there can be only one geometrically correct viewing position for any image, perceived 3D structure from conventional '2D' pictures is surprisingly consistent when viewing from other positions [96]. In stereo images, however, depth can appear very distorted, and if the observer moves without compensation in the images on the screen, the 3D structure of the scene appears to distort dramatically (you can easily see this effect by moving your head side-to-side while viewing a stereogram), something that would be highly undesirable in a sports VE [97]. As noted earlier, this problem can be solved by tracking the head position and updating the two eyes' images correctly, in real time. Note, however, that the orientation of the head must also be tracked and corrected for, or the player may tilt his or her head to one side, requiring vertical vergence eye movements (moving one eye up, and the other down, relative to the head) to fuse the stereoscopic images. Such eye movements are rare in natural viewing and are known to cause significant discomfort [98].

Fifth, many current stereoscopic display systems present the left and right eye's images field-sequentially, which can result in perceivable judder in moving stimuli, especially for rapid motion. Attention is frequently paid to reducing perceived flicker, by using presentation rates (at each eye) that exceed the visual system's flicker fusion rate (~60 Hz [99]). However, motion judder is in part caused by the insertion of blank frames in each eye's 'image stream'–the left eye's image is blank while the right eye's image is displayed, and vice versa – and remains perceivable at presentation rates that are high enough to avoid flicker [94]. Field-sequential stereoscopic presentation can also result in distortions in perceived depth, in which the perceived trajectory of laterally moving objects differs significantly from that in the original scene. The two eyes' images are captured simultaneously (by pairs of cameras), but presented at different points in time. Thus, for a given left-eye frame, for instance, there is uncertainty about whether the brain should compute binocular disparities by comparing it to the previous, or next, right-eye frame. Because the visual system integrates over time this leads to average biases in the estimate of depth from binocular disparity [99]. Like motion judder, this problem is dependent on the speed of the moving stimulus, and so is likely to be particularly problematic in sports simulators. Note that in practice, these problems are not limited to shutter glasses systems, in which field-sequential presentation is an inherent feature, because systems based on comb wavelength filters or polarisation also often use field-sequential presentation so that only one projector is required.

Clearly stereoscopic presentation can, in some circumstances, significantly improve depth perception, and the viewer's sense of immersion in a scene. However, given the numerous problems with current display technologies, and the fact that many of these are particularly acute in situations with large changes in stereoscopic depth, and moving objects, the use of stereoscopic presentation in virtual sports environments needs to be considered carefully, in light of the particular features and requirements of the depicted scene (see [97] for a review).

5.5. Is high fidelity always better?

The level of realism achieved in different VE systems can vary enormously and there are potentially important trade-offs to be made between what can be achieved in a practical, affordable system with current technology, and what is desirable for maximum effect. An important general distinction can be made between the extent to which the sports VE should depict the appearance of the real world (perceptual fidelity) and the extent to which it should behave like the real world when a participant interacts with it (functional fidelity).

One highly relevant area is in deciding the level of graphical realism required. Graphical realism is constantly improving, mainly due to the popularity of CGI films and video games, but photorealistic rendering is computationally expensive and may be impossible in a real-time interactive system. It might initially seem that the more like the real world the VE appears, then the better will be the athlete's performance during skills acquisition exercises. However, even simple stimuli such as animated point-light figures can be effective in presenting movements of an opponent [71,72], suggesting that the level of rendering detail is not necessarily a significant factor in the success of acquiring a new skill.

A key aspect of the visuo-motor skills involved in ball sports is that they require perception of the movement of players and objects in three dimensions. Thus, from a purely perceptual standpoint, it may be possible to present information about 3D structure and motion in the scene in a highly simplified manner, and still achieve training effectiveness. The challenge here is that identifying the information used in real-world tasks is far from straightforward, and there is typically no simple answer. Consider catching a ball, for example. This requires judgements about the trajectory, speed, and 'time-to-contact' of an approaching object. A large body of work in psychophysics has shown that this can be achieved using a combination of information from visual direction, binocular disparity, inter-ocular velocity differences, changing size, and to some extent even knowledge of an object's size [100–104]. Recent studies are consistent with the idea, described earlier, that the brain integrates information from all available sources of information, weighted according to their reliability [105]. Critically, this reliability changes dynamically, depending on geometrical factors [76–105]. Thus, the likelihood is that there is no fixed answer to the question of how much 'weight' a given cue receives generally, or even in a particular task. This means that while individual cues, in simplified environments, may evoke a compelling percept of 3D motion, the brain is not necessarily relying on the same information it would do in a detailed real scene. Details of any optimised rendering techniques used (removing certain depth cues) is typically omitted from the papers reviewed. However, it appears from the sample images provided that the graphics are rendered with correct perspective and use standard shading and lighting techniques (the use of shadows as an extra cue for depth perception is not often used, and no example has been found where shadows are applied to the player avatars). Ideally, the implications of such approaches for training need to be established empirically, so that rendering can be simplified without loss of effectiveness.

The above discussion considers how graphical realism may not be critical for producing veridical perception of a three dimensional scene. It may be important, however, in creating the sense of immersion or 'presence' in a VE. Presence is a much-debated concept, with many different definitions having been proposed [106,107]. The current definition of presence in a VE is 'the feeling of being there'. The standard method of measuring presence is a questionnaire, although biomechanical analysis has been investigated [67]. Both a pre-experimental questionnaire and a
post-experimental questionnaire are used. Video footage of real opponents can be effective in a sports scenario, for example [32], and virtual characters or opponents assist in improving the realism of the environment or to get the user to interact, such as in an attacking move [108]. However, virtual characters and environments do have a wider range of functions available, mainly because once a video is made it is unchangeable, whereas a VE can react to the user and change the game as it is being played. Video footage is ideal if the virtual characters or environment are required to execute the same simple procedure every time, but this will not be an acceptable method of engaging the player. Presence could be an excellent benchmark for VEs, but will be unusable until a definition is agreed upon and a standard method of measurement is established. Moreover, the importance of presence in training effectiveness needs to be evaluated empirically for different situations and tasks.

As well as the properties of the user interface, the degree of functional fidelity of the modelled world must be considered. A high functional fidelity simulator will typically use physics models to provide the most realistic simulation of an event that is possible, which is a challenge for real-time response. For sports-based VEs, this applies specifically to the motion of virtual objects such as a ball or projectile (shuttlecock, arrow, etc.) when travelling through the air or rolling along the ground. The real physics parameters (such as surface properties of a ball) are needed for the mathematical model, but can be difficult to obtain without the involvement of an industry partner. Often when companies do undertake such research it is kept private to avoid aiding competitors, making it difficult for academic groups to acquire the appropriate information, which increases the difficulty of building an accurate model simulation. Academic groups are often forced to either search for existing free-to-use parameters from other research groups or to perform in-house experiments to derive or acquire the required parameters. Further, due to high computational demands, real-time simulations based on accurate physics models are hard to achieve. This leads to an important trade-off: the high complexity of a mathematical model produces more accurate results, but involves more parameters and requires greater computational power — often too much for a real-time solution. A compromise must be reached whereby limitations and assumptions simplify the modelling of the problem, but also reduce the accuracy; the chosen solution depends on the resources available to the group and the complexity of the model. As with the example of depth information, perceptual and motor experiments can in principle be carried out to determine which simplifications to the physics models can be made without incurring costs in training effectiveness, but this is likely to be a difficult and time-consuming process.

5.6. How, what and when should feedback be delivered to the learner?

In order to learn a skill, feedback can be delivered to the user in a number of ways. Eaves et al. investigated [109] the use of VEs for teaching real-world motor skills for dance and sports. They found that the ability to direct the learner’s attention to the key anatomical features of a to-be-learned action was important. Ruffaldi et al. [110] discuss different types of feedback appropriate for sports training in a VE (rowing is used to illustrate their work, but the points raised are equally relevant to ball sports). The two main categories of feedback are:

- Informative feedback, which involves supplying the user with information and statistics regarding their performance (e.g., knowledge of results such as a score);
- Guidance feedback, which directs the user about how to perform the next action (e.g., knowledge of performance such as body movements).

Refer also to Salmoni et al. [111] for a classic review of the effects of information feedback on motor learning. In both cases the feedback can be delivered in various ways: during (concurrent feedback), immediately following (terminal feedback) or some period after the completed skill (delayed feedback). In reviewing these various feedback deliveries Salmoni et al. proposed the guidance hypothesis. This states that feedback essentially guides the performer to the correct movement pattern and increases skill acquisition. However, if the learner receives feedback too frequently they may develop a dependency on it, and thus ignore the processing of important intrinsic sensory feedback required for error detection and correction. Consequently, when augmented feedback is not available, performance suffers, as the learner has come to rely upon it to produce the required skill effectively. Thus avoiding negative training can be helped by progressively reducing the feedback presentations across the learning cycle and thus removing the dependency effect. Ruffaldi et al. [110] note that the individual methods of feedback are rarely considered carefully in designing a VE, although they ought to be. Methods of reducing the amount of required learning time can be employed by using specific forms of feedback and analysis, known as ‘accelerators’. Accelerators can be categorised into augmentation (Ruffaldi states: ‘the ways the training experience is enriched with respect to the real situation’) — information, correction and task enrichment; simplification (‘it tries to make the user perform the task in an easier way with respect to the way the task is performed in the real world’) and variability (‘changes in the training environment aimed at forcing the user to leave a stabilized but novice behaviour and move toward a transitory unstable expert behaviour’).

An example of informative feedback can be found in the golf swing trainer described by Kelly et al. [112]. Forty male golfers were recorded using a Vicon motion capture system while attempting to hit the ball into a net 3 m away. The players were split into groups of different skill levels; the ‘expert’ level players’ movements were averaged into a single movement, which was applied to the ‘coach’ avatar. Users were then captured and displayed as an ‘apprentice’ avatar next to the coach, allowing them to compare their movements with those of the coach in great detail. The user had full control over the zoom, angle, playback speed and positioning of the coach; they also had access to graphs comparing the different ‘angle(s) of interest’ with the coach. It is also interesting to note the findings of Chiviacowsky and Wulf [113], however, who investigated the motivational aspects of feedback and demonstrated that learning is facilitated if feedback is provided after good rather than poor trials. Visual and haptic cues can also be used to provide guidance. For example, the optimum trajectory that a ball should follow to reach a desired target could be displayed in the VE using appropriate graphical glyphs. None of the projects examined in this survey currently do this, however.

5.7. When is a VE not successful in teaching motor skills?

A danger with any VE that aims to train a particular skill is that it trains the skill incorrectly and results in a negative efficacy. This is just as much a danger in a sports trainer, although the side effects may not be as catastrophic as negative efficacy in a flight simulator! Li et al. [114] discuss negative efficacy in the context of using haptics to improve performance of manual control tasks. Their experiment, based around a target-hitting control task, indicated that the acquisition of motor skill is a complex
phenomenon that is not aided with haptic guidance during training for that particular task. Although as noted above, progressive use of haptics does offer benefits. Results such as these must be considered when designing and building a sports VE.

Another problem is time delays, or latency, particularly for networked VEs or VEs for fast-paced sports such as table tennis. Here, even a small delay can make the game highly unnatural, and even unplayable. Latency also reduces the feeling of immersion in a VE, one consequence of which is also to contribute towards negative efficacy of the training experience. Consider the V-Pong system [29,108], shown in Fig. 3. Two tiled projection screens form a stereoscopic image behind two 2 m × 3 m wall panels. The player sees the table directly in front of him as though he is playing a real game, with a VO standing at the other end of the table. Restrictions are placed on the VO to ensure it is beatable; a maximum speed for its movements is set and random noise is added to its movements to stop a perfect performance. The biggest issue with this system was that the speed of a game of table tennis is much higher than the system can cope with. Latency is a problem with many virtual reality systems, but with table tennis it was far more obvious. To tackle this problem, the team devised a prediction system which predicts the next location of the tracked racket and glasses from the speed and direction they are currently moving in, accounting for the approximate latency of 50 ms. The prediction system is adjustable, allowing for changes to be made for different people who move at different speeds.

The need for high speed tracking was also demonstrated in a two-player table tennis game [115], seen in Fig. 4, in which the players are immersed into three screens in the shape of 3/8ths of an octagon. Each player wears circularly polarised glasses, which show the screen in stereo and are motion tracked, and they each hold a tracked wand to represent their rackets. To model the ball, simplified physics laws were applied for collision detection and movement. The system was developed largely to test a new high-speed wireless tracking system, which was found to be responsive to the user. The system was successful in displaying the opposing player’s movements through the on-screen avatar, although the virtual scene itself was very simplistic using basic colours and avatars with rigid bodies. It is noted that for future work, the authors would like to not only create more realistic avatars, but also improve the physics and utilise full-body tracking.

Of course, for any VE to successfully teach motor skills, or anything else, it must minimise side effects such as latency because they can also cause cybersickness [116,117], due to the conflict between vestibular signals to the brain and the (delayed) visual motion information. Cybersickness does not affect all VE users, and it is believed that the brain may be able to adapt and become tolerant to sensory conflict after prolonged exposure to situations in which it is common [117]. Nonetheless, validation studies are required to confirm that training effectiveness is not affected.

5.8. What does it cost?

A further problem involved with creating an effective sports-themed VE is the cost. Costs associated with all kinds of VEs include the cost of software, hardware and maintenance, and validation. Unless the software is developed entirely using open-source packages, it is likely to be expensive. Whilst some VEs discussed in this paper use only readily available hardware, some use specialist hardware such as HMDs, CAVE setups and motion capture systems, which are not only very expensive to purchase, but can also be expensive to maintain. The projects that are described above range in cost from around €10,000 to well over €250,000 (if a CAVE is used, for example). It should be noted, however, that there are cheaper VE installations with good functionality available.

Robustness of equipment should also be considered alongside cost, as some equipment may be subject to more stress than normal in active sports VEs. An appropriate investment must be made, however, or otherwise the training benefits achieved will be marginal at best.
6. Summary and future research directions

Training of sports-related skills is a fast emerging application of VEs and there are many different options for software and hardware, each with their own benefits and problems. There is no single solution and the choice of the equipment deployed is largely based on what suits each specific sport best. In this paper, we have reviewed the different concepts and technologies involved in current VEs in the context of ball sports and identified the key research and development issues that need to be considered by researchers and potential users of this technology. In particular, eight different challenges/issues have been categorised and the extent to which they have been overcome has been discussed with reference to the current state-of-the-art. The cost range of the systems in current use is large but it is not always the most expensive systems that produce the best results. For example, although most systems have invested in display equipment that will offer stereoscopic viewing, the practical, perceptual and ergonomic problems of this technology means that its use should be carefully considered. Indeed, the amount of both perceptual and functional fidelity required to effectively train a task is still unclear and in some cases a low fidelity, inexpensive system can perform well. Another common problem is how to represent a potentially large playing area (e.g., a football field) within the physical constraints of the VE? Any constraints that take you further away from the real training environment are going to impact on the functional fidelity of the VE. Removing the inherent constraints of the hardware deployed is an open research topic. Even when a good representation of the sport can be constructed within the VE there remains a danger of delivering negative efficacy in the training task. Latency is one contributory factor in negative efficacy, but there are other potential pitfalls such as how to apply haptic cues appropriately. This is another area where more research is needed. On the question of feedback, then there are successful examples of providing informative feedback in a ball sports VE. The development of guidance feedback is far less advanced, however.

One advantage of using a VE should be that it provides the flexibility to conveniently allow learners to practise a wide range and number of skills. This is fundamental to improving performance. However this requirement has not yet been fully addressed, as most of the examples that we have reviewed tend to implement just a small number of skill scenarios. This will be particularly important to address for commercial products.

As the domain of sport-themed VEs matures, then more validation studies will be possible. Results of the currently published validations are inconclusive, with evidence being presented that in some cases there is skill transfer but in other cases there is not. There are enough results, however, to suggest that the improvement of motor control skills in ball sports is possible. Anticipation and decision making skills are also well suited for training in a VE, and the level of difficulty of the task can be increased over time. We predict that this area will grow quickly in the next few years with more and more examples coming out of research laboratories and being used by professional sports associations.

In our own research project we are developing a VE for rugby training concentrating on passing skills (Fig. 5) [118]. The issues and solutions identified and discussed in this review paper will be invaluable in our goal to produce an effective training environment for this purpose. Our hope is to contribute to a future Rugby World Cup win by Wales!

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References


Fig. 5. Our VERST (Virtual Environment for Rugby Skills Training) system, a work in progress. The rugby ball is covered in retroreflective markers and captured by the PST (Personal Space Tracker by Personal Space Technologies B.V., Amsterdam, The Netherlands) device. It is also tethered to the ground using a training bungee to avoid any equipment damage when it is thrown. The virtual rugby ball is projected onto a screen in front of the player and its movement is calculated by a physical model based on the speed and trajectory of the real ball as it leaves the players hands.


