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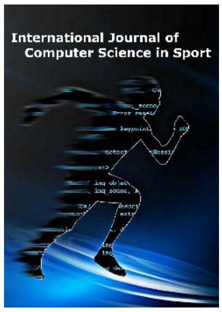

Using Several Types of Virtual Characters in Sports - a Literature Survey

Petri, K., Bandow, N., Witte, K.

Otto-von-Guericke-University Magdeburg, Germany, Department of Sports Engineering and Movement Science

Abstract

This article discusses the development and application of virtual environments (VEs) in the domain of exercise as well as research in recreational and high-performance sports. A special focus is put on the use of virtual characters (VCs). For its elaboration, the following criteria parameters were chosen: scene content and the role of the VC, output device, kind of additional feedback, level of expertise of the tested participants, kind of user's movement (reaction), kind of the visualization of the user's body, kind of study and kind of evaluation. We explored the role of VCs embodying virtual opponents, teammates, or coaches in sports. We divided these VCs in passive and autonomous characters. Passive VCs are not affected by the user, whereas autonomous VCs adapt autonomously to the user's movements and positions. We identified 44 sport related VEs, thereof 22 each in the domain of recreational sports and high-performance sports: of the identified 44 VEs, 19 VEs are without VC, 20 VEs with passive VCs, and 5 VEs with autonomous VCs. We categorized studies examining expert athletes in high-performance sports as well as studies analyzing novices, beginners or advanced athletes in recreational sports. Nevertheless, all identified systems are suitable for athletes of recreational and high-performance level.

KEYWORDS: VIRTUAL REALITY, VIRTUAL CHARACTER, VIRTUAL ENVIRONMENT, SPORT RELATED VE, HIGH-PERFORMANCE SPORTS

Introduction

Virtual Reality (VR) is an often-utilized tool in sports science due to immersion, interaction and visualization. It provides the advantage of standardized and thus easy controllable stereoscopic conditions. Manipulations can be made, which are not possible in the real world (Bandow et al., 2012, Covaci, Olivier & Multon, 2015a,b, Zaal & Bootsma, 2011), for example a change of weather conditions (Aleshin et al., 2012) and the combination of indoor and outdoor sports (de Bruin, Schoene, Pichierri & Smith, 2010). The effects of these controlled or manipulated conditions can then be analyzed (Craig, 2013). VR scenarios can be designed individually, they offer safe learning conditions, and they increase the user's motivation if they can take part in the decision-making (Argelaguet & Andujar, 2013, Covaci, Olivier and Multon, 2015 a,b, Sigrist et al., 2015). Further advantages are: autonomous feedback, good representation possibilities, manipulations, such as different color, size freezing and change of velocities in display methods. Wiemeyer and Müller (2015) recommend using ICT-enhanced learning and training in addition to conventional learning which could also be satisfied by using VR. However, one must consider, that VR can cause cybersickness, - a physical reaction due to a sensory mismatch which arises from mismapping between user action (motor outflow) and sensory feedback (motor inflow) (Biocca, 1997).

Fig. 1 provides a schematic overview of sport related virtual environments on the basis of several review articles, e.g. Argelaguet and Andujar (2013), Bowman and McMahan (2007), Craig (2013), Ida (2015), Katz, Parker, Tyreman & Levy (2008), LaViola (2000), Lin & Wolgedeorgis (2015), Müller & Abernethy (2012), Pinder, Davids, Rensahw and Araùjo (2011), Plass, Homer and Haywards (2009), Rebenitsch and Owen (2016), Renner, Velichkovsky and Helmert (2013), Schuemie, van der Straaten, Krijn and van der Mast (2001), Steuer (1992), Wang, Li, Zhang and Chen (2016), Zaal and Bootsma (2011) and Zeltzer (1992).

In general, VR contains virtual characters (VCs) and virtual environments (VEs) in the form of scene content and (sports) equipment. Using VR, it is possible to recreate a various amount of interactions in sports, which always occur with other humans as well as with the environment e.g. sports equipment or floor. Therefore, we explored virtual characters (VCs) and virtual environments (VEs) in the domain of sports. In sports, the importance of other VCs is given by the physical and social interaction with opponents or teammates, coaches, referees or auditory. Interactions with the environments take place in form of sports equipment (e.g. racquets, balls, clothes, such as shoes or floors). Here, we examined the use of VCs in sport related VEs and divided them in two categories: passive and autonomous VCs. On the one hand, we defined passive VCs as characters that are not affected by users, similar like video play-backs. By using passive VCs, a supervisor may program the VC to perform certain actions without taking the user's actions into account autonomously. Autonomous VCs, on the other hand, take the user's behavior into account and may be able to respond to it, without help or instructions of a supervisor. In contrast to passive VCs, autonomous VCs are able to react to the movements and the position of the user. Sport related VEs also exist without VCs; they only show scene content and sport equipment as well as provide visual feedback in the form of trajectories or optical flow.

In sports, the application is found in the field of exercise (e.g. prevention, therapy and motor learning, e.g. de Bruine, Schoene, Pichierri & Smith, 2010), training (e.g. Gray, 2017), research (e.g. cognition and anticipation, with analyzing perception and decision making, e.g. Craig, 2013), as well as in the preparation of competitions in recreational and high-performance sports. Sport specific requirements are technical demands for powerful hardware and software as well as human demands for user's acceptance of VR. Thus, technical demands for e.g. realistic rendering and the reduction of latencies (time delays between user's action and adaptation of the VR), and human demands, such as the reduction of cybersickness and the implementation of a natural sports setting, where sports specific behavior is allowed and can be analyzed, are important to achieve functional fidelity, immersion and interactivity. Furthermore, additional feedback, such as sound, haptics or smell can be implemented to involve all senses of the user (Katz, Parker, Tyreman & Levy, 2008). However, one should be aware of the Cyborg's dilemma (Biocca, 1997), where symptoms of discomfort can arise, when several kinds of feedback produce a sensory mismatch due to latencies. VCs can be created by use of motion capturing technologies (Miles et al., 2012) or 3D body scans. Furthermore, Cummins and Craig (2016) propose the application of hybrid tracking systems (combination of motion capturing and low-cost sensors) to reduce delays. For the creation of a VE, adequate programming skills (often C++) and a powerful 3D engine are necessary. Moreover, VEs can be created by using single images (Tanaka, 2017) or 360° cameras so that recordings of real environments can be seen in the VR. The latter method could be suitable for the comparison of training or movement analysis in VR and in actual reality. Depending on the type of application in sports, the appropriate visualization device should be chosen (CAVE (Cave Automatic Virtual Environment), HMD (Head Mounted Display), Powerwall or desktop VR).

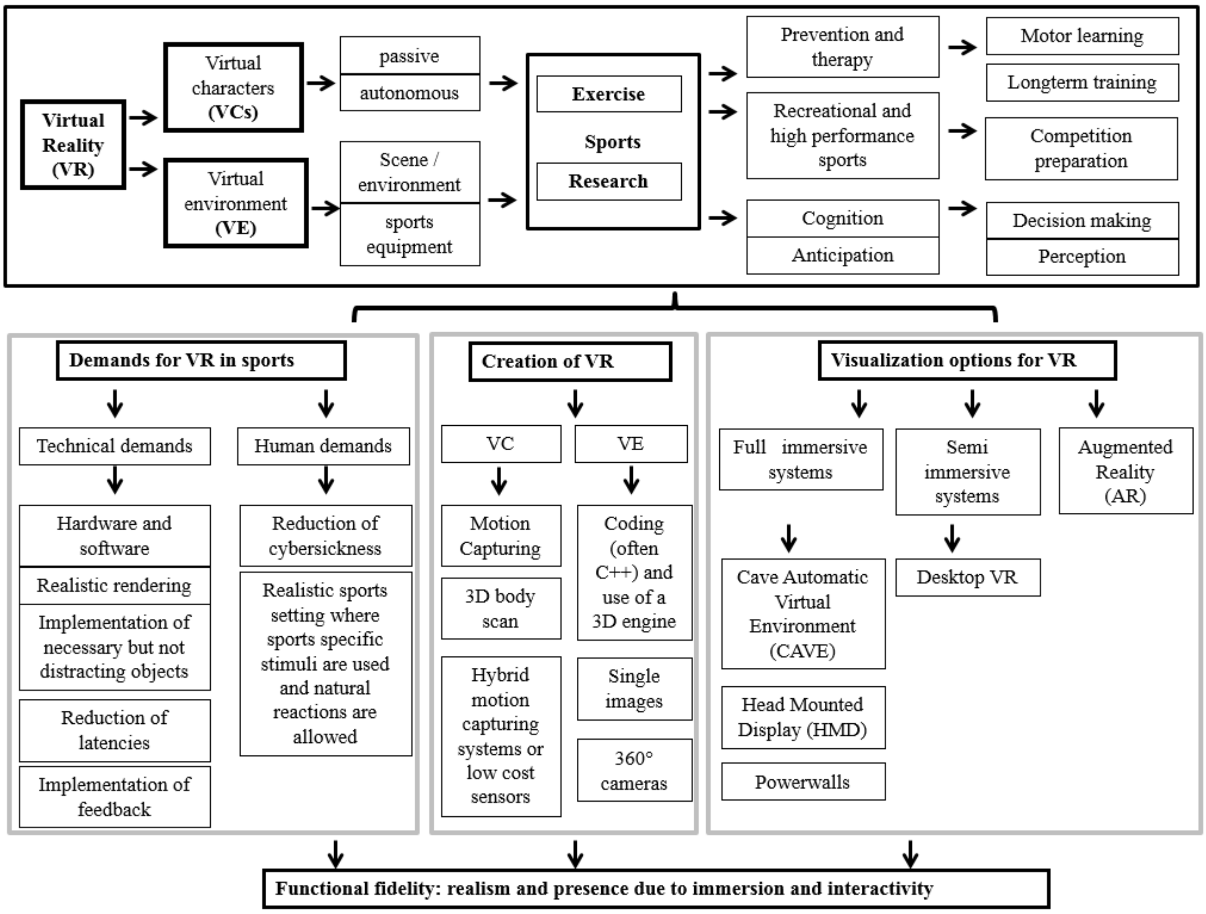

Figure 1: Schematic overview of sport related virtual environments on the basis of recent research.

For VR in sports, the minimum element is the VE in a sport context (e.g. a sports hall) which updates in real-time dependent on the user's head movements. As output device, at least a desktop VR or a powerwall should be chosen. However, a HMD would be best to ensure a maximum degree of immersion (Rebenitsch & Owen, 2016), due to the complete blocking of the real world. Furthermore, the degree of realism is higher, when there is also additional feedback and VC(s) the user can interact naturally with.

The current work focusses on the development and application of virtual reality (VR) systems and especially on virtual characters (VCs) used in virtual environments (VEs) in the domain of exercise and research of recreational and high-performance sports. Until now, we identified only four reviews in the context of competitive sports: one short review (Wang, 2012), one review article concerning ball sports in VR (Miles et al., 2012), one review focusing on possibilities to analyze perception-action-coupling in sports using VR (Craig, 2013) and one SWAT analysis about the potential usefulness of VR for athletes (Düking, Holmberg & Sperlich, 2018). So far, no review article focused on VCs in sports although recent research detected that VCs are essential to improve performance in VR (e.g. Camporesi & Kallmann, 2016, Gonzalez-Lanier & Franco, 2017).

As a list of criteria we chose in style of PICOS (Liberati et al. 2009) the following parameters: scene content and the role of the VC, output device, kind of additional feedback (if available), level of expertise of the tested participants, kind of user's movement (reaction), kind of the visualization of the user's body and the kind of study and the kind of evaluation (Table 1 and Table 2).

We addressed five questions (please see below) with regard to the criteria described above. Therefore, the results are divided into five sections. In every section, we answer the respective question and also discuss our findings related to further research demands.

- In which sports are sport related virtual environments available and for which purpose are they used?
- Which functions do virtual characters have in sport related virtual environments and how should they be designed?
- What kind of studies have been made and which level of expertise did the tested users have?
- Which feedback systems have been implemented in sport related virtual environments?
- Which visualization devices are used in sport related virtual environments and how should the athlete's body be virtualized?

Methods

The literature research is based on findings from the time period between summer 2010 and february 2018 by all authors. Studies were identified by searching electronic databases (pubmed, scopus, IEEE, ACM and the IAT-database (IAT, Germany)) and manual searches through reference lists of articles. Limitations were set for the language, as only articles in English and German language were considered. We used the following search items in our databases: virtual reality, VR, virtual environment, VE, biomechanics, virtual character, Head Mounted Display, HMD, interactivity, autonomy, perception and anticipation.

All study designs concerning VR applications in the field of recreational and high-performance sports between 1997 until 2017 were included. Studies containing VR in rehabilitation and therapy were excluded. The current review therefore presents and discusses virtual characters in sport related VEs with emphasis on scopes and applications of VR in recreational and high-performance sports, less on technological solutions.

Figure 2 shows the PRISMA flowchart for the search item “sport related virtual environment” in the databases pubmed, scopus, IEEE and ACM. Our search was made with all items in all databases according to the example given in Figure 2.

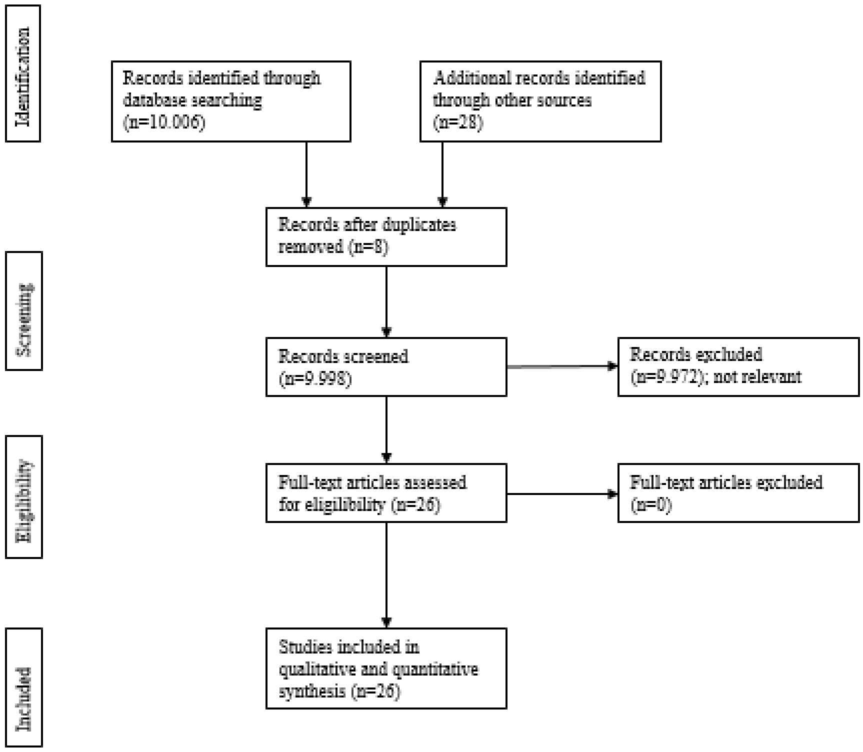

Figure 2: PRISMA flowchart of study selection process. Example for the item “sport related virtual environment” in four databases.

Results

Table 1 and Table 2 show our results of 44 sport related VEs, of which 19 VEs are with no VC, 20 VEs with passive VC(s), and five VEs with autonomous VC(s). 22 VEs of the 44 VEs are in the domain of recreational sports and 22 VEs in the domain of high-performance sports. In Table 1 we show all studies found in recreational sports and Table 2 shows all identified VEs in high-performance sports.

As mentioned above, we identified 19 VEs with no VC (thereof 12 systems in recreational sports and seven in the domain of high-performance sports), 20 VEs with passive VC (thereof eight systems in the domain of recreational sports and 12 systems in the domain of high-performance sports). Of the five VEs with autonomous VC, are two in the domain of recreational sports and three in the domain of high-performance sports. We only categorized VE systems for high-performance sports which were tested with experts. Nevertheless, all identified systems are suitable for athletes of recreational and high-performance level. In the following sections all questions are answered on the basis of Table 1 and Table 2.

Table 1. 22 Sport related VEs in the domain of recreational sports: 12 VEs with no VC, 8 VEs with passive(s) VC(s) and 2 VEs with autonomous VC(s).

No VC, VE only

Authors	**Sports**	**Scene content**	**Output device**	**Kind of additional feedback**	**Level of expertise**	**Kind of the user's movement / reaction**	**Kind of the user's visualization**	**Kind of study**	**Evaluation**	**Results**
Bandow et al. (2012)	ball catching	ball	CAVE	scene content only	sports students (n=33)	sports specific (ball catching)	no	technical report, cross-sectional study	analysis of reaction times in three different conditions (3D VR, 2D film and reality) and questionnaire	reaction times in VR are closer to reaction times in reality than reaction times to video material
Brunnett, Rusdorf & Lorenz (2006)	table tennis	sports hall with table tennis table, racquet and ball, interaction due to a prediction system	Powerwall	audio feedback (ball)	several novices and advanced players	sports specific (table tennis with real racquet)	no	technical report	unspecific user testing for evaluation of the system (feasibility study)	users are able to play against the VE

Authors	**Sports**	**Scene content**	**Output device**	**Kind of additional feedback**	**Level of expertise**	**Kind of the user's movement / reaction**	**Kind of the user's visualization**	**Kind of study**	**Evaluation**	**Results**
Covaci, Olivier & Multon, (2015a,b)	basketball	Sports hall with basket and ball(trajectories) from different perspectives	CAVE	scene content only	novices (n=20) and experts (n=7)	sports specific (free throws)	no (only the ball was visualized)	technical report, cross-sectional study	analysis of success rate in VR in different perspectives and in reality	success is greater in third person view and additional feedback (ball trajectories) than in first person view
Craig, Bastin & Montague (2011)	soccer	soccer pitch and ball	HMD	scene content only	advanced players (n=7)	sports specific (catching free kicks)	no	technical report, cross-sectional study	analysis of performance of catching free kicks with and without sidespin clockwise and counterclockwise	the optical system is unable to process side spin correctly
Kayatt & Nakamura (2015)	soccer	soccer pitch and ball	HMD and desktop VR	scene content only	novices (n=10)	sports specific (jump for ball catching)	no	cross-sectional study	questionnaire and comparison of reaction times between HMD and desktop VR	shorter reaction times in HMD than in desktop VR

Authors	Sports	Scene content	Output device	Kind of additional feedback	Level of expertise	Kind of the user's movement / reaction	Kind of the user's visualization	Kind of study	Evaluation	Results
Lammfromm & Gopher (2011)	juggling	juggling balls	Powerwall	scene content only	sport students (n=24)	sports specific (juggling)	hands	randomized-controlled trial / intervention study	analysis of training transfer from VR into reality due to performance analysis (sensors at the hands), comparison of training in reality to training in reality and VR	training in VR is better than training in reality and transfer from VR into reality is given
Miles et al. (2014)	rugby	rugby stadium and ball	CAVE and Powerwall	scene content only	advanced players (n=4) and novices (n=6)	sports specific (ball throwing)	no	technical report, two cross-sectional studies	analysis of distances in VR and the distance between the user and the screen and analysis of stereoscopy, verbal reports and questionnaires	participants did not respond well to simulated target distances and only the user's physical distance from the screen had an effect on the distance thrown

Authors	Sports	Scene content	Output device	Kind of additional feedback	Level of expertise	Kind of the user's movement / reaction	Kind of the user's visualization	Kind of study	Evaluation	Results
Rauter et al. (2013)	rowing	landscape, optical flow	CAVE	audio, visual and haptic feedback	novices (n=8)	sports specific (rowing)	no (only parts of the boat were visualized)	pilot transfer study / intervention study	analysis of training transfer from VR into reality, comparison of training in VR and in reality, biomechanical analysis	training in VR is better than training in reality and transfer from VR into reality is given
Ruffaldi et al. (2013) / Ruffaldi & Filippeschi (2013)	rowing	landscape, optical flow	CAVE	audio, visual and haptic feedback	novices (n=8)	sports specific (rowing)	no	technical report / intervention study	analysis of effectiveness of vibrotactile training	the multimodal platform is suitable and realistic for rowing
Sigrist et al. (2015)	rowing	landscape, optical flow	CAVE	audio, visual and haptic feedback	novices (n=24)	sports specific (rowing)	no (only parts of the boat were visualized)	randomized-controlled trial / intervention study	comparison of training with different feedback, analysis of spatial error and questionnaire	training with visual and audio feedback enhances learning while haptic feedback did not improve learning

Authors	Sports	Scene content	Output device	Kind of additional feedback	Level of expertise	Kind of the user's movement / reaction	Kind of the user's visualization	Kind of study	Evaluation	Results
Tirp et al. (2015)	darts throwing	dartboard	desktop VR	scene content only	novices (n=38)	sports specific (darts throwing)	no	randomized-controlled-trial	comparison of accuracy and quit eye duration in VR and in reality, within-subject-design	similar outcome in VR and reality, but differences in movement pattern and gaze behavior between VR and reality
Todorov, Shamder & Bizzi (1997)	table tennis	table tennis table and ball	desktop VR	audio feedback (ball contact)	novices (n=42 and n=21)	sports specific (table tennis)	ball and racquets	randomized-controlled-trials, two experiments	comparison of training in VR and reality due to kinematic analysis and score report	training in VR is better than training in reality

Passive VC

Authors	Sports	Scene content and role of VC	Output device	Kind of additional feedback	Level of expertise	Kind of the user's movement / reaction	Kind of the user's visualization	Kind of study	Evaluation	Results
Chan, Leung, Tang & Komura (2011)	dance	one VC as coach and the own body	Powerwall	Visual feedback (color, score report and slow motion replay)	students (n=6) for technical report, students (n=8) for intervention	sports specific (imitating the teacher)	full body, cylindrical form of the avatar	technical report / randomized controlled trial /intervention study	comparison of training in VR and self-learning training due to movement analysis and questionnaire	VE is appropriate to guide students to improve their skills. Participants were motivated.
Chua et al. (2003)	tai chi	chinese martial arts temple and one or several VC(s) as coach(s) and the own body	HMD	scene content only	students (n=40)	sports specific (imitating the teacher)	full body, natural avatar	technical report / randomized-controlled trial / cross-sectional study	comparison of five visual conditions with several teachers, students and perspectives. Movement analysis and questionnaire	no significant difference between the condition. It would be best to provide one VC (teacher) directly in front of the user

Authors	Sports	Scene content and role of VC	Output device	Kind of additional feedback	Level of expertise	Kind of the user's movement / reaction	Kind of the user's visualization	Kind of study	Evaluation	Results
Cummins & Craig (2016)	rugby	rugby stadium / one VC as opponent	Powerwall	audio feedback (game commentary)	novices (n=360)	sports specific (sidesteps to block the opponent)	no	technical report, evaluation of the game	unspecific user testing (feasibility study)	user testing showed usability, robustness and enjoyment
Kelly, Healy, Moran & O'Connor (2010)	golf	VC as coach and the own body	CAVE	scene content only	advanced players (n=40)	sports specific (golf swing)	full body, avatar in cylindrical form	technical report, cross-sectional study	evaluation of the system and analysis of the X-factor	calculation of the X factor (for hitting distance)
Kojima, Hiyama, Miura & Hirose (2014)	baseball	VC as coach	HMD	visual feedback (difference between own and coach's movements)	advanced players (n=17)	sports specific (baseball throwing)	full body, natural avatar	technical report, cross-sectional study	evaluation of the system by measurement of the throwing distance and expert interviews	measurement of throwing distance for evaluation of the VR
Pronost et al. (2008)	kung-fu	VC as opponent	Powerwall	scene content only	novice (n=1)	sports specific	no	technical report	technological evaluation and unspecific user testing (feasibility study)	the user is able to react to the virtual attacks

Authors	Sports	Scene content and role of VC	Output device	Kind of additional feedback	Level of expertise	Kind of the user's movement / reaction	Kind of the user's visualization	Kind of study	Evaluation	Results
Varlet et al. (2013)	rowing	landscape, boat and VC as teammate	CAVE	audio, visual and haptic feedback	novices (n=16)	sports specific (rowing)	no	randomized-controlled trial /intervention study	analysis of interpersonal coordination due to training in VR and in reality	participants improve their coordination with a real and with a virtual teammate
Watson at al. (2011)	rugby	rugby stadium and VCs as two opponents	HMD	scene content only	novices (n=14)	unspecific (button press)	no	cross-sectional study	analysis of ball passing due to different gaps between the two opponents in a temporal occlusion paradigm	a tau-based information is used for passibility affordance

Autonomous VC

Authors	**Sports**	**Scene content and role of VC**	**Output device**	**Kind of additional feedback**	**Level of expertise**	**Kind of the user's movement / reaction**	**Kind of the user's visualization**	**Kind of study**	**Evaluation**	**Results**
Argelaguet Sanz, Multon & Lécuyer (2015)	10m pistol shooting	Shooting range and several VCs as opponents and as auditory	CAVE	visual feedback (score report)	novices (n=18)	sports specific (shooting)	no	within-subject design, cross-sectional study	analysis of anxiety in two conditions due to score report, shooting time and biological parameters and questionnaire	VR is suitable to induce stress and VR is appropriate for training
De Kok et al. (2015) / Hülsmann et al. (2016)	squats	VC as coach and the own body	CAVE	visual (color) and audio feedback (advices from the virtual coach)	no	sports specific (squats)	full-body, natural avatar	No study available, only technical report	no evaluation available, only future perspectives	the multimodal platform is suitable for squats and further analyses

Table 2. 22 Sport related VEs in the domain of high-performance sports: 7 VEs with no VC, 12 VEs with passive(s) VC(s) and 3 VEs with autonomous VC(s).

No VC, VE only

Authors	Sports	Scene content	Output device	Kind of additional feedback	Level of expertise	Kind of the user's movement / reaction	Kind of the user's visualization	Kind of study	Evaluation	Results
Aleshin et al. (2015)	skiing	skislope with several weather conditions, optical flow	Power wall	scene content only	expert (n=1)	sports specific (skiing)	no	technical report	analysis of skiing performance in different conditions for analysis of depth cues	the role of the accommodation depth cue in VR is underestimated
Colley, Väyrynen & Häkkila (2015)	skiing/ snow board	skislope, optical flow	HMD	audio (real sounds), smell and haptic feedback (ground contact) due to blended VR	experts (n=2)	sports specific	no	technical report, case study, pilot study	unspecific user testing for evaluation of the system (feasibility study) and prototype testing (ski mouse)	the users were able to perform skiing and snowboard in blended VR. The functionality of the ski mouse was proven.

Authors	Sports	Scene content	Output device	Kind of additional feedback	Level of expertise	Kind of the user's movement / reaction	Kind of the user's visualization	Kind of study	Evaluation	Results
Craig et al. (2006)	soccer	soccer pitch, ball and ball trajectories	HMD	scene content only	expert footballers (n=11) and expert goalkeepers (n=9)	unspecific (mouse click)	no	technical report, cross-sectional study	analysis of perception of free kicks with and without sidespin	the optical system is not able to perceive side spin
Craig et al. (2009)	soccer	soccer pitch and ball	HMD	scene content only	novices (n=13) compared to the subjects of Craig et al. (2006) and novices (n=8)	unspecific (button press)	no	two cross-sectional studies	analysis of perception of free kicks with and without sidespin from different start positions and different cutoff distances	the optical system is not able to perceive side spin

Authors	Sports	Scene content	Output device	Kind of additional feedback	Level of expertise	Kind of the user's movement / reaction	Kind of the user's visualization	Kind of study	Evaluation	Results
Dessing & Craig (2010)	soccer	soccer pitch and ball trajectories	HMD	scene content only	advanced (n=10) and expert goalkeepers (n=2)	unspecific (hand movements)	no	cross-sectional study and creation of a goalkeeper model	analysis of performance of catching free kicks with spin-induced lateral ball acceleration	the visual system has a limited sensitivity for detecting accelerations
Morey Sorrentino, Levy, Katz & Peng (2005)	ice skating	skating track	Power wall	scene content only	experts (n=5)	unspecific (mouse and controller)	no	pilot study	written observations by a psychologist and debriefing sessions in regard to usability of VR and well being	the VR is usable for the athletes and they accept the VR

Authors	Sports	Scene content	Output device	Kind of additional feedback	Level of expertise	Kind of the user's movement / reaction	Kind of the user's visualization	Kind of study	Evaluation	Results
von Zitzewitz et al. (2008)	rowing	landscape, optical flow	CAVE	visual (graphs), audio and haptic feedback	experts (n=4)	sports specific (rowing)	no	technical report	question-naire and comparison between VR and reality	participants rate the platform realistic and applicable for future studies. Data of velocity and oar force were similar in VR and reality

Passive VC

Authors	**Sports**	**Scene content and role of the VC**	**Output device**	**Kind of additional feedback**	**Level of expertise**	**Kind of the user's movement / reaction**	**Kind of the user's visualization**	**Kind of study**	**Evaluation**	**Results**
Bandow et al. (2014)	karate	sports hall with fight arena / one VC as opponent	CAVE	scene content only	experts (n=5)	sport specific	no	cross-sectional study	comparison of VR and 2D film, score report of correct reactions, within-subject-design and analysis of anticipatory cues	athletes feel better in VR compared to 2D. first anticipatory cues for two karate attacks were analyzed: leg for mawashi-geri and shoulder and punching arm for Gyaku-Zuki
Bideau et al. (2003/2004)	Hand ball	sports hall / one VC as opponent (thrower)	CAVE	scene content only	expert goalkeepers (n=1 and n=8)	sport specific (prevent goals)	no	technical report, case study, pilot study	analysis of movement behavior in VR and in reality	similar movement pattern between VR and reality

Authors	**Sports**	**Scene content and role of the VC**	**Output device**	**Kind of additional feedback**	**Level of expertise**	**Kind of the user's movement / reaction**	**Kind of the user's visualization**	**Kind of study**	**Evaluation**	**Results**
Bideau et al. (2010)	rugby / hand ball	sports hall / one VC as opponent (runner (rugby) and thrower (handball))	HMD (rugby) / CAVE (hand ball)	scene content only	novices and experts (each n=8, rugby), experts (n=2, handball)	unspecific (button press), sports specific (handball)	no	cross-sectional study (rugby) /case study (handball)	analysis of perception of opponent's running directions due to occlusions (rugby). Analysis of anticipation due to success rate and response times (handball)	experts are better in the usage of information. skilled experts couple their response time to their physical skills. Experts with fast movement executions wait longer with the response to be less susceptible to feints

Authors	Sports	Scene content and role of the VC	Output device	Kind of additional feedback	Level of expertise	Kind of the user’s movement / reaction	Kind of the user’s visualization	Kind of study	Evaluation	Results
Brault et al. (2012)	rugby	rugby stadium / one VC as opponent	HMD	scene content only	novices (n=14) and experts (n=14)	unspecific (button press), sports specific (side step)	no	two cross-sectional studies	analysis of perception and anticipation of opponent’s running directions due to occlusions. Comparison of success rate between experts and novices	experts perceive true signals and are less susceptible for deceptive movements

Authors	Sports	Scene content and role of the VC	Output device	Kind of additional feedback	Level of expertise	Kind of the user's movement / reaction	Kind of the user's visualization	Kind of study	Evaluation	Results
Correia, Araùjo, Cummins & Craig (2012)	rugby	rugby stadium / VCs as three opponents and two teammates	HMD	audio feedback (calls of the VCs)	novices (n=9), beginners (n=9), advanced players (n=16) and expert players (n=12)	sports specific (ball throwing)	hands	cross-sectional study	analysis of perception and action possibilities due to different gaps between the opponents	emergence of gaps in the defensive line with respect to the participant's own position influenced action selection. There was also a positive relationship between expertise and task achievement
Dhawan et al. (2016)	cricket	cricket stadium / one VC as opponent	HMD	audio feedback (ball contact)	experts (n=2)	sports specific	no	technical report, case study	expert interviews	the cricket simulator is realistic and suitable for future studies

Authors	Sports	Scene content and role of the VC	Output device	Kind of additional feedback	Level of expertise	Kind of the user's movement / reaction	Kind of the user's visualization	Kind of study	Evaluation	Results
Gray (2002, 2004, 2009a,b)	Base ball	playing field, ball and VC as opponent (pitcher)	Power wall	visual, audio and haptic feedback about success	several advanced players, novices and experts	sports specific (baseball batting)	no	Technical report, cross-sectional studies	analysis of perception and anticipatory cues due to performance analysis	visual signals have more weight than audio or tactile signals
Gray (2017)	Base ball	playing field, ball and VC as opponent (pitcher)	Power wall	visual, audio and haptic feedback about success	nearly expert players (n=80)	sports specific (baseball batting)	no	randomiz ed-controlled trial with interventi on study	comparison of training in VR and in reality, analysis of transfer due to performance analysis	training in VR is better than training in reality and transfer from VR to reality is given
Ranganathan & Carlton (2007)	Base ball	baseball field and VC as opponent	CAVE	scene content only	novices (n=10) and experts (n=10)	unspecific (verbal reports) and sports specific (bat swung)	no	technical report, cross-sectional study	analysis of kind of response (uncoupled or coupled) to baseball throws with temporal occlusions	response behavior of experts is better in the coupled response condition

Authors	Sports	Scene content and role of the VC	Output device	Kind of additional feedback	Level of expertise	Kind of the user's movement / reaction	Kind of the user's visualization	Kind of study	Evaluation	Results
Vignais et al. (2009)	Hand ball	sports hall and VC as opponent (thrower)	CAVE	scene content only	expert goal-keepers (n=10)	sports specific	no	technical report, cross-sectional study	analysis of the performance and reaction due to different graphical visualizations	graphical implementation must be natural, otherwise the movement pattern changes → idea of a graphical threshold
Vignais et al. (2015)	Hand ball	sports hall and VC as opponent (thrower)	CAVE	scene content only	expert goal-keepers (n=10)	almost sports specific (hand movement) and sports specific (catching a ball)	no	within-subject design, cross-sectional study	analysis of performance (correct responses) in VR and due to 2D film.	VR is better for analysis of perception than video material due to depth information

Authors	Sports	Scene content and role of the VC	Output device	Kind of additional feedback	Level of expertise	Kind of the user's movement / reaction	Kind of the user's visualization	Kind of study	Evaluation	Results
Witte, Emmer-macher, Bandow & Masik (2012)	karate	sports hall with fight arena / one VC as opponent	CAVE	scene content only	experts (n=6)	sports specific	no	technical report / cross-sectional study	analysis of reaction times	it is possible to couple spatial and temporal occlusions and eyetracking in VR to study response behavior in future studies
Autonomous VC										
Authors	**Sports**	**Scene content and role of the VC**	**Output device**	**Kind of additional feedback**	**Level of expertise**	**Kind of the user's movement / reaction**	**Kind of the user's visualization**	**Kind of study**	**Evaluation**	**Results**
Multon, Hoyet, Komura & Kulpa (2007)	gymna-stics	VC, who performs aerial movements due to user's arm move ments	Desktop VR	scene content only	several experts	unspecific (arm move-ments)	no	technical report	analysis of angular momentum	VR is suitable to learn aerial movements in a safe condition. Aerial movement behavior is realistic

Authors	**Sports**	**Scene content and role of the VC**	**Output device**	**Kind of additional feedback**	**Level of expertise**	**Kind of the user's movement / reaction**	**Kind of the user's visualization**	**Kind of study**	**Evaluation**	**Results**
Petri et al. (2017)	karate	sports hall with fight arena / one VC as opponent	CAVE and HMD	scene content only	experts and advanced athletes (n=6)	sports specific (karate response)	hands	technical report, evaluation of the system	expert interviews in regard to usability of VR	the autonomous VC is realistic and suitable for future studies
Zhang et al. (2018)	karate	fight arena / one VC as opponent	Powerwall and HMD	scene content only	experts and advanced athletes (n=10)	sports specific (karate response)	hands	technical report, evaluation of the system	technological tests and questionnaire in regard to usability of VR	the autonomous VC is realistic and suitable for future studies

In which sports are sport related virtual environments available and for which purpose are they used?

Most VCs are created for analysis in ball sports and martial arts with the limitation that only one user can react to one virtual character (see Table 3). Ball sports here include soccer, handball, rugby, baseball (always 1:1 situations), golf, cricket, and table tennis. There are only two studies available in ball sports, where there is indeed a 1:1 situation (table tennis). Martial arts studies in this context comprise karate, taekwondo, tai chi and kung-fu. For VE systems without VCs, also sports are considered where no direct opponents exist: rowing or classic ski slope or downhill snowboard.

Table 3. Number of sport related VEs with no, passive and autonomous VCs in recreational and high-performance sports.

Sports	**VE without VC(s) (n=19)**		**VEs with passive VC(s) (n=20)**		**VEs with autonomous VC(s) (n=5)**	
	recreational sports (n=12)	**high-performance sports (n=7)**	**recreational sports (n=8)**	**high-performance sports (n=12)**	**recreational sports (n=2)**	**high-performance sports (n=3)**
ball sports	8	3	4	10		
martial arts			2	2		2
rowing	3	1	1			
dancing/ gymnastics			1			1
pistol shooting					1	
winter sports		2				
skating		1				
squats					1	
dart throwing	1					

As can be seen in Table 4, the number of exercise and research studies is balanced. Exercise studies using no VCs (VE only) were made for several purposes: in the field of motor learning it is used to examine different training conditions with different user perspectives (e.g. Covaci, Olivier & Multon, 2015a,b), to analyze distance estimation (e.g. Miles et al., 2014) and to investigate different forms of feedback (e.g. Sigrist et al., 2015). Additionally, Brunnett, Rusdorf and Lorenz (2006) developed an autonomous VE but without VC, in which the user could play table tennis against an opposing racquet.

Exercise studies using passive VCs were either developed to examine different learning methods (e.g. Kojima, Hiyama, Miura & Hirose, 2014), or to gain insights into interpersonal coordination (e.g. Varlet et al., 2013). Bideau et al. (2003, 2004), for example used this sort of system to analyze and compare goalkeeper's movement behavior between VR and reality.

Cummins and Craig (2016) used a passive VC, but the whole VE was autonomous, due to an autonomous collision detection system between the athlete and the passive VC. Here, the user had to respond to the passive VC with a blocking movement. When the user blocked the VC correctly, the system would detect a collision.

Autonomous characters were created for training of squats (de Kok et al., 2015) or aerial gymnastic movements (Multon, Hoyet, Komura & Kulpa, 2007). However, neither of the two sport related VEs have actually been used in further studies so far. All exercise studies using autonomous VCs are based on decision systems (Hülsmann et al., 2016), or are created on the basis of competition analysis and in consultation with expert coaches (e.g. Petri et al., 2017).

Most research studies in sports are found in the field of cognition including decision-making, anticipation and perception research. For VEs using no VCs, only a few studies have been performed to analyze the effects of spin in ball trajectories (Craig et al, 2006, Craig, Bastin & Montague, 2011, Dessing & Craig, 2010).

Passive VCs are found in studies in the field of anticipation research, where the intention is to identify relevant cues (e.g. Bandow et al., 2014), or to analyze deceptive movements (Bideau et al., 2010, Brault et al., 2012). Furthermore, a study exists that examines the kind of response to different types of stimuli (Ranganathan & Carlton, 2007). Watson et al. (2011) conducted a study in the field of perception to analyze the “passability”. A following study by Correia, Araùjo, Cummins and Craig (2012) investigated decision-making and resulting actions in the context of gaps in the defense line. Vignais et al. (2015) examined, if VR or film-material was more appropriate to analyze perception in sports. They detected that using VR is more suitable to investigate visual perception, because users make less errors in VR compared to 2D video footage due to depth information in VR. This is in line with Witte, Emmermacher, Bandow and Masik (2012), who found that reaction times in VR are more similar to reaction times in reality, than reaction times due to 2D film material.

With regard to the use of autonomous VCs, we only found plans to use these systems in anticipation research in the future, but no specific studies exist until now (Petri et al., 2017, Zhang et al., 2018). Argelaguet Sanz, Multon & Lécuyer (2015) use an autonomous VE to analyze anxiety and pressure considering two scenarios: training (no stress) and competition (stress by loud audience). All of these VE systems shall also be used for exercise in the future.

Most studies using VR technology take place in laboratories, but Colley, Väyrynen and Häkkila (2015) present an approach to implement VR in the real world (blended VR). Athletes should ski and snowboard in reality while wearing a HMD. This approach shows that VR is portable into the real world to analyze sport performance in a real setting. Thus, further acoustic and haptic implementations would not be necessary to provide immersion.

Discussion

Within the analyzed studies, we identified, that due to present-day technological barriers, VEs are often limited to one user and one VC. We know that it is still a technical challenge to create a sport related VE for several users and with more than one virtual character, but first approaches can already be seen today. It would be interesting to enlarge VE sports scenarios to team sports with several VCs, as it can be seen by Correia, Araùjo, Cummins and Craig (2012) or Watson et al. (2011). In many sports, such as martial arts and racquet sports, anticipation and decision-making are performance limiting factors (Craig, 2013). Nevertheless, they are of great importance in team ball sports, where in comparison to only one opponent, several opponents and teammates have to be taken into account. It would further be interesting to develop VEs, where several people can interact with each other, especially when they are not at the same place at the same time. Then, sports competitions could be performed over larger distances as it is already presented by Mueller (2008), where geographically distant participants could play a soccer-like or air hockey game against each other. Furthermore, research studies could be made without the necessity of two (or more) athletes having to be at the same place at the same time.

Table 4. Application areas of sport related VEs with no, passive and autonomous VCs in recreational and high-performance sports.

Appli-cation	**VE without VC(s) (n=19)**		**VEs with passive VC(s) (n=20)**		**VEs with autonomous VC(s) (n=5)**	
	recrea-tionnal sports (n=12)	**high-perfor-mance sports (n=7)**	**recreational sports (n=8)**	**high-perfor-mance sports (n=12)**	**recreational sports (n=2)**	**high-perfor-mance sports (n=3)**
exercise	6	3	2	4	1	1
research	4	4	2	8		
exercise and research	2		4		1	2

It is possible to implement VCs in VEs with whom the users can interact as opponents, teammates, coaches or referees. Passive VCs provide a one-way interaction: the user adapts to the VC and can respond sports specifically. These VCs can be used to analyze human behavior with regard to anticipation, cognition and decision-making. In comparison, autonomous VCs provide a two-way interaction: the VC responds to the athlete’s behavior and thus, the athlete can again respond sports specifically. These autonomous VCs might be more suitable for exercise studies as they create a greater interaction between VC and the user and therefore, gain a higher degree of realism. However, such VCs are still in the development and therefore, have so far not been used a lot in exercise and research (Table 1 and 2).

In general, VR might be an appropriate tool for the application of natural sport settings to analyze sports specific behavior. Further, it can be a useful tool in recreational and high-performance sports, especially in the preparation of competitions, because virtual opponents can be adapted to real opponents. Measuring devices, such as e.g. eye tracking or sensors can also be implemented in VR to gain additional data. Furthermore, the tracking data, which is used for the virtualization of the athlete’s body and for the interaction with a VE and VCs, can also be utilized for training control. Although, it still has to be explored if athletes and their coaches accept VR as a training tool, Gradl et al. (2016) analyzed that although many athletes and their coaches have not heard of VR before, they are very interested in using it.

In the domain of research, it would be interesting to use VR for further manipulations that are not possible in the real world, as it was done by Craig et al. (2006). For example, different environments or floor clothes could be tested, or variable perspectives could be analyzed. The following questions could be answered: Does the learning process improve, if someone can see himself or other VCs as well as the environment from different perspectives, e.g. from behind or from the top? How should virtual coaches be positioned to optimize the athlete’s performance?

There are several open questions concerning exercise and research. In the field of exercise, we need studies to explore whether training in VR can truly replace conventional training or whether VR training should only be given additionally to improve certain aspects (integrated in the course of the conventional training). The beneficial duration of athletes in VR should be analyzed and concrete training recommendations should be examined. To our opinion, autonomous VCs are adequate for standalone training in quite natural conditions due to the possibility of interaction. Passive VCs are more appropriate for research or for improving certain training aspects (e.g. a reaction training where athletes can react to attacks of a VC which has the advantage to not get fatigued). Concerning anticipation research, there is a use of occlusion techniques in VR, but studies using eye tracking in VR still haven't been performed.

Which functions do virtual characters have in sport related virtual environments and how should they be designed?

Table 5 shows the utilized functions of the VCs in the identified studies. Sport related VEs have been existing since 1997 (Todorv, Shamder & Bizzi, 1997). Passive VCs are available since 2003. Here, Bideau et al. (2003, 2004) were the first to verify that response behavior of real athletes was similar between VR and reality using virtual opponents. Chua et al. (2003) created the first passive virtual coach. The first autonomous VE sport system was created by Brunnett, Rusdorf and Lorenz (2006). Nevertheless, in this case, no VC was visible, only racquet and ball. Multon, Hoyet, Komura and Kulpa (2007) created the first character that reproduced user's arm movements and based on these conducted aerial gymnastic motions. The first autonomous virtual coach was made available 2015 by de Kok and coworkers. Petri et al. (2017) and Zhang et al. (2018) developed the first autonomous opponent which can perform an adequate attack against a moving athlete. Previous autonomous VCs were created using a prediction system (e.g. Brunnett, Rusdorf & Lorenz, 2006) or a decision system (e.g. Hülsmann et al., 2016, Zhang et al., 2018).

As can be seen in Table 1 and 2, most sport related VEs have either no VC or they use passive VCs, and thus provide no natural interaction between virtual characters and real users. The users can only respond to the VE or the VC, whereas the VC does not take the user' movements into account. In most cases, VCs are opponents (e.g. Bideau et al., 2010), where users have to respond to their upcoming actions, but they can also be teammates, as in Varlet et al. (2013). Furthermore, VCs can be coaches showing certain movements, which have to be imitated by the users (e.g. Chua et al., 2003) or they can give verbal instructions (e.g. de Kok et al., 2015). However, there are also first studies working with two (Watson et al., 2011) or more VCs (e.g Argelaguet-Sanz, Multon & Lécuyer, 2015, Correia, Araùjo, Cummins & Craig, 2012). The latter shows a three vs. three scenario, where an athlete has to react to three opponents and cooperate with two teammates. In the study of Argelaguet-Sanz, Multon and Lécuyer (2015) several virtual opponents and an auditory were used.

All used VCs in the identified studies had a natural look, but a stiff face without facial expressions or eye movements. Furthermore, hair and clothes were rigid.

Discussion

Already Gonzalez-Franco and Lanier (2017) highlighted the importance of VCs for human-machine interactions. Humans are always in communication with each other. Thus, communication between users and VCs has to be similar to communication in reality (Sun, Truong, Pantic & Nijholt, 2011). The brain recognizes the VCs as humans and real users interact with these VCs following socio-cultural rules. Pan et al. (2012) showed that men who were shy dealing with women, were also shy when interacting with female VCs. There is also a link between the design of the VC and the own movement behavior due to mimicry and the existence of stereotypes (Bourgeois & Hess (2008).

Table 5. The role of VCs in sport related VEs with no, passive and autonomous VCs in recreational and high-performance sports.

Role of the VC	**VEs with passive VC(s) (n=20)**		**VEs with autonomous VC(s) (n=5)**	
	recreational sports (n=8)	**high-performance sports (n=12)**	**recreational sports (n=2)**	**high-performance sports (n=3)**
opponent	2	11		2
several opponents	1			
coach	3		1	
several coaches	1			
teammate	1			
avatar controlled by the user				1
several functions		1	1	

Filippetti and Tsakiris (2016) and Ganesh et al. (2011) pointed out the importance of the VC's faces. VCs provided with a familiar face (or a face very similar to the own face) are accepted more easily by users. Because of that, Cummins and Craig (2016) presented an approach to implement natural faces and clothes into VR through the use of single images. Ida (2015) demonstrated 3D laser scanning, where face morphing, muscle activity and wrinkles can be implemented. Camporesi and Kallmann (2016) stated that today's VCs in sports do not have facial expressions and eye movements, but stiff, blanc faces with only few details, so that the users do not get disturbed. However, Kibele (2006) and Prigent et al. (2015) doubted the importance of facial expressions and eye movements in sports, because athletes rely more on kinematic information for correct anticipation and response behavior. In this case, Narang et al. (2017) recommended improving the movements of VC's, because present movement behavior does not fully satisfy the demands of sports. On the contrary, Sun, Truong, Pantic and Nijholt (2011) assumed that VR could be an appropriate tool to further investigate the impact of facial expressions on performance in sport.

Narang et al. (2017) proved that rich detail avatars were more appropriate to recognize own movements in VR, while for movement recognition of other humans, kinematic information was sufficient. Camporesi and Kallmann (2016) demonstrated the importance of VCs in sports for example when learning a new movement. Users were able to perform movements faster and more accurate with the help of VCs. What becomes evident from Table 7 is, that studies in high-performance sports where expert athletes are tested, most VR system use a VC. This might be a further cue that interactions with VCs are important to provide a high degree of realism and to achieve good performance.

Although spatial information is available in VR, there is still a problem with correct estimation of distance and heights of objects (Covaci, Olivier & Multon, 2015a,b, Rebenitsch & Owen, 2016, Renner, Velichkovsky, & Helmert, 2013). There are many studies available with regard to perception of distance in VR (e.g. Interrante et al., 2008, Knapp & Loomis, 2004, Linn & Woldegeorgis, 2015, Zielinski, Rao, Sommer & Kopper, 2015), but the actual reason for distance underestimation has not been found yet. However, studies have shown that the integration of a VC might help to better orientate and estimate distances in VR because the VC can be taken as a reference point (Ries, Interrante, Kaeding & Anderson, 2009). Bailenson, Blascovich, Beall and Loomis (2003) investigated interpersonal distances in VR between real users and VCs. Distance was chosen farther, when an agent (controlled by a computer) approached, compared to an approaching avatar (controlled by a human). Moreover, people maintained greater distance from VCs when approaching from the front, compared to from the back.

In general, it is more complicated and technologically challenging to create a VE with a VC, especially with an autonomous VC, because of the massive computational power needed to create a large movement database for a VC (Düking, Holmberg & Sperlich, 2018). Furthermore, the level of graphical visualization must be high to ensure natural movement patterns of real users (Vignais et al., 2009). Capturing the movements that are used in VCs is expensive and time-consuming. In order to create a more realistic character in sports, only movements from highly skilled athletes should be captured. The use of VCs is complicated and leads to longer processing times and thus, latencies. This might also be the reason why VEs with autonomous VCs have to undergo long technological evaluations. Studies with autonomous VEs or VCs often limit the feasibility of their reports and only show future directions. Furthermore, autonomous VCs have only been developed in recent years, and are newer compared to the majority of systems with no VCs and passive VCs. There are many VEs available where no VC exists, due to the high working load development. Nevertheless, by the use of artificial intelligence or adaptive algorithms, VCs could be produced without the need of hundreds of motion capturing records.

Although evidence exists, that VCs and their interaction with real users are important in the domain of sports, concrete design recommendations concerning the appearance of VCs are missing. However, the implementation of VCs in VR in the domain of sports is quite new. It would be interesting, if there are differences in behavior and distance estimation between users in real scenarios and between users and VCs in VR. It would be necessary to investigate if there are further differences between different kinds of VCs and how they have to be designed to provide natural interpersonal behavior. To ensure a natural behavior, users should get a natural (maybe even self-chosen) VC, with which they show the same movement behavior as in the real world. Otherwise, for manipulations of training, it would be interesting if athletes benefit from VCs who look e.g. more aggressive or dominant. This design could help them to change their own behavior. However, concrete rules for a VC design have not been identified so far.

What kind of studies have been made and which level of expertise did the tested users have?

Table 6 (on the basis of Table 1 and 2) shows the different study designs. Almost one third of all studies is only a technical report with short feasibility studies (e.g. Aleshin et al., 2015, Dhawan et al., 2016). This phenomenon is most pronounced in VEs with autonomous systems (e.g. de Kok et al., 2015, Multon, Hoyet, Komura & Kulpa, 2007). The most used study design is a cross-sectional study design (used for almost half of the analyzed studies) (e.g. Chua et al., 2003, Kayatt & Nakamura, 2015). We identified only a few intervention studies using VEs either without VC (Lammfromm & Gopher, 2011, Rauter et al., 2013, Sigrist et al., 2015, Todorov, Shamder & Bizzi, 1997), or with passive VC (Chan, Leung, Tang & Komura, 2011, Gray, 2017, Varlet et al., 2013), but no intervention study using VEs with an autonomous VC. The creation of autonomous VCs is the most expensive, due to the need of motion capture data, powerful hardware and software as well as the creation of artificial intelligence (Düking, Holmberg & Sperlich, 2018). Furthermore, the development of VEs with autonomous VCs is quite new, what may explain the lack of applications for these systems.

Table 6. Kind of study in sport related VEs with no, passive and autonomous VCs in recreational and high-performance sports.

Kind of study	**VE without VC(s) (n=19)**		**VEs with passive VC(s) (n=20)**		**VEs with autonomous VC(s) (n=5)**	
	recreational sports (n=12)	**high-performance sports (n=7)**	**recreational sports (n=8)**	**high-performance sports (n=12)**	**recreational sports (n=2)**	**high-performance sports (n=3)**
technical report/ feasibility study /case study	1	4	3	2	1	3
cross-sectional study	7	3	3	9	1	
intervention study	4		2	1		

In Table 7 (on the basis of Table 1 and 2) we show our findings concerning tested users in the identified VE systems. Tested participants are: participants with no special experiences in the required tasks (students and novices), beginners (only a few experiences at recreational level), advanced athletes (recreational sports or near-expert-level-expertise) and expert athletes (national or international-level- expertise). The number of tested athletes varied from one to three hundred sixty (Table 1 and 2). Almost a quarter of the identified studies compared several levels of expertise. Although there are many studies available in the field of high-performance sports, often only a small number of tested expert athletes (only up to five) is included (e.g. Bandow et al., 2014, Vignais et al., 2015, 2009, Witte, Emmermacher, Bandow & Masik, 2012, see also Table 2).

Table 7. Tested participants in sport related VEs with no, passive and autonomous VCs in recreational and high-performance sports.

Tested participants	VE without VC(s) (n=19)		VEs with passive VC(s) (n=20)		VEs with autonomous VC(s) (n=5)	
	recreational sports (n=12)	**high-performance sports (n=7)**	**recreational sports (n=8)**	**high-performance sports (n=12)**	**recreational sports (n=2)**	**high-performance sports (n=3)**
students	2		2			
novices	6		4		2	
advanced athletes	1		2			
expert athletes		5		7		3
advanced and expert athletes		1				
novices and advanced athletes	2					
novices and expert athletes	1	1		3		
novices, beginners, advanced and expert athletes				2		

Table 8 (on the basis of Table 1 and 2) demonstrates the user's movements or reactions in the studies. The great majority of the studies allowed and analyzed sports specific reactions (coupled responses), so that the participants were able to link perception and action, what is an important demand for VR concerning human factors (Craig, 2013, Pinder, Davids, Renshaw & Araùjo, 2011). There were only five studies available with unspecific (uncoupled) reactions (verbal reports, mouse klick or bottom press) (Watson et al., 2011, Craig et al., 2006, 2009, Dessing & Craig, 2010, Morey Sorrentino, Levy, Katz & Peng, 2008). All of these studies (except of Watson et al., 2011) were performed in the domain of high-performance sports. In a few studies both types of reactions were analyzed with the result, that sports specific responses are more appropriate, especially when testing expert athletes, because these highly skilled athletes can show their expertise better in a realistic environment where natural movement behavior is allowed (e.g. Ranganathan & Carlton, 2007).

Table 8. User's movements or reactions in sport related VEs with no, passive and autonomous VCs in recreational and high-performance sports.

User's movements / reactions	**VE without VC(s) (n=19)**		**VEs with passive VC(s) (n=20)**		**VEs with autonomous VC(s) (n=5)**	
	recrea-tional sports (n=12)	**high-perfor-mance sports (n=7)**	**recreatio-nal sports (n=8)**	**high-perfor-mance sports (n=12)**	**recreatio-nal sports (n=2)**	**high-perfor-mance sports (n=3)**
unspecific		4	1			1
sports specific	12	3	7	8	2	2
both				4		

Discussion

Although a great amount of sports related VEs in the field of exercise and research with several kinds of VCs exist, many open questions remain. The use of randomized-controlled trials is rare. We only detected nine studies with randomization of groups (Table 1 and 2). Furthermore, long-term exercise interventions in VR as well as more transfer tests from training in VR to benefits in reality are needed. Especially, the benefit of VEs with autonomous VCs in exercise and research is unproven.

Transfer studies in table tennis (Todorov, Shamder & Bizzi, 1997), juggling (Lammfromm & Gopher, 2011), rowing (Rauter et al., 2013) and baseball (Gray, 2017) examined positive transfer effects of VR into reality, whereas Tirp et al. (2015) found an equal effect of darts training in VR and in reality. Thus, more sports specific training and transfer studies are needed, especially training studies with advanced or expert athletes.

Further missing topics are concrete intervention and safety recommendations and validation standards of sport related VEs (Rebenitsch & Owen, 2016, Schuemie, van der Straaten, Krijn & van der Mast, 2001). With regard to the latter, each VR is evaluated in a different way, making it hard to compare these systems with each other. Based on our analysis, tested participants are beginners, advanced players and expert athletes. Nevertheless, especially in interventions the majority of studies examined novices as opposed to more experienced athletes. Also, the differences in the amount of analyzed participants in different sports, the grouping into beginners, advanced players and experts and examination of individual differences make it difficult to draw general recommendations. However, concrete exercise recommendations can lead to reductions in development costs and improvement of efficiency of VEs (Ida, 2015).

Furthermore, we need studies to compare gaze behavior between VR and reality to make sure that perception and information intake is similar in both conditions. Therefore, research is needed comparing movement execution and trainings in reality and in VR. Only if no differences in perception and movement behavior occur, training in VR could be deployed actually.

Which feedback systems have been implemented in sport related virtual environments?

In all VEs the scene content changed in real-time accordingly to the head rotation of the user. Table 9 shows the additional feedback. In half of all identified VEs no additional feedback was implemented (scene content only). In three VEs there is an additional visual feedback in form of score reports (e.g. Argelaguet-Sanz, Multon & Lécuyer, 2015), slow motion replay (Chan, Leung, Tang & Komura, 2011) or color (de Kok et al., 2015). We further found seven VEs with additional sound (ball contact, e.g. Brunnett, Rusdorf & Lorenz, 2006), noises of the environment (e.g. the auditory in Argelaguet Sanz, Multon & Lécuyer, 2015 or the water in Ruffaldi et al., 2013), calling teammates (Correia, Araùjo, Cummins & Craig, 2012) or verbal advices of a coach (de Kok et al., 2015). Moreover, 20% of the identified systems contain a multimodal feedback (visual and audio feedback or visual, audio and tactile feedback). E.g. Varlet et al. (2013) used a haptic feedback in form of a force feedback (vibruotactile feedback in the tiller). Colley, Väyrynen and Häkkila (2015) show the blended VR, where VR is applied in the real world. Thus, real environmental noises and haptics, such as real ground forces are available.

Table 9. Additional feedback in sport related VEs with no, passive and autonomous VCs in recreational and high-performance sports.

Additio-nal feedback	**VE without VC(s) (n=19)**		**VEs with passive VC(s) (n=20)**		**VEs with autonomous VC(s) (n=5)**	
	recrea-tional sports (n=12)	**high-perfor-mance sports (n=7)**	**recrea-tional sports (n=8)**	**high-perfor-mance sports (n=12)**	**recreational sports (n=2)**	**high-perfor-mance sports (n=3)**
scene content only	7	5	2	9		3
visual			2		1	
audio	1	1	3	1		
visual and audio					1	
visual, audio and haptic	4	1	1	2		

All studies using VEs report further that all participants felt well in VR and no symptoms of cybersickness (symptoms of discomfort due to VR) occurred. The latencies where often not reported in detail, but no latencies above 200ms were stated. Therefore, the technical and human demands (decreased latencies, which also decrease cybersickness and increase the user's feeling of presence and realism) seem to be fulfilled.

Discussion

Generally, there exist several forms of feedback - informative and guidance feedback - and this feedback can be given during or after movement execution or delayed after execution. For review see Miles et al. (2012) and Plass, Homer, and Hayward (2009). Feedback should help improving the learning process without making users dependent on it (Sigrist et al., 2015). Therefore, the feedback should be adapted both to the user's skills and to the task complexity.

Visual information is usable for spatial information. Acoustic information (e.g. by use of sonification) is appropriate for velocities, accelerations and regularities and might help to maintain the focus. Tactile information can be used for force feedback, but it can be bidirectional. Sigrist et al. (2015) found out that acoustic feedback enhances motor learning, especially in beginners, while haptic feedback led to no further enhancement. It is possible that haptic feedback is only appropriate for advanced learners, who already have a movement conception. Feedback is well known to reduce learning time (Covaci, Olivier & Multon, 2015a, Miles et al., 2012). By use of a decision system based on literature and expert knowledge, the VR system can search for poses, angles, velocities, etc. in the movement of the users and compare them to optimal values. If a pose is detected, a specific feedback has to occur (either visually or acoustically) and the system searches for the next pose. Thus, it is possible to give a precise real-time feedback depending on different movement stages (Hülsmann et al., 2016). Renner, Velichkovsky and Helmert (2013) also show that feedback and exercise improve distance estimation in VR. Katz, Parker, Tyreman and Levy (2008) stress the importance of audio in VR, which can be given in three ways: music, sound effects and speech. Sound is a key indicator of motion and it can reflect the environment. It can be both heard and felt, therefore, increasing the degree of realism, and thus, user's acceptance (Karageorghis & Priest, 2002).

Haptic feedback as the feeling of touch is not often available in VE sports systems (Miles et al., 2012, Zaal & Bootsma, 2011) perhaps of the technological challenge to synchronize a tactile feedback (e.g. a vibrotactile feedback or a force feedback) with the VE system. A kind of collision system has to occur in systems like combat sports, where a tactile feedback of attack hits would make sense. Furthermore, the accurate sense of necessary force has to be implemented (Katz, Parker, Tyreman & Levy, 2008).

For an adequate interaction and to avoid cybersickness it is necessary to reduce latencies between the user and the responding VC and also between the user's movement and the adaptation of the virtual scene to avoid sensory mismatch (e.g. Waltemate et al., 2015, 2016). However, in our opinion it is important to investigate individual reaction times of athletes. VEs should have latencies of exactly these sports specific reaction times to ensure natural behavior. VEs reacting too fast could on the one hand be used for specific reaction training, but on the other hand they could impair exercise and thus, the desired transfer from VR into reality. Although there are first autonomous sport related VEs available, where users have an influence on VR, only few VEs in fast reacting sports due to the problems of increased latencies, exist.

Which visualization devices are used in sport related virtual environments and how should the athlete's body be virtualized?

In the field of recreational and high-performance sports CAVES and HMDs are utilized, due to the demand of greater immersion. CAVE and HMD share almost equally parts. For more detail

Table 10. Usage of visualization devices in sport related VEs with no, passive and autonomous VCs in recreational and high-performance sports.

Output device	**Period of time**	**VE without VC(s) (n=19)**		**VEs with passive VC (s) (n=20)**		**VEs with autonomous VC(s) (n=5)**	
		recrea-tional sports (n=12)	**high-performance sports (n=7)**	**recrea-tional sports (n=8)**	**high-performance sports (n=12)**	**recrea-tional sports (n=3)**	**high-performance sports (n=2)**
CAVE	1997-2014	3	2	2	5		
	2015-2017	1			1	2	
HMD	1997-2014	1	2	3	2		2
	2015-2017		1		1		
CAVE and HMD	1997-2014				1		
	2015-2017						
Power wall	1997-2014	2	1	2	1		
	2015-2017	1	1	1	1		
CAVE and Power wall	1997-2014	1					
	2015-2017						
Desktop VR	1997-2014	1				1	
	2015-2017	1					
HMD and desktop VR	1997-2014						
	2015-2017	1					

see Table 10. Nowadays, a growing amount of studies is available using HMDs, due to having less weight and being cheaper since they reached commercial availability (Fernandez & Feiner, 2016). Petri et al. (2017) showed that HMDs are preferred by karate athletes compared to CAVEs, as with HMD there is more space to move. Chua et al. (2003) even recommend wireless HMDs for less obstruction of movement executions and less accidents by falling over cables.

HMDs provide more immersion with a wide field of view. The visual stimuli can also be controlled better compared to screen-based VRs (Rebenitsch & Owen, 2016). Unfortunately, the resolution often is not that high like in CAVEs or Powerwalls (Miles et al., 2012). Although, the range of field of view is growing with the fast-technological development (Ida, 2015), it is still not possible, to provide natural peripheral vision. When wearing a HMD, the user is completely separated from the reality and, if this feature is not integrated, is not able to see his own body. To provide a more natural setting and avoid cybersickness, it is therefore necessary to virtualize the user's body including his nose which can be realized through the user tracking (Lugrin, Latt & Latoschick, 2015, Whittinghill, Zieglert, Moore & Case, 2015).

Based on our results of Table 1 and 2, we found five studies where the athlete's body was fully visualized, either as a natural character (e.g. Chua et al., 2003) or in the form of cylindrical human models (e.g. Kelly, Healy, Moran & O'Connor, 2010). In three studies only some body parts, in all cases the hands, were visualized (e.g. Petri et al., 2017). Further, there are four VEs available, which virtualize sports equipment. Covaci, Olivier and Multon (2015,a,b) virtualize the ball, while Ruffaldi et al. (2013), Sigrist et al. (2015) and Varlet et al. (2013) virtualize the rowing boat and the oar. However, the vast majority of studies renounced the visualization of the athlete's body (Table 11).

Table 11. Visualization of the user's body in sport related VEs with no, passive and autonomous VCs in recreational and high-performance sports.

Visualization of the user's body	**VE without VC(s) (n=19)**		**VEs with passive VC(s) (n=20)**		**VEs with autonomous VC(s) (n=5)**	
	recreational sports (n=12)	**high-performance sports (n=7)**	**recreational sports (n=8)**	**high-performance sports (n=12)**	**recreational sports (n=3)**	**high-performance sports (n=2)**
Full-body			4		1	
Body parts	1			1		2
No visualization	11	7	4	11	1	1

Discussion

Based on the reported tendency, we expect that HMDs will be used in studies more frequently. However, up to now the use of HMDs has not been much investigated regarding the required type of visualization of the user's body, as well as familiarization times. Due to the complete separation of the real and the virtual world, it seems important to investigate, if adaptation phases would be appropriate and how they should be designed. It is possible that younger people and people who already have experiences with video or computer games need shorter or even no adaptation times at all than older people, and thus, accept VR more easily. Experiences with technology can be an important factor for performance and motivation in VR.

There are two possibilities to visualize the user in VR; either to visualize the whole body or only some parts of the body. Kilteni, Groten and Slater (2012) showed that the virtualization of the athlete’s body plays a major role to increase the sense of body ownership, because the body is the source of all experiences. A virtual body might help to have a better orientation in VR and hence to better estimate distances by using the own body as reference system. Blanke, Slater and Serino (2015) detected a drift towards the virtual body, meaning the virtual body is accepted as the own body. Steptoe, Steed and Slater (2013) demonstrated the ability of the human brain to accept the VR as a real world and a virtual body as the own body. The brain can even integrate further body segments (e.g. a tail) into the existing body scheme. Users identify themselves with their VCs and learn to use their virtual bodies. Normand, Giannopoulos, Spanlang and Slater (2011) demonstrated that users who see a VC who is bigger than their actual body have the feeling that they are really bigger. This phenomenon is more pronounced in first person perspective than in third person perspective (Steptoe, Steed & Slater, 2013). Slater, Spanlang, Sanchez-Vive and Blanke (2010) showed body transfer illusions when perception in reality and VR is similar. Then, phenomenon such as rubber-hand or enfacement can take place (Blanke, Slater & Serino, 2015).

Furthermore, Biocca (1997) underlies the importance of the visualization of the user’s body to provide a greater feeling of presence, and thus, embodiment in VR. However, this author also points out the technological challenge of body visualization due to the problems of arising latencies, and thus, the imperfect mapping of the human body to the interface. VR is still an immature technology (Biocca, 1997).

Ferreira dos Santos et al. (2016) identified seven virtualization options in VR: indirect (changes in the context, optical flow), abstract (not rich detail), augmented reality VR (real body in VR), avatar VR (complete avatar or body parts), tracking VR (visual input by trajectories or auditory signals), combined (more than one visualization) and no visualization. They found out that the most often used visualization is the indirect one by using optical flow (e.g. Mohler et al., 2007), meaning no visualization of the human body what is in line with our results. While previous research has shown that VCs and also the virtualization of the athlete’s body (especially in case of HMD) are advantageous, most VEs only show scene content without integrating the user’s body in VR. A reason could be that the virtualization is also a complicated process and increases latencies due to the real-time tracking of the human body.

Further studies are needed to compare the different visualizations and hence to develop recommendations concerning the type of visualization (rich detailed avatars, vs. point light or stick figures, full-body vs. body parts or even no visualization) for different athletes and sports. It is also possible that different body parts need different visualizations (Ferreira dos Santos et al., 2016).

Conclusion

We analyzed sport related VEs in the domain of recreational and high-performance sports, with a special focus on virtual characters, which were divided into passive and autonomous VCs. In our research, we looked at: different sports and applications where VEs were used, the role of VCs, different kind of studies and feedback, tested participants, the used output devices and virtualization of users. Most studies focus on ball sports and martial arts, where normally a passive or no VC at all is used. For these two type of sports, the VC usually plays the role of an opponent. Studies were made in research (perception, anticipation and decision-making) and in exercise. Intervention studies with expert athletes are rare. The most used additional feedback is an audio feedback in form of noises of the environment, such as ball contacts. The mainly utilized output devices are CAVE and HMD. Although, we expect that in the future, studies using HMDs will be used more frequently. Nevertheless, most studies renounce the visualization of the user's body, which could especially be difficult in HMDs.

For a sport related VE, the minimum requirements are: an adequate creation and depiction of the VE (at least using desktop VR), and a real-time update of the scene content, based on the user's movements. For a best case scenario, we additionally consider the creation of VC(s) (at least a passive one) and the implementation of further feedback (e.g. real-time feedback of acoustics and haptics). As output device, we prefer a HMD, although that implies that at least some body parts (e.g. the hands) of the user have to be visualized for better orientation.

VR with VCs can be a suitable tool for both exercise and research in the field of sports. Nevertheless, autonomous VCs are still in the development. Today`s autonomous VCs do not provide complete natural interactivity, but with future development, we expect that autonomous VCs offer more advantages than passive ones. However, we must take into account that all VEs, especially VEs with autonomous VCs, are cost-intensive and time-consuming. Thus, costs and benefits have to be evaluated. The decision whether to use passive or autonomous VCs or no VC at all, depends on the research question, and with that, which sport related VE is to be created and used. However, in the domain of sports, we recommend to utilize VCs for a more natural interaction and a better orientation in the VR.

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