Review

Sensing In Exergames for Efficacy and Motion Quality: Scoping Review of Recent Publications

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Abstract

Background: Many studies have shown a direct relationship between physical activity and health. It has also been shown that the average fitness level in Western societies is lower than recommended by the World Health Organization. One tool that can be used to increase physical activity for individual people is exergaming, that is, serious games that motivate players to do physical exercises.

Objective: This scoping review of recent studies regarding exergame efficacy aims to evaluate which sensing modalities are used to assess exergame efficacy as well as motion quality. We also analyze how the collected motion sensing data is being leveraged with respect to exergame efficacy and motion quality assessment.

Methods: We conducted 2 extensive and systematic searches of the ACM Digital Library and the PubMed database, as well as a single search of the IEEE Xplore database, all according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement. Overall, 343 studies were assessed for eligibility by the following criteria: The study should be peer-reviewed; the year of publication should be between 2015 and 2023; the study should be available in English or German; the study evaluates the efficacy of at least 1 exergame; sensor data is recorded during the study and is used for evaluation; and the study is sufficiently described to extract information on the exergames, sensors, metrics, and results.

Results: We found 67 eligible studies, which we analyzed with regard to sensor usage for both efficacy evaluation and motion analysis. Overall, heart rate (HR) was the most commonly used vital sign to evaluate efficacy (n=52), while the Microsoft Kinect was the most commonly used exergame sensor (n=26). The results of the analysis show that the sensors used in the exergames and the sensors used in the evaluation are, in most cases, mutually exclusive, with motion quality rarely being considered as a metric.

Conclusions: The lack of motion quality assessment is identified as a problem both for the studies and the exergames themselves since incorrectly executed motions can reduce an exergame's effectiveness and increase the risk of injury. Here we propose how to use the same sensors both as input for the exergame and to assess motion quality by presenting recent developments in motion recognition and sensing.

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Introduction

Exergames are interactive games with the additional goal of engaging players in physical activity to promote a healthy lifestyle and increase players' physical fitness [1,2]. Increasing availability of commercial sensing technologies has allowed exergames such as Beat Saber (Beat Games) [3] for various virtual reality (VR) systems and Ring Fit Adventure (Nintendo) for Nintendo Switch [4] to reach a large audience and become highly commercially successful, selling more than 4 million and 14 million copies, respectively [5,6]. Typically, these exergames use sensing technologies as input devices to either control an in-game avatar or detect the execution of specified motions. However, previous studies on motion-based games suggest that exergames should also give feedback on the motion's quality and provide specific guidelines to follow [7,8]. Without these measures, players may not perform the demanded motions correctly, leading to diminished health benefits and risk of injury [9].

A common research question with regards to exergames is that of their efficacy. Efficacy refers to the effectiveness or ability of exergames to achieve their intended goals or their desired effect. This goal can be defined as an increase in the participants' performance, physical activity, or motivation [10]. Previous reviews and meta-analyses on exergames generally confirm the existence of positive effects associated with exergames [10-13]. Nevertheless, the reviews primarily assert that exergames are most effective in facilitating light- to moderate-intensity physical activity, and only a small proportion of exergames have demonstrated the ability to significantly increase physical activity levels among users [14-16]. Furthermore, previous reviewers have primarily focused on assessing the efficacy of exergames in specific populations, such as children and adolescents without [11,12,16] or explicitly with adults with overweight [13] or older adults [15,17-19]. Only a few reviews encompass a broader range of participants and do not specifically focus on any particular population [14].

The evaluation process, particularly sensor technology usage, is typically not the focus of existing reviews. Hence, this paper investigates recent studies on the efficacy of exergames to identify which sensing technologies are used both in the exergames themselves and in their evaluation. We further review whether current exergames and their evaluations include any motion quality assessment. Motion Quality as a term is not clearly defined and is often visually evaluated by a professional physiotherapist or sports scientist. One of the most comprehensive approaches to defining the term is given by Skjaerven et al [20], who found that motion quality has many different aspects, including biomechanical as well as physiological and temporal characteristics. Therefore, motion quality assessment requires evaluating the motion of all relevant body parts at every point in time. Since we want to focus on the study design and methodology, with little regard for results or target group, we opt for a scoping review approach. For each study, we assess how the sensing data is being leveraged with respect to exergame efficacy and motion quality assessment. Based on our findings, we discuss how state-of-the-art methods for assessing motion quality and already used sensing technologies could be used to improve the efficacy of exergames and reduce the risk of injury during play.

Methods

Overview

The goal of this scoping review was to identify sensing modalities in recent studies that evaluate exergame efficacy. For this, 3 systematic searches were conducted in accordance with the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) statement [21] and PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews) [22]. A PRISMA-ScR checklist is provided in Multimedia Appendix 1. The database searches were conducted at different points in time by one of the researchers, each without a detailed review protocol.

Search Strategy and Search Terms

Due to the interdisciplinary nature of the research field, 3 different databases were included in the review. To cover both computer science and clinical research, the ACM Digital Library and the subject-specific PubMed database were searched on September 14, 2022, and again on July 14, 2023. A final search on the engineering-focused IEEE Xplore database was conducted on January 15, 2024.

We defined 4 main requirements for studies to be included in our review. First, studies have to feature the evaluation of an exergame. Second, the evaluation has to be conducted quantitatively with sensors with regard to the game's efficacy. Third, the games should focus on general fitness or sports to avoid studies focusing on activities of daily living. Finally, the studies should be recent, which we defined as being published between 2015 and 2023. Based on these requirements, relevant search terms were identified, combined, and generalized as follows:

(exergam* OR "fitness game")

AND (efficacy OR evaluat* OR "heart rate" OR vo2 OR oxygen)

AND (fitness OR sport)

For ACM Digital Library, the search terms were searched for in the categories "Title," "Abstract," and "Author Keyword," each category connected with an OR operator, whereas for PubMed and IEEE Xplore, the search terms were typed "as is" into the "Query Box" and "Command Search," respectively. A detailed search strategy is given in Multimedia Appendix 2.

Study Eligibility Criteria and Selection

Afterward, the following eligibility criteria based on the previously stated requirements were defined. The results were screened and filtered accordingly:

1. Publication type: Peer-reviewed study
2. Publication year: 2015 to 2023
3. Available in English or German
4. The study evaluates the efficacy of at least one exergame

5. Sensor data is recorded during the study and used for evaluation
6. The study is sufficiently described to extract information on the exergames, sensors, metrics, and results

The studies were split among the authors to be screened by abstract and assessed for eligibility. The results of this screening process were then presented and discussed conjointly.

Data Extraction and Data Analysis

Eligible studies were evaluated with regard to their general study design (including participant numbers and focus group), their evaluation methods (including evaluation metrics, vital signs, and sensor usage), and the exergames used (including exergame sensors as well as additional motion sensing). The results were again discussed, assessed for relevance for the review, and generalized conjointly.

Results

Overview

The first search yielded 253 studies of which 30 were removed before the screening process as they were duplicates or not available in English or German. An additional 31 studies were identified through previous work of included authors and citation searching, resulting in a total of 258 studies included in the screening process. 208 studies were excluded in this screening process based on the eligibility criteria stated above, leaving a total of 49 eligible studies. The second search yielded an additional 40 studies, of which 32 were excluded from the screening process. The final search, conducted on the IEEE Xplore database, yielded another 50 studies. After screening by title, abstract, and eligibility criteria, 10 studies were deemed fitting, resulting in a total of 67 studies that were included in our review.

Table 1 gives a brief summary of the vital sign-sensing statistics. Multimedia Appendix 3 [23-89] and Multimedia Appendix 4 [23,24,26-58,60-90] feature additional tables that present details for all 67 studies included in the review. Multimedia Appendix 3 provides an overview of the study design, participants, and how efficacy was assessed. Participation numbers ranged from 6 [23] to 360 [24], with a median of 28. There was a large variety of different focus groups, with the biggest group being healthy adults (n=19 studies). Multimedia Appendix 4 details the exergames and corresponding sensors used in each study and gives information on additional motion sensing if there were any. Not all studies explicitly mention all the exergames evaluated; some feature the evaluation of a multitude of different games, and some tested games they developed themselves. Overall, the 67 studies included in our review feature the evaluation of approximately 49 different exergames. The overall review process with all screening steps is outlined in the PRISMA flow diagram in Figure 1.

Table 1. Summary of vital sign sensing statistics. Detailed statistics for each study can be found in Multimedia Appendix 3.

	Measured vital signs			Evaluated metrics						Evaluation criteria analyzed over time			
	HR[a]	VO_2	Other	mean HR	peak HR or % max HR	peak VO_2 or % max VO_2	MET[b]	EE[c]	Other	Performance	Intensity or PA[d]	Motivation	Other
Number of studies	52	22	18	35	31	21	16	15	45	18	11	6	10
Proportion of studies, %	78	33	27	52	46	31	24	22	67	27	16	9	15

[a]HR: heart rate.

[b]MET: metabolic equivalent of task.

[c]EE: energy expenditure.

[d]PA: physical activity.

Figure 1. PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) [21] flow diagram of the systematic review process.
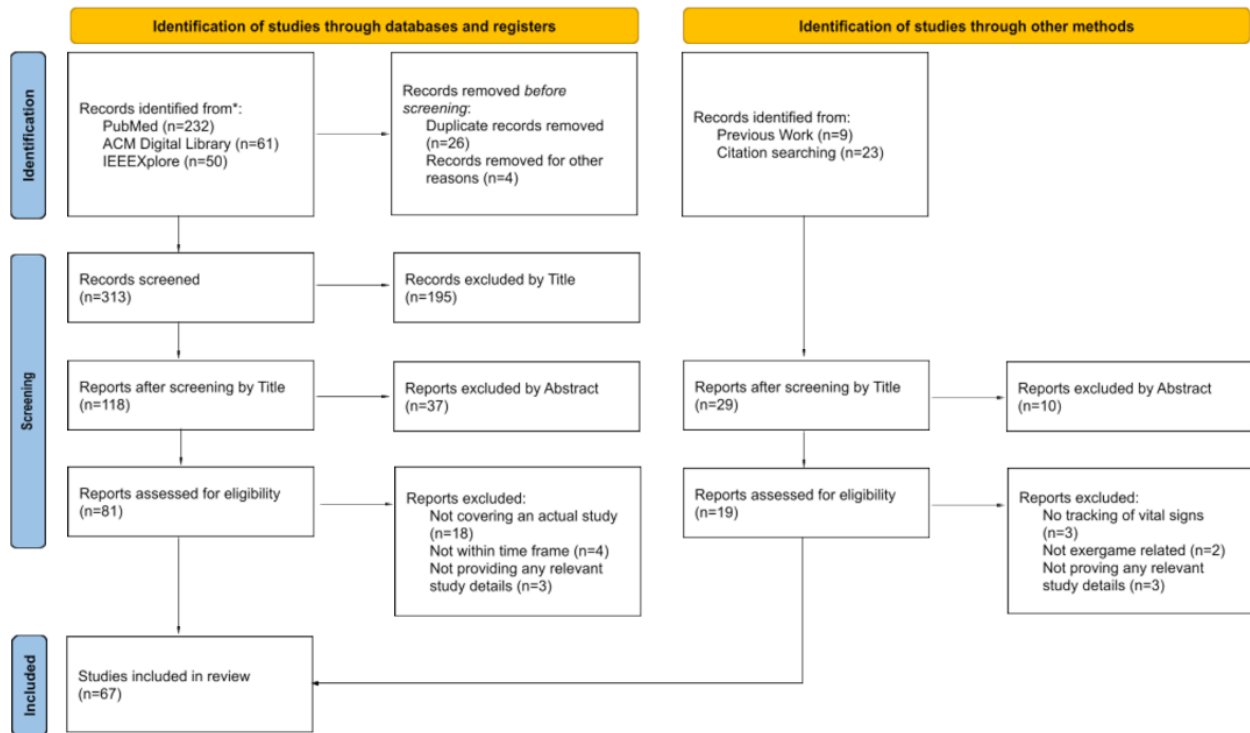
Vital Sign Sensing Technologies

As per our inclusion criterion, all 67 studies aim to assess efficacy. For that, 54 studies used sensors to measure vital signs, while 11 studies relied only on motion sensing, and 2 studies assessed efficacy without any sensors but with standardized tests only. The majority, that is, 52 of the 54, measured the player's heart rate (HR), and 22 measured the oxygen uptake (VO_2) (more details in Table 1). Furthermore, 18 studies measured other vital signs such as blood pressure, blood lactate concentration, and carbon dioxide production.

Efficacy Assessment

In the context of exergames, efficacy refers to the effectiveness or ability of exergames to achieve their intended goals or their desired effect under optimal or controlled conditions. Efficacy is distinguished from effectiveness, with efficacy focusing on how well an approach works in ideal conditions, while effectiveness considers its performance in real-world or practical situations [91]. However, this distinction is not always clearly made by the researchers [25]. Therefore, in the context of this review, the 2 terms are used interchangeably. Typical goals for exergames can be defined as an increase in the participants' performance, physical activity, or motivation [10,92]. Exergame efficacy is usually evaluated by analyzing these metrics over time or in comparison with conventional physical exercises. Often, they are estimated by measuring vital signs, doing standardized tests, or filling out questionnaires. Efficacy is a highly individual metric and will vary for different activities, different target demographics, and from person to person [10].

When looking at the studies' approaches to assessing exergame efficacy, several different study designs were identified. First of all, a distinction can be made by whether the studies evaluate a single group or compare 2 or more groups. The former is

referred to as a within-subject or cross-over study. The latter category is referred to as controlled studies, which again can be split into 2 subcategories. Randomized controlled studies compare randomly split groups, while cross-section studies compare nonrandomized groups based on preexisting conditions. The studies can also be categorized by how many measurements are done. Single-measurement studies use measured metrics and questionnaires to compare the participants' performance, motivation, and general physical activity with nongaming-related exercises. Alternatively, studies with the repeated-measures design, focusing on the long-term effects of exergaming, do the same measurements more than once to observe longitudinal developments. The latter approach was used by 22 studies, while the other 45 studies focused on the first approach. Details on the study design of every included study can be found in Multimedia Appendix 3.

Acute Effects

A total of 53 out of the 67 (79%) studies focus on efficacy evaluation by measuring vital signs in their studies. Out of all analyzed studies (more details in Table 1), 35 reported mean HR, and 31 reported peak HR or proportionate maximum HR (%max HR), with the maximum HR commonly being age-predicted. Ventilation-based evaluation took place in 21 analyzed studies, reporting peak VO_2 or proportionate maximum VO_2 (%max VO_2).

Based on the recorded vital signs, 15 studies processed their participants' data to indicate the recorded energy expenditure (EE) for the exergame activity. In total, 16 studies calculated and reported the metabolic equivalent of task (MET) values for each activity. A total of 8 studies overlapped with studies reporting EE. Furthermore, noteworthy vital-sign-based evaluation metrics are systolic and diastolic blood pressure

[26-29], heart rate reserve [30-33], pulse wave velocity with total peripheral resistance and stroke volume [34], respiratory exchange rate [35,36], lactate concentration [37,38], maximum power output [39], muscle activity [40], concentration through EEG (electroencephalography) [41]. In 3 studies, other derived indicators are used: play intensity and hemodynamic reactivity are calculated based on players' heart rate [37], and the so-called activity counts are based on accelerometer measurements [42,43]. Many studies used subjective questionnaire scales for assessment, which we do not evaluate as they are unrelated to vital sign sensing.

Long-Term Effects

Although many analyzed studies (35 out of 67) comprised more than 1 session of playing exergames, only a minority evaluated changes over time (22 out of 67), and thus qualifies as a longitudinal study in the context of this paper. The evaluation time for longitudinal studies ranged from 4 weeks [44-47] to 6 months [48].

As detailed in Multimedia Appendix 3, most researchers analyzed players' performance. The performance evaluation was predominantly done objectively by tracking changes in anaerobic [46,49,50] or muscular fitness [51,52], functional strength [50], peak VO_2 [28,48], postural control [45], reaction time [24], or cognitive function [53]. The performance was sometimes evaluated subjectively using exercise self-efficacy score [54].

Other evaluation metrics analyzed over time include changes in intensity, usually based on HR or EE [29,45,55,56], whereas further research publications evaluated playtime for different physical activity levels [28,48,51]. In addition to performance and intensity, 6 research publications analyzed changes in motivation, such as play frequency and duration [56] as well as flow [45], player engagement [55] or enjoyment [54], and happiness [57].

Motion Sensing Technologies

The 67 reviewed studies assess various exergames that use different motion sensing technologies, among which the Kinect for Xbox 360 (Microsoft Corp) [93] is the most commonly used (26 out of 67). The Kinect combines a regular RGB (red-green-blue) camera with a depth sensor and can thus be considered a camera-based system. In addition, 1 study each included an exergame using the EyeToy (London Studio) for PlayStation 2 [54] and PS Move (Sony Interactive Entertainment) for PlayStation 3 [44], resulting in 28 out of 67 studies featuring at least one camera-based system. Ergometers, dance mats, balance boards, and other sensing technologies specialized for specific motions are used in 21 out of 67 studies and, thus, make up the second-most common type of motion sensing technology.

VR systems and body-worn inertial measurement units (IMUs) are featured less commonly. Only 5 out of 67 studies feature body-worn IMUs for motion sensing, and only one of them uses IMUs not included in a smartphone or game controller. Furthermore, 7 studies evaluate exergames that use the Nintendo Wii remote controllers held in the player's hands. These controllers are not body-worn and combine an IMU and an

infrared sensor with an external emitter for tracking. Together with VR systems, which were used in 16 out of 67 studies as either standalone or within the so-called ExerCube (Sphery AG) [94], they make up the category of hybrid sensing (overall n=22). Finally, one study [58] features a game that does not use any form of motion sensing.

Out of the 67 studies, 21 did additional motion sensing during the exergaming for evaluation purposes. Common motion sensors used for this task are body-worn accelerometers and IMUs (used in 12 studies) and force plates (used in 4 studies). Furthermore, 2 studies used hybrid motion-capture systems, and 2 used camera-based systems. A specialized system to measure reaction times, an exercise bike, surface electromyography, and a handgrip dynamometer were used in 1 study each.

Motion Quality Assessment

Motion quality, as a term, is not clearly defined and is often visually evaluated by a professional physiotherapist or sports scientist. One of the most comprehensive approaches to defining the term is given by Skjaerven et al [20], where they investigated the lived experiences of a group of expert physiotherapists in search of essential characteristics and features of the term. They found that motion quality has many different aspects, including the biomechanical "characteristics of path and form in [motion]" as well as the physiological and temporal "characteristic of flow, elasticity, vitality, and rhythm in [motion]." Therefore, to provide specific feedback on the full motion quality, it would be necessary to assess the whole motion by tracking and evaluating the motion of all relevant body parts at every point in time, independent from the gameplay.

An essential part of exergaming is the game's ability to track and analyze the player's motions to judge the player's gameplay and their exercise quality. Often, exergames focus on the gameplay aspect, only evaluating motions implicitly by requiring players to interact with the virtual environment, for example, slashing, collecting, or avoiding virtual objects [3,39,40,95,96]. Alternatively, some games combine both evaluations by having players fit a predefined shape [59,97,98]. While such an approach might be suitable to verify if players are performing a specific motion at all, it only enables detecting static poses or certain joints without analyzing the holistic motion execution.

None of the 49 games featured in the studies explicitly assess the quality of exercises performed. However, 7 studies use additional motion sensing to do some form of quality assessment during their evaluation. In addition, 4 of these 7 studies focus on specific motion aspects, such as assessing the angular displacement or range of motion of certain joints [41,55], quantifying postural sway [45], and evaluating shoulder flexibility [26]. Only 3 studies [44,51,60] assess the players' motion quality as a whole, using a multitude of sensors and either a standardized test or a professional physiotherapist. However, for 2 of the studies, these assessments do not happen during the exergame but are used to identify general motion quality at times when the subjects are not playing. The final study [44] employs an expert to do an analysis of gross upper body biomechanics based on video recordings of the subjects during the exergames. Therefore, this is the only study in our

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review that fulfills the condition of holistically evaluating all relevant body parts at every point in time during the exercise, which we consider necessary for motion quality assessment, according to Skjaerven et al [20]. However, this is not an automated process and instead requires manual input from an expert.

Discussion

Overview

To the best of our knowledge, this review represents the first work analyzing sensor usage in studies that examine exergame efficacy. We found 67 eligible studies, which we analyzed with regard to sensor usage for both efficacy evaluation and motion analysis. Overall, HR was the most commonly used vital sign to evaluate efficacy (n=52), while the Microsoft Kinect was the most commonly used exergame sensor (n=26). The results of the analysis show that the sensors used in the exergames and the sensors used in the evaluation are, in most cases, mutually exclusive.

Principal Findings

From the review, 2 main conclusions can be drawn: First, the majority of papers focus on measuring vital signs to infer a physical activity metric. Second, an overall lack of motion quality assessment can be stated among exergame studies. For the studies, this lack of quality assessment can lead to undetected and unwanted influences on the results. For example, it might be hard to differentiate if a lack of efficacy should be attributed to the exergame or to the participants' execution, especially in longitudinal studies. Furthermore, it also poses a problem for the exergames themselves since the players are incentivized to optimize for score, which might lead to optimal gameplay that does not coincide with a correct exercise execution and might lead to injuries instead of increased health [9]. Therefore, in the following outlook, we outline how different types of sensor technologies could be used with existing motion analysis techniques to assess motion quality in exergames.

Outlook

Quality Assessment Based on Cameras

Overview

While the traditional approach of motion analysis by a camera is a hybrid one with visual markers attached to certain body parts, a lot of recent research has focused on markerless methods solely based on single-camera video images [99]. This gives cameras a few advantages over other sensing methods: They are unobtrusive to the players and allow them a full range of motion; they can be easily set up and moved around, and they are comparably cheap and widely available [99]. The recent approaches can be differentiated by their modality: While classic RGB cameras are mostly used when no depth information is needed, so-called RGB-D (red-green-blue-depth) cameras like the Microsoft Kinect [93] are able to also record depth information [100,101].

RGB-D

As stated, 26 of the 28 exergames considered in the review that used cameras for the gaming input relied on the Kinect RGB-D camera. In addition to the advantages of cameras already listed, the Kinect also has its origin in gaming, making it a widespread tool not only for scientists but also for game developers. However, all papers in our review use the Kinect only as input for the games, not for an explicit motion quality assessment. This is surprising as, outside of the exergaming context, RGB-D cameras are used in several motion research areas, such as gait analysis [102-104] and fall detection [105], where they have shown to be a reliable tool to capture and evaluate full-body movements. Sporadically, the Kinect has been used in exergaming-related motion analysis as well, albeit not for quality control in an efficacy assessment study. Examples include motion dissimilarity analysis [106] or interrater reliability evaluation between a Kinect system [107] and a human rater.

RGB

In contrast, classic RGB cameras are not commonly used as motion sensors in exergaming, aside from rare examples [108]. This is also apparent from our review since only 2 exergames used an RGB camera compared to the 26 using the Kinect. However, studies without exergame context have shown that modern RGB-based systems are well-suited to do quantitative motion analysis. Systems like MonoCap (Zhejiang University) [109], OpenPose (Carnegie Mellon University) [110], and MediaPipe Pose (Google) [111] have proven that full-body pose estimation can be done with high accuracy. One of the most well-researched applications of RGB-based motion analysis is gait analysis, which can either be done with a feature-based approach using pose estimation [112-114] or a feature-less approach directly on the images [115,116]. More complex medical applications such as joint load prediction [117] and motion limitation analysis [118] indicate the method's ability to do precise quality assessment of human movements. Furthermore, RGB cameras have already been used in sports analysis [119]. These use cases imply the suitability of RGB cameras as a tool for both gaming input and quality assessment in exergaming.

Quality Assessment Based on Hybrid Sensing Techniques

The release of consumer-grade virtual reality systems contributed to the development of many immersive exergames. An analysis of the 29 top VR exergames from a recent review [120] shows that players prefer games providing a high level of exertion (equivalent to real-world exercise level), whereas a high level of immersion is important for distraction (reducing perceived exertion). Most reviewed exergames using hybrid sensing technology indeed provide a playful fitness experience; nevertheless, existing approaches often fail to analyze motion execution to detect errors or to provide specific feedback on motion quality. For example, approaches letting players fit a predefined shape [59,97,98] might be suitable to verify if players are performing a specific motion at all. However, they only enable the detection of static poses without analyzing motion execution. Furthermore, many VR exergames enabling

interaction with VR objects usually depend only on hand-held devices and often lack lower body movement.

To overcome this limitation, other researchers use additional off-the-shelf VR sensors. Previous studies already concluded that VR sensors are feasible for clinical, research, and industry usage [121,122]. For example, Martin-Niedecken et al [90,123] demonstrated how trackers attached to wrists and ankles can be used to recognize different exercises, such as burpees, lunges, and punches. The motion quality, presented by a star ranking, is then assessed according to how well players reached predetermined target points and how quickly they returned to their initial pose. A further study [124] also analyzes the entire motion execution of different yoga poses and thereby identifies execution errors.

Another possibility to assess motion quality is marker-based motion capture systems, for example, OptiTrack (NaturalPoint Inc.) [125] and Vicon Tracker (Vicon Motion Systems Ltd.) [126]. These systems are the gold standard for tracking individual joint positions and angular movements with high accuracy and low latency [127,128]. However, as such systems require several markers and cameras, they can be obtrusive and not suitable for home or clinical environments. Nevertheless, previous research publications have already demonstrated that motion capture suits are reliable for analyzing holistic motion executions during dance [129], identifying exercise execution errors during physical exercise [130], or conducting kinematic trunk motion analysis [60].

Quality Assessment Based on Body-Worn Sensors

IMUs consisting of an accelerometer, a gyroscope, and sometimes a magnetometer are the most common types of body-worn sensors. They are integrated into commercial devices such as smartphones, smartwatches, and fitness trackers. Among other things, they are often used to track fitness activities and activities of daily living. Compared with camera-based or hybrid approaches, they are particularly well suited to track nonstationary activities. In the following, we will not discuss other body-worn sensors, such as EMG sensors, because of their limited availability and applicability.

While regular body-worn IMUs do not provide as extensive motion data as camera-based or hybrid systems, exergames could use them as robust, low-cost sensors to assess specific quality metrics and enable tracking without a stationary setup. An example of this can be seen in the commercially successful exergame Ring Fit Adventure (Nintendo) for the Nintendo Wii, which tracks and assesses performed exercises through IMUs placed at the thigh and the inside of an elastic ring held by the user. Alternatively, commercial IMU-based systems such as Xsens (Movella) [131], Noraxon Ultium Motion (Noraxon) [132], or the Teslasuit (Teslasuit, Deep Divers Ltd) [133] could be used for an extensive motion analysis in a mobile setting [130].

Whereas some exergames in our reviewed papers use controllers that incorporate an IMU, none rely purely on body-worn sensors for tracking. In 7 papers [41,43,51,60-64], body-worn IMUs are used to assess physical activity. Only Ko et al [41] and Mueller et al [60] additionally use body-worn IMU data for quality assessment by determining the users' range of motion and back posture respectively.

In their review, Rana and Mittal [134] show that wearable sensors can be successfully deployed for kinematic analysis in a variety of sports applications. While these included sports applications such as swimming [135,136], which are ill-suited for exergames, most sports applications presented could be integrated into exergames. Particularly noteworthy applications are swing sports such as tennis [137-143] and badminton [140,144], in which IMUs can either be wrist-worn or integrated into the racket to track and assess individual swings, as it can be difficult to track these with stationary setups in a practical setting.

Limitations

This scoping review is prone to the same search-related limitations as other reviews of this type. First, only articles published in international journals and full articles published in conference proceedings written in English or German are considered. Therefore, potentially relevant studies published in other languages may have been missed. Second, some articles were excluded from the analysis because the required information to assess their eligibility based on the inclusion criteria was not provided. Third, we assess a lack of reproducibility for the ACM Digital Library. In general, a very high volatility can be noted in the amount of records ACM's search function returns when changing individual words or operators. Since the current search results in less records than the original search, which were all included in the review, we consider this to be a minor limitation. Finally, out of the 67 studies included in this scoping review, 8 studies were not found firsthand using the search terms but instead through previous work of included authors and citation searching. This may indicate that there would have been even more fitting search terms for the review question. However, due to the author's experience with the topic and the unambiguity of the results, we are confident that we were able to mitigate any possible negative effects and that the included studies present a complete overview of the current state of research.

In addition to limitations related to the search, we can also note 2 limitations related to the scope of evaluation. They are a deliberately chosen result of our research focus, which means to analyze the studies' methodology with regards to sensing instead of their results. First, the definitions for the terms "efficacy" and "motion quality" used in this paper focus on how these 2 metrics are evaluated and do not go into detail on what qualifies as "good" efficacy or motion quality. Instead, we evaluate how well the studies are able to assess efficacy and motion quality with the methodology and especially the sensors they use. Therefore, we do not define what a "high/low quality motion" may look like as this question is highly specific to the individual motion and therefore cannot be answered generally. For the same reason, we also do not go into detail on the cohorts' age, sex, and focus group as they are predominantly relevant to the studies' results.

Conclusions

In this paper, we conduct a scoping review of recent studies that examine exergame efficacy to determine which sensors are being used and how they are being used during gameplay and evaluation. Our results show that most studies evaluate exergame efficacy by measuring vital signs, the most common being heart rate (52 out of 67) and oxygen consumption (22 out of 67). However, motion quality is only assessed in 7 out of 67 studies despite being an important factor in an exergame's effectiveness and risk of injury. Furthermore, out of the 49 exergames evaluated in the reviewed studies, none feature quality assessment during or after gameplay, and only 3 studies feature motion quality assessment beyond the exergame's feedback.

Since exergames already use motion sensing technologies to track the player's motions, they could also be used for external quality assessment. Therefore, we discuss recent advances in the field of motion analysis and potential use cases of different sensors commonly used in exergames. We come to the conclusion that many of the same sensing technologies typically used in exergames and exergame studies are well-suited for additional motion quality assessment to ensure consistent exergame effectiveness and reduce the likelihood of injury while exergaming.

Authors' Contributions

SD contributed to the investigation, methodology, conceptualization, and writing the original draft. PNM contributed to the investigation, methodology, conceptualization, and writing the original draft. SD and PNM contributed equally as shared first authors. PC contributed to the investigation, writing the original draft, and visualization; SG contributed to conceptualization, writing, reviewing, and editing. CHA contributed to conceptualization, writing, reviewing, and editing. TT contributed to the investigation, methodology, conceptualization, writing the original draft, and supervision.

Conflicts of Interest

None declared.

Multimedia Appendix 1

Preferred reporting items for systematic reviews and meta-analyses extension for scoping reviews (PRISMA-ScR) checklist.
[PDF File (Adobe PDF File), 549 KB-Multimedia Appendix 1]

Multimedia Appendix 2

Search strategies and results for individual databases.
[DOCX File , 15 KB-Multimedia Appendix 2]

Multimedia Appendix 3

Summary of studies with regards to the Evaluation of Exergame Efficacy.
[DOCX File , 51 KB-Multimedia Appendix 3]

Multimedia Appendix 4

Summary of studies with regards to the Evaluation of Games and Motion Sensing.
[DOCX File , 42 KB-Multimedia Appendix 4]

References

1. Dörner R, Göbel S, Effelsberg W, Wiemeyer J. Serious Games: Foundations, Concepts and Practice. India. Springer; 2016.
2. Staiano AE. Exergames, energy expenditure, and obesity. In: The International Encyclopedia of Media Psychology. United States. John Wiley & Sons, Ltd; 2020:1-7.
3. Beat Saber - VR Rhythm Game. URL: https://beatsaber.com/ [accessed 2022-11-11]
4. Ring Fit AdventureTM for Nintendo SwitchTM. URL: https://ringfitadventure.nintendo.com/ [accessed 2022-12-22]
5. IR Information: Sales Data - Top Selling Title Sales Units, Nintendo Co., Ltd. URL: http://www.nintendo.co.jp/ir/en/finance/software/index.html [accessed 2022-11-11]
6. Verdu M. From Bear to Bull: How Oculus Quest 2 Is Changing the Game for VR. URL: https://www.oculus.com/blog/from-bear-to-bull-how-oculus-quest-2-is-changing-the-game-for-vr/ [accessed 2022-11-11]

XSL•FO

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7. Caserman P, Hoffmann K, Müller P, Schaub M, Straßburg K, Wiemeyer J, et al. Quality criteria for serious games: serious part, game part, and balance. JMIR Serious Games. 2020;8(3):e19037. [FREE Full text] [doi: 10.2196/19037] [Medline: 32706669]

8. Mueller F, Isbister K. Movement-based game guidelines. Association for Computing Machinery; 2014. Presented at: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems; 2014 April 26:2191-2200; New York, NY, USA. [doi: 10.1145/2556288.2557163]

9. Slobounov SM. Injuries in Athletics: Causes and Consequences. Germany. Springer Science & Business Media; 2008.

10. Whitehead A, Johnston H, Nixon N, Welch J. Exergame effectiveness: what the numbers can tell us. Association for Computing Machinery; 2010. Presented at: Proceedings of the 5th ACM SIGGRAPH Symposium on Video Games; 2010 July 28:55-62; New York, NY, USA. [doi: 10.1145/1836135.1836144]

11. Gao Z, Chen S, Pasco D, Pope Z. A meta-analysis of active video games on health outcomes among children and adolescents. Obes Rev. 2015;16(9):783-794. [doi: 10.1111/obr.12287] [Medline: 25943852]

12. Joronen K, Aikasalo A, Suvitie A. Nonphysical effects of exergames on child and adolescent well-being: a comprehensive systematic review. Scand J Caring Sci. 2017;31(3):449-461. [doi: 10.1111/scs.12393] [Medline: 27862145]

13. Andrade A, Correia CK, Coimbra DR. The psychological effects of exergames for children and adolescents with obesity: a systematic review and meta-analysis. Cyberpsychol Behav Soc Netw. 2019;22(11):724-735. [doi: 10.1089/cyber.2019.0341] [Medline: 31697604]

14. Peng W, Crouse JC, Lin JH. Using active video games for physical activity promotion: a systematic review of the current state of research. Health Educ Behav. 2013;40(2):171-192. [doi: 10.1177/1090198112444956] [Medline: 22773597]

15. Larsen LH, Schou L, Lund HH, Langberg H. The physical effect of exergames in healthy elderly-a systematic review. Games Health J. 2013;2(4):205-212. [doi: 10.1089/g4h.2013.0036] [Medline: 26192224]

16. LeBlanc AG, Chaput JP, McFarlane A, Colley RC, Thivel D, Biddle SJH, et al. Active video games and health indicators in children and youth: a systematic review. PLoS One. 2013;8(6):e65351. [FREE Full text] [doi: 10.1371/journal.pone.0065351] [Medline: 23799008]

17. Cacciata M, Stromberg A, Lee JA, Sorkin D, Lombardo D, Clancy S, et al. Effect of exergaming on health-related quality of life in older adults: a systematic review. Int J Nurs Stud. 2019;93:30-40. [FREE Full text] [doi: 10.1016/j.ijnurstu.2019.01.010] [Medline: 30861452]

18. Skjæret N, Nawaz A, Morat T, Schoene D, Helbostad JL, Vereijken B. Exercise and rehabilitation delivered through exergames in older adults: an integrative review of technologies, safety and efficacy. Int J Med Inform. 2016;85(1):1-16. [FREE Full text] [doi: 10.1016/j.ijmedinf.2015.10.008] [Medline: 26559887]

19. Li J, Erdt M, Chen L, Cao Y, Lee SQ, Theng YL. The social effects of exergames on older adults: systematic review and metric analysis. J Med Internet Res. 2018;20(6):e10486. [FREE Full text] [doi: 10.2196/10486] [Medline: 29954727]

20. Skjaerven LH, Kristoffersen K, Gard G. An eye for movement quality: a phenomenological study of movement quality reflecting a group of physiotherapists' understanding of the phenomenon. Physiother Theory Pract. 2008;24(1):13-27. [doi: 10.1080/01460860701378042] [Medline: 18300105]

21. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. Syst Rev. 2021;10(1):89. [FREE Full text] [doi: 10.1186/s13643-021-01626-4] [Medline: 33781348]

22. Tricco AC, Lillie E, Zarin W, O'Brien KK, Colquhoun H, Levac D, et al. PRISMA extension for scoping reviews (PRISMA-ScR): checklist and explanation. Ann Intern Med. 2018;169(7):467-473. [FREE Full text] [doi: 10.7326/M18-0850] [Medline: 30178033]

23. Wünsche BC, Abernethy M, Hyniewska S, Luo Z, Pawar RP, Cao S, et al. Rift racers - effect of balancing and competition on exertion, enjoyment, and motivation in an immersive exergame. 2021. Presented at: Proceedings of the 36th International Conference on Image and Vision Computing New Zealand (IVCNZ); 2021 December 9-10; Tauranga, New Zealand. [doi: 10.1109/ivcnz54163.2021.9653159]

24. Badau D, Badau A, Ene-Voiculescu C, Larion A, Ene-Voiculescu V, Mihaila I, et al. The impact of implementing an exergame program on the level of reaction time optimization in handball, volleyball, and basketball players. Int J Environ Res Public Health. 2022;19(9):5598. [FREE Full text] [doi: 10.3390/ijerph19095598] [Medline: 35564993]

25. Singal AG, Higgins PDR, Waljee AK. A primer on effectiveness and efficacy trials. Clin Transl Gastroenterol. 2014;5(1):e45. [FREE Full text] [doi: 10.1038/ctg.2013.13] [Medline: 24384867]

26. Li J, Li L, Huo P, Ma C, Wang L, Theng YL. Wii or kinect? A pilot study of the exergame effects on older adults' physical fitness and psychological perception. Int J Environ Res Public Health. 2021;18(24):12939. [FREE Full text] [doi: 10.3390/ijerph182412939] [Medline: 34948547]

27. Neves LEDS, Cerávolo MPDS, Silva E, De Freitas WZ, Da Silva FF, Higino WP, et al. Cardiovascular effects of zumba(®) performed in a virtual environment using XBOX Kinect. J Phys Ther Sci. 2015;27(9):2863-2865. [FREE Full text] [doi: 10.1589/jpts.27.2863] [Medline: 26504312]

28. Berg J, Haugen G, Wang AI, Moholdt T. High-intensity exergaming for improved cardiorespiratory fitness: a randomised, controlled trial. Eur J Sport Sci. 2022;22(6):867-876. [FREE Full text] [doi: 10.1080/17461391.2021.1921852] [Medline: 33944698]

29.   Mologne MS, Hu J, Carrillo E, Gomez D, Yamamoto T, Lu S, et al. The efficacy of an immersive virtual reality exergame incorporating an adaptive cable resistance system on fitness and cardiometabolic measures: a 12-week randomized controlled trial. Int J Environ Res Public Health. 2022;20(1):210. [FREE Full text] [doi: 10.3390/ijerph20010210] [Medline: 36612530]

30.   Lisón JF, Cebolla A, Guixeres J, Álvarez-Pitti J, Escobar P, Bruñó A, et al. Competitive active video games: physiological and psychological responses in children and adolescents. Paediatr Child Health. 2015;20(7):373-376. [FREE Full text] [doi: 10.1093/pch/20.7.373] [Medline: 26526217]

31.   Polechoński J, Dębska M, Dębski PG. Exergaming can be a health-related aerobic physical activity. Biomed Res Int. 2019;2019:1890527. [FREE Full text] [doi: 10.1155/2019/1890527] [Medline: 31275964]

32.   Çakir-Atabek H, Aygün C, Dokumacı B. Active video games versus traditional exercises: energy expenditure and blood lactate responses. Res Q Exerc Sport. 2020;91(2):188-196. [doi: 10.1080/02701367.2019.1653431] [Medline: 31625817]

33.   Evans E, Naugle KE, Kaleth AS, Arnold B, Naugle KM. Physical activity intensity, perceived exertion, and enjoyment during head-mounted display virtual reality games. Games Health J. 2021;10(5):314-320. [doi: 10.1089/g4h.2021.0036] [Medline: 34449262]

34.   Kircher E, Ketelhut S, Ketelhut K, Röglin L, Martin-Niedecken AL, Hottenrott K, et al. Acute effects of heart rate-controlled exergaming on vascular function in young adults. Games Health J. 2022;11(1):58-66. [doi: 10.1089/g4h.2021.0196] [Medline: 34986027]

35.   McGuire S, Willems ME. Physiological responses during multiplay exergaming in young adult males are game-dependent. J Hum Kinet. 2015;46:263-271. [FREE Full text] [doi: 10.1515/hukin-2015-0054] [Medline: 26240669]

36.   Ciążyńska J, Maciaszek J. Effects of low-immersive vs. High-immersive exercise environment on postural stability and reaction and motor time of healthy young adults. J Clin Med. 2023;12(1):389. [FREE Full text] [doi: 10.3390/jcm12010389] [Medline: 36615191]

37.   Ketelhut S, Ketelhut RG, Kircher E, Röglin L, Hottenrott K, Martin-Niedecken AL, et al. Gaming instead of training? Exergaming induces high-intensity exercise stimulus and reduces cardiovascular reactivity to cold pressor test. Front Cardiovasc Med. 2022;9:798149. [FREE Full text] [doi: 10.3389/fcvm.2022.798149] [Medline: 35155627]

38.   Chung LMY, Sun FH, Cheng CTM. Physiological and perceived responses in different levels of exergames in elite athletes. Games Health J. 2017;6(1):57-60. [doi: 10.1089/g4h.2016.0074] [Medline: 28192034]

39.   Farrow M, Lutteroth C, Rouse PC, Bilzon JLJ. Virtual-reality exergaming improves performance during high-intensity interval training. Eur J Sport Sci. 2019;19(6):719-727. [FREE Full text] [doi: 10.1080/17461391.2018.1542459] [Medline: 30403927]

40.   Feodoroff B, Konstantinidis I, Froböse I. Effects of full body exergaming in virtual reality on cardiovascular and muscular parameters: cross-sectional experiment. JMIR Serious Games. 2019;7(3):e12324. [FREE Full text] [doi: 10.2196/12324] [Medline: 31464194]

41.   Ko J, Jang SW, Lee HT, Yun HK, Kim YS. Effects of virtual reality and non-virtual reality exercises on the exercise capacity and concentration of users in a ski exergame: comparative study. JMIR Serious Games. 2020;8(4):e16693. [FREE Full text] [doi: 10.2196/16693] [Medline: 33112240]

42.   Sousa CV, Hwang J, Cabrera-Perez R, Fernandez A, Misawa A, Newhook K, et al. Active video games in fully immersive virtual reality elicit moderate-to-vigorous physical activity and improve cognitive performance in sedentary college students. J Sport Health Sci. 2022;11(2):164-171. [FREE Full text] [doi: 10.1016/j.jshs.2021.05.002] [Medline: 34004390]

43.   Pasco D, Roure C, Kermarrec G, Pope Z, Gao Z. The effects of a bike active video game on players' physical activity and motivation. J Sport Health Sci. 2017;6(1):25-32. [FREE Full text] [doi: 10.1016/j.jshs.2016.11.007] [Medline: 30356595]

44.   Rosly MM, Halaki M, Rosly HM, Hasnan N, Husain R, Davis GM. Arm exercises for individuals with spinal cord injury: exergaming versus arm cranking. 2019. Presented at: 2019 IEEE 7th International Conference on Serious Games and Applications for Health (SeGAH); 2019 August 05-07:1-7; Kyoto, Japan. [doi: 10.1109/segah.2019.8882460]

45.   Barry G, van Schaik P, MacSween A, Dixon J, Martin D. Exergaming (XBOX Kinect™) versus traditional gym-based exercise for postural control, flow and technology acceptance in healthy adults: a randomised controlled trial. BMC Sports Sci Med Rehabil. 2016;8(1):25. [FREE Full text] [doi: 10.1186/s13102-016-0050-0] [Medline: 27555917]

46.   Wu YS, Wang WY, Chan TC, Chiu YL, Lin HC, Chang YT, et al. Effect of the nintendo ring fit adventure exergame on running completion time and psychological factors among university students engaging in distance learning during the COVID-19 pandemic: randomized controlled trial. JMIR Serious Games. 2022;10(1):e35040. [FREE Full text] [doi: 10.2196/35040] [Medline: 35315780]

47.   Sheu FR, Lee YL, Hsu HT, Chen NS. Effects of gesture-based fitness games on functional fitness of the elders. 2015. Presented at: 2015 IEEE 15th International Conference on Advanced Learning Technologies; 2015 July 06-09; Hualien, Taiwan. [doi: 10.1109/icalt.2015.35]

48.   Berg J, Wang AI, Lydersen S, Moholdt T. Can gaming get you fit? Front Physiol. 2020;11:1017. [FREE Full text] [doi: 10.3389/fphys.2020.01017] [Medline: 32973553]

49.   Ketelhut S, Röglin L, Martin-Niedecken AL, Nigg CR, Ketelhut K. Integrating regular exergaming sessions in the ExerCube into a school setting increases physical fitness in elementary school children: a randomized controlled trial. J Clin Med. 2022;11(6):1570. [FREE Full text] [doi: 10.3390/jcm11061570] [Medline: 35329896]

50. Smits-Engelsman BCM, Jelsma LD, Ferguson GD. The effect of exergames on functional strength, anaerobic fitness, balance and agility in children with and without motor coordination difficulties living in low-income communities. Hum Mov Sci. 2017;55:327-337. [doi: 10.1016/j.humov.2016.07.006] [Medline: 27423302]

51. Comeras-Chueca C, Villalba-Heredia L, Perez-Lasierra JL, Marín-Puyalto J, Lozano-Berges G, Matute-Llorente A, et al. Active video games improve muscular fitness and motor skills in children with overweight or obesity. Int J Environ Res Public Health. 2022;19(5):2642. [FREE Full text] [doi: 10.3390/ijerph19052642] [Medline: 35270330]

52. Lin CC, Lin YS, Yeh CH, Huang CC, Kuo LC, Su FC. An exergame-integrated IoT-based ergometer system delivers personalized training programs for older adults and enhances physical fitness: a pilot randomized controlled trial. Gerontology. 2023;69(6):768-782. [doi: 10.1159/000526951] [Medline: 36617413]

53. Gouveia ÉR, Smailagic A, Ihle A, Marques A, Gouveia BR, Cameirão M, et al. The efficacy of a multicomponent functional fitness program based on exergaming on cognitive functioning of healthy older adults: a randomized controlled trial. J Aging Phys Act. 2021;29(4):586-594. [FREE Full text] [doi: 10.1123/japa.2020-0083] [Medline: 33361495]

54. Dos Santos H, Bredehoft MD, Gonzalez FM, Montgomery S. Exercise video games and exercise self-efficacy in children. Glob Pediatr Health. 2016;3:2333794X16644139. [FREE Full text] [doi: 10.1177/2333794X16644139] [Medline: 27336015]

55. Bronner S, Pinsker R, Naik R, Noah JA. Physiological and psychophysiological responses to an exer-game training protocol. J Sci Med Sport. 2016;19(3):267-271. [doi: 10.1016/j.jsams.2015.03.003] [Medline: 25824058]

56. Kaos MD, Beauchamp MR, Bursick S, Latimer-Cheung AE, Hernandez H, Warburton DER, et al. Efficacy of online multi-player versus single-player exergames on adherence behaviors among children: a nonrandomized control trial. Ann Behav Med. 2018;52(10):878-889. [doi: 10.1093/abm/kax061] [Medline: 30212848]

57. Hastürk G, Akyıldız Munusturlar M. The effects of exergames on physical and psychological health in young adults. Games Health J. 2022;11(6):425-434. [doi: 10.1089/g4h.2022.0093] [Medline: 36126314]

58. Patten JW, Iarocci G, Bojin N. A pilot study of children's physical activity levels during imagination-based mobile games. J Child Health Care. 2017;21(3):292-300. [doi: 10.1177/1367493517708477] [Medline: 29119828]

59. Born F, Abramowski S, Masuch M. Exergaming in VR: the impact of immersive embodiment on motivation, performance, and perceived exertion. 2019. Presented at: 2019 11th International Conference on Virtual Worlds and Games for Serious Applications (VS-Games); 2019 September 04-06; Vienna, Austria. [doi: 10.1109/vs-games.2019.8864579]

60. Mueller J, Niederer D, Tenberg S, Oberheim L, Moesner A, Mueller S. Acute effects of game-based biofeedback training on trunk motion in chronic low back pain: a randomized cross-over pilot trial. BMC Sports Sci Med Rehabil. 2022;14(1):192. [FREE Full text] [doi: 10.1186/s13102-022-00586-z] [Medline: 36372870]

61. Mackintosh KA, Standage M, Staiano AE, Lester L, McNarry MA. Investigating the physiological and psychosocial responses of single- and dual-player exergaming in young adults. Games Health J. 2016;5(6):375-381. [FREE Full text] [doi: 10.1089/g4h.2016.0015] [Medline: 27782766]

62. McDonough DJ, Pope ZC, Zeng N, Lee JE, Gao Z. Comparison of college students' energy expenditure, physical activity, and enjoyment during exergaming and traditional exercise. J Clin Med. 2018;7(11):433. [FREE Full text] [doi: 10.3390/jcm7110433] [Medline: 30423805]

63. McDonough DJ, Pope ZC, Zeng N, Lee JE, Gao Z. Retired elite athletes' physical activity, physiological, and psychosocial outcomes during single- and double-player exergaming. J Strength Cond Res. 2019;33(12):3220-3225. [doi: 10.1519/JSC.0000000000003386] [Medline: 31567792]

64. Lin Y, Wang J, Luo Z, Li S, Zhang Y, Wünsche BC. Dragon hunter: loss aversion for increasing physical activity in AR exergames. 2023. Presented at: Proceedings of the 2023 Australasian Computer Science Week, in ACSW; 2023 March 13:212-221; New York, NY, USA. [doi: 10.1145/3579375.3579403]

65. Wu PT, Wu WL, Chu IH. Energy expenditure and intensity in healthy young adults during exergaming. Am J Health Behav. 2015;39(4):556-561. [doi: 10.5993/AJHB.39.4.12] [Medline: 26018104]

66. Hoffmann K, Sportwiss D, Hardy S, Wiemeyer J, Göbel S. Personalized adaptive control of training load in cardio-exergames--a feasibility study. Games Health J. 2015;4(6):470-479. [doi: 10.1089/g4h.2014.0073] [Medline: 26484388]

67. Rodrigues GAA, Felipe DDS, Silva E, De Freitas WZ, Higino WP, Da Silva FF, et al. Acute cardiovascular responses while playing virtual games simulated by Nintendo wii(®). J Phys Ther Sci. 2015;27(9):2849-2851. [FREE Full text] [doi: 10.1589/jpts.27.2849] [Medline: 26504308]

68. Benzing V, Heinks T, Eggenberger N, Schmidt M. Acute cognitively engaging exergame-based physical activity enhances executive functions in adolescents. PLoS One. 2016;11(12):e0167501. [FREE Full text] [doi: 10.1371/journal.pone.0167501] [Medline: 28030542]

69. Moholdt T, Weie S, Chorianopoulos K, Wang AI, Hagen K. Exergaming can be an innovative way of enjoyable high-intensity interval training. BMJ Open Sport Exerc Med. 2017;3(1):e000258. [FREE Full text] [doi: 10.1136/bmjsem-2017-000258] [Medline: 29021913]

70. Tietjen AMJ, Devereux GR. Physical demands of exergaming in healthy young adults. J Strength Cond Res. 2019;33(7):1978-1986. [doi: 10.1519/JSC.0000000000002235] [Medline: 29189579]

71. Rodrigues GAA, Rodrigues PC, da Silva FF, Nakamura PM, Higino WP, de Souza RA. Mini-trampoline enhances cardiovascular responses during a stationary running exergame in adults. Biol Sport. 2018;35(4):335-342. [FREE Full text] [doi: 10.5114/biolsport.2018.78052] [Medline: 30765918]

72. Viana RB, Gentil P, Andrade MS, Vancini RL, de Lira CAB. Is the energy expenditure provided by exergames valid? Int J Sports Med. 2019;40(9):563-568. [doi: 10.1055/a-0955-9394] [Medline: 31295745]

73. Roure C, Pasco D, Benoît N, Deldicque L. Impact of a design-based bike exergame on young adults' physical activity metrics and situational interest. Res Q Exerc Sport. 2020;91(2):309-315. [doi: 10.1080/02701367.2019.1665621] [Medline: 31718499]

74. Berg J, Moholdt T. Game on: a cycling exergame can elicit moderate-to-vigorous intensity. a pilot study. BMJ Open Sport Exerc Med. 2020;6(1):e000744. [FREE Full text] [doi: 10.1136/bmjsem-2020-000744] [Medline: 32341801]

75. Martin-Niedecken AL, Schwarz T, Schättin A. Comparing the impact of heart rate-based in-game adaptations in an exergame-based functional high-intensity interval training on training intensity and experience in healthy young adults. Front Psychol. 2021;12:572877. [FREE Full text] [doi: 10.3389/fpsyg.2021.572877] [Medline: 34234705]

76. Aygün C, Çakir-Atabek H. Alternative model for physical activity: active video games lead to high physiological responses. Res Q Exerc Sport. 2022;93(3):447-456. [doi: 10.1080/02701367.2020.1864258] [Medline: 34252344]

77. Soria Campo A, Wang AI, Moholdt T, Berg J. Physiological and perceptual responses to single-player vs. Multiplayer exergaming. Front Sports Act Living. 2022;4:903300. [FREE Full text] [doi: 10.3389/fspor.2022.903300] [Medline: 35784804]

78. Ketelhut S, Röglin L, Kircher E, Martin-Niedecken A, Ketelhut R, Hottenrott K, et al. The new way to exercise? Evaluating an innovative heart-rate-controlled exergame. Int J Sports Med. 2022;43(1):77-82. [doi: 10.1055/a-1520-4742] [Medline: 34255326]

79. Marks DW, Rispen L, Calara G. Greater physiological responses while playing XBox kinect compared to nintendo wii. Int J Exerc Sci. 2015;8(2). [FREE Full text] [doi: 10.13140/RG.2.1.3302.5446]

80. Monedero J, Murphy EE, O'Gorman DJ. Energy expenditure and affect responses to different types of active video game and exercise. PLoS One. 2017;12(5):e0176213. [FREE Full text] [doi: 10.1371/journal.pone.0176213] [Medline: 28459835]

81. Dębska M, Polechoński J, Mynarski A, Polechoński P. Enjoyment and intensity of physical activity in immersive virtual reality performed on innovative training devices in compliance with recommendations for health. Int J Environ Res Public Health. 2019;16(19):3673. [FREE Full text] [doi: 10.3390/ijerph16193673] [Medline: 31574911]

82. Stewart TH, Villaneuva K, Hahn A, Ortiz-Delatorre J, Wolf C, Nguyen R, et al. Actual vs. perceived exertion during active virtual reality game exercise. Front Rehabil Sci. 2022;3:887740. [FREE Full text] [doi: 10.3389/fresc.2022.887740] [Medline: 36189005]

83. Wouda MF, Gaupseth JA, Bengtson EI, Johansen T, Brembo EA, Lundgaard E. Exercise intensity during exergaming in wheelchair-dependent persons with SCI. Spinal Cord. 2023;61(6):338-344. [FREE Full text] [doi: 10.1038/s41393-023-00893-3] [Medline: 37012335]

84. Muñoz JE, Goncalves A, Cameirao MS, Bermúdez i Badia S, Gouveia ER. Measured and perceived physical responses in multidimensional fitness training through exergames in older adults. 2018. Presented at: 2018 10th International Conference on Virtual Worlds and Games for Serious Applications (VS-Games); 2018 September 05-07:1-4; Würzburg, Germany. [doi: 10.1109/vs-games.2018.8493433]

85. Munoz Cardona JE, Cameirao MS, Paulino T, Bermudez i Badia S, Rubio E. Modulation of physiological responses and activity levels during exergame experiences. 2016. Presented at: 2016 8th International Conference on Games and Virtual Worlds for Serious Applications (VS-GAMES); 2016 September 07-09:1-8; Barcelona, Spain. [doi: 10.1109/vs-games.2016.7590353]

86. Liu H, Wang Z, Mousas C, Kao D. Virtual reality racket sports: virtual drills for exercise and training. 2020. Presented at: 2020 IEEE International Symposium on Mixed and Augmented Reality (ISMAR); 2020 November 09-13:566-576; Porto de Galinhas, Brazil. [doi: 10.1109/ismar50242.2020.00084]

87. Martin Dantas EH, Bastos Andrade K, Silva Bezerra MR, Ramos Coelho R, Scudese E, Nunes Calvacante EM, et al. Neuromotor and functional adaptations in schoolchildren practicing exergames. 2022. Presented at: 2022 International Conference on Technology Innovations for Healthcare (ICTIH); 2022 September 14-16:42-46; Magdeburg, Germany. [doi: 10.1109/ictih57289.2022.10111946]

88. Han L, Pan Z, Zhang M, Tian F. A pleasurable persuasive model for e-fitness system. 2016. Presented at: 2016 International Conference on Cyberworlds (CW); 2016 September 28-30:89-96; Chongqing, China. [doi: 10.1109/cw.2016.20]

89. Julianjatsono R, Ferdiana R, Hartanto R. Development and evaluation of a low cost music based exergame using microsoft kinect. 2016. Presented at: 2016 8th International Conference on Information Technology and Electrical Engineering (ICITEE); 2016 October 05-06:1-4; Yogyakarta, Indonesia. [doi: 10.1109/iciteed.2016.7863261]

90. Martin-Niedecken AL, Rogers K, Turmo Vidal L, Mekler ED, Márquez Segura E. ExerCube vs. Personal trainer: evaluating a holistic, immersive, and adaptive fitness game setup. 2019. Presented at: Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems; 2019 May 02:1-15; New York, NY, USA. [doi: 10.1145/3290605.3300318]

91. Revicki DA, Frank L. Pharmacoeconomic evaluation in the real world. Effectiveness versus efficacy studies. Pharmacoeconomics. 1999;15(5):423-434. [doi: 10.2165/00019053-199915050-00001] [Medline: 10537960]

92. Lima A, Moreira MT, Ferreira MS, Parola V, Sampaio F, Nóbrega MDP, et al. Efficacy of the use of exergames in promoting the mental health of the elderly: protocol of a systematic review. JAL. 2023;3(3):191-202. [doi: 10.3390/jal3030015]

93. Kinect for Windows. URL: https://learn.microsoft.com/en-us/windows/apps/design/devices/kinect-for-windows [accessed 2023-01-20]

94. The ExerCube, Sphery. URL: https://sphery.ch/exercube/ [accessed 2023-01-20]

95. Audioshield on Steam. URL: https://store.steampowered.com/app/412740/Audioshield/ [accessed 2022-08-30]

96. BOXVR on Steam. URL: https://store.steampowered.com/app/641960/BOXVR/ [accessed 2022-10-24]

97. OhShape on Steam. URL: https://store.steampowered.com/app/1098100/OhShape/ [accessed 2022-08-30]

98. Hot Squat on Steam. URL: https://store.steampowered.com/app/553590/Hot_Squat/ [accessed 2022-08-30]

99. Gong W, Zhang X, Gonzàlez J, Sobral A, Bouwmans T, Tu C, et al. Human pose estimation from monocular images: a comprehensive survey. Sensors (Basel). 2016;16(12):1966. [FREE Full text] [doi: 10.3390/s16121966] [Medline: 27898003]

100. Zhang S, Wei Z, Nie J, Huang L, Wang S, Li Z. A review on human activity recognition using vision-based method. J Healthc Eng. 2017;2017:3090343. [FREE Full text] [doi: 10.1155/2017/3090343] [Medline: 29065585]

101. Colyer SL, Evans M, Cosker DP, Salo AIT. A review of the evolution of vision-based motion analysis and the integration of advanced computer vision methods towards developing a markerless system. Sports Med Open. 2018;4(1):24. [FREE Full text] [doi: 10.1186/s40798-018-0139-y] [Medline: 29869300]

102. Gabel M, Gilad-Bachrach R, Renshaw E, Schuster A. Full body gait analysis with Kinect. Annu Int Conf IEEE Eng Med Biol Soc. 2012;2012:1964-1967. [doi: 10.1109/EMBC.2012.6346340] [Medline: 23366301]

103. Albert JA, Owolabi V, Gebel A, Brahms CM, Granacher U, Arnrich B. Evaluation of the pose tracking performance of the azure kinect and kinect v2 for gait analysis in comparison with a gold standard: a pilot study. Sensors (Basel). 2020;20(18):5104. [FREE Full text] [doi: 10.3390/s20185104] [Medline: 32911651]

104. Bari ASMH, Gavrilova ML. Artificial neural network based gait recognition using kinect sensor. IEEE Access. 2019;7:162708-162722. [doi: 10.1109/access.2019.2952065]

105. Eichler N, Raz S, Toledano-Shubi A, Livne D, Shimshoni I, Hel-Or H. Automatic and efficient fall risk assessment based on machine learning. Sensors (Basel). 2022;22(4):1557. [FREE Full text] [doi: 10.3390/s22041557] [Medline: 35214471]

106. Passos P, Campos T, Diniz A. Quantifying the degree of movement dissimilarity between two distinct action scenarios: an exploratory approach with procrustes analysis. Front Psychol. 2017;8:640. [FREE Full text] [doi: 10.3389/fpsyg.2017.00640] [Medline: 28503159]

107. Rosenberg M, Thornton AL, Lay BS, Ward B, Nathan D, Hunt D, et al. Development of a kinect software tool to classify movements during active video gaming. PLoS One. 2016;11(7):e0159356. [FREE Full text] [doi: 10.1371/journal.pone.0159356] [Medline: 27442437]

108. Assad O, Hermann R, Lilla D, Mellies B, Meyer R, Shevach L, et al. Motion-based games for parkinson's disease patients. In: Anacleto JC, Fels S, Graham N, Kapralos B, Saif El-Nasr M, Stanley K, editors. Entertainment Computing - ICEC 2011. Berlin, Heidelberg. Springer Berlin Heidelberg; 2011.

109. Zhou X, Zhu M, Pavlakos G, Leonardos S, Derpanis KG, Daniilidis K. MonoCap: monocular human motion capture using a CNN coupled with a geometric prior. IEEE Trans Pattern Anal Mach Intell. 2019;41(4):901-914. [doi: 10.1109/TPAMI.2018.2816031] [Medline: 29993801]

110. Cao Z, Hidalgo G, Simon T, Wei SE, Sheikh Y. OpenPose: realtime multi-person 2D pose estimation using part affinity fields. IEEE Trans Pattern Anal Mach Intell. 2021;43(1):172-186. [doi: 10.1109/TPAMI.2019.2929257] [Medline: 31331883]

111. Bazarevsky V, Grishchenko I, Raveendran K, Zhu T, Zhang F, Grundmann M. BlazePose: on-device real-time body pose tracking. Computer Science Computer Vision and Pattern Recognition. 2020. [doi: 10.48550/ARXIV.2006.10204]

112. Viswakumar A, Rajagopalan V, Ray T, Parimi C. Human gait analysis using OpenPose. 2019. Presented at: 2019 Fifth International Conference on Image Information Processing (ICIIP); 2019 November 15-17:310-314; Shimla, India. [doi: 10.1109/iciip47207.2019.8985781]

113. Zago M, Luzzago M, Marangoni T, De Cecco M, Tarabini M, Galli M. 3D tracking of human motion using visual skeletonization and stereoscopic vision. Front Bioeng Biotechnol. 2020;8:181. [FREE Full text] [doi: 10.3389/fbioe.2020.00181] [Medline: 32195243]

114. Albuquerque P, Verlekar TT, Correia PL, Soares LD. A spatiotemporal deep learning approach for automatic pathological gait classification. Sensors (Basel). 2021;21(18):6202. [FREE Full text] [doi: 10.3390/s21186202] [Medline: 34577408]

115. Kidziński L, Yang B, Hicks JL, Rajagopal A, Delp SL, Schwartz MH. Deep neural networks enable quantitative movement analysis using single-camera videos. Nat Commun. 2020;11(1):4054. [FREE Full text] [doi: 10.1038/s41467-020-17807-z] [Medline: 32792511]

116. Leu A, Ristić-Durrant D, Gräser A. A robust markerless vision-based human gait analysis system. 2011. Presented at: 2011 6th IEEE International Symposium on Applied Computational Intelligence and Informatics (SACI); 2011 May 19-21:415-420; Timisoara, Romania. [doi: 10.1109/saci.2011.5873039]

117. Mehrizi R, Peng X, Metaxas DN, Xu X, Zhang S, Li K. Predicting 3-D lower back joint load in lifting: a deep pose estimation approach. IEEE Trans Hum-Mach Syst. 2019;49(1):85-94. [doi: 10.1109/thms.2018.2884811]

118. Trinidad-Fernández M, Cuesta-Vargas A, Vaes P, Beckwée D, Moreno FA, González-Jiménez J, et al. Human motion capture for movement limitation analysis using an RGB-D camera in spondyloarthritis: a validation study. Med Biol Eng Comput. 2021;59(10):2127-2137. [FREE Full text] [doi: 10.1007/s11517-021-02406-x] [Medline: 34467447]

119. Wang T, Goto D, Manno M, Okada S, Shiozawa N, Ueta K. Movement coordination during forward and backward rope jumping: a relative phase study. Annu Int Conf IEEE Eng Med Biol Soc. 2021;2021:4627-4630. [doi: 10.1109/EMBC46164.2021.9630017] [Medline: 34892245]

120. Faric N, Potts HWW, Hon A, Smith L, Newby K, Steptoe A, et al. What players of virtual reality exercise games want: thematic analysis of web-based reviews. J Med Internet Res. 2019;21(9):e13833. [FREE Full text] [doi: 10.2196/13833] [Medline: 31538951]

121. Borrego A, Latorre J, Alcañiz M, Llorens R. Comparison of oculus rift and HTC vive: feasibility for virtual reality-based exploration, navigation, exergaming, and rehabilitation. Games Health J. 2018;7(3):151-156. [doi: 10.1089/g4h.2017.0114] [Medline: 29293369]

122. Jost TA, Drewelow G, Koziol S, Rylander J. A quantitative method for evaluation of 6 degree of freedom virtual reality systems. J Biomech. 2019;97:109379. [doi: 10.1016/j.jbiomech.2019.109379] [Medline: 31679757]

123. Martin-Niedecken AL, Mekler ED. The ExerCube: participatory design of an immersive fitness game environment. In: Göbel S, Garcia-Agundez A, Tregel T, Ma M, Baalsrud Hauge J, Oliveira M, et al, editors. Serious Games. Cham. Springer International Publishing; 2018:263-275.

124. Caserman P, Liu S, Gobel S. Full-body motion recognition in immersive- virtual-reality-based exergame. IEEE Trans Games. 2022;14(2):243-252. [doi: 10.1109/tg.2021.3064749]

125. OptiTrack. URL: http://optitrack.com/index.html [accessed 2023-02-03]

126. Vicon. URL: https://www.vicon.com/ [accessed 2023-02-03]

127. Nagymáté G, Kiss RM. Application of OptiTrack motion capture systems in human movement analysis: a systematic literature review. RIiM. 2018;5(1):1. [doi: 10.17667/riim.2018.1/13]

128. Windolf M, Götzen N, Morlock M. Systematic accuracy and precision analysis of video motion capturing systems--exemplified on the vicon-460 system. J Biomech. 2008;41(12):2776-2780. [doi: 10.1016/j.jbiomech.2008.06.024] [Medline: 18672241]

129. Chan JCP, Leung H, Tang JKT, Komura T. A virtual reality dance training system using motion capture technology. IEEE Trans Learn Technol. 2011;4(2):187-195. [doi: 10.1109/tlt.2010.27]

130. Caserman P, Krug C, Göbel S. Recognizing full-body exercise execution errors using the teslasuit. Sensors (Basel). 2021;21(24):8389. [FREE Full text] [doi: 10.3390/s21248389] [Medline: 34960481]

131. Xsens. URL: https://www.movella.com/products/xsens [accessed 2023-01-20]

132. Measure 3D body movement using inertial measurement units (IMUs). Noraxon. URL: https://www.noraxon.com/our-products/3d-motion-capture-imu/ [accessed 2023-01-20]

133. Meet our haptic VR suit and glove with force feedback. Teslasuit. URL: https://teslasuit.io/ [accessed 2023-01-20]

134. Rana M, Mittal V. Wearable sensors for real-time kinematics analysis in sports: a review. IEEE Sensors J. 2021;21(2):1187-1207. [doi: 10.1109/jsen.2020.3019016]

135. Lee J, Leadbetter R, Ohgi Y, Thiel D, Burkett B, James DA. Quantifying and assessing biomechanical differences in swim turn using wearable sensors. Sports Technology. 2012;4(3-4):128-133. [doi: 10.1080/19346182.2012.725171]

136. Davey N, Anderson M, James DA. Validation trial of an accelerometer-based sensor platform for swimming. Sports Technol. 2008;1(4-5):202-207. [doi: 10.1002/jst.59]

137. Büthe L, Blanke U, Capkevics H, Tröster G. A wearable sensing system for timing analysis in tennis. 2016. Presented at: 2016 IEEE 13th International Conference on Wearable and Implantable Body Sensor Networks (BSN); 2016 June 14-17:43-48; San Francisco, CA, USA. [doi: 10.1109/bsn.2016.7516230]

138. Takano K, Li KF. A multimedia tennis instruction system: tracking and classifying swing motions. IJSSC. 2013;3(3):155-168. [doi: 10.1504/ijssc.2013.056406]

139. Clarke SR, Norman JM. Optimal challenges in tennis. J Oper Res Soc. 2012;63(12):1765-1772. [doi: 10.1057/jors.2011.147]

140. Anand A, Sharma M, Srivastava R, Kaligounder L, Prakash D. Wearable motion sensor based analysis of swing sports. 2017. Presented at: 2017 16th IEEE International Conference on Machine Learning and Applications (ICMLA); 2017 December 18-21:261-267; Cancun, Mexico. [doi: 10.1109/icmla.2017.0-149]

141. Ahmadi A, Rowlands D, James DA. Towards a wearable device for skill assessment and skill acquisition of a tennis player during the first serve. Sports Technol. 2009;2(3-4):129-136. [doi: 10.1080/19346182.2009.9648510]

142. Benages Pardo L, Buldain Perez D, Orrite Uruñuela C. Detection of tennis activities with wearable sensors. Sensors (Basel). 2019;19(22):5004. [FREE Full text] [doi: 10.3390/s19225004] [Medline: 31744136]

143. Srivastava R, Patwari A, Kumar S, Mishra G, Kaligounder L, Sinha P. Efficient characterization of tennis shots and game analysis using wearable sensors data. IEEE; 2015. Presented at: 2015 IEEE SENSORS; 2015 November 01-04; Busan, Korea (South). [doi: 10.1109/icsens.2015.7370311]

144. Lin J, Chang CW, Wang CH, Chi HC, Yi CW, Tseng YC, et al. Design and implement a mobile badminton stroke classification system. 2017. Presented at: 2017 19th Asia-Pacific Network Operations and Management Symposium (APNOMS); 2017 September 27-29:235-238; Seoul, Korea (South). [doi: 10.1109/apnoms.2017.8094141]

Abbreviations

EE: energy expenditure
EEG: electroencephalography
HR: heart rate
IMU: inertial measurement unit
MET: metabolic equivalent of task
PRISMA: Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PRISMA-ScR: Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews
RGB: red-green-blue
RGB-D: red-green-blue-depth
VO2: oxygen uptake
VR: virtual reality