

## Chapter 4

### **AR-Driven Exergaming Systems, Digital Health and AI-Based Support**

**Kevin Roy**

PG Scholar, Department of Computer Science, Christ University, Bengaluru, India

**Dr. Helen K Joy & Dr Rupali Wagh**

Professor, Department of Computer Science, Christ University, Bengaluru, India

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#### **Abstract**

Augmented reality exergaming spans two primary hardware paradigms, mobile smartphone-based applications and head-mounted displays, each exerting distinct influences on exercise efficacy, enjoyment, and adherence. Recent findings highlight differences in physiological outcomes such as heart rate elevation, metabolic intensity, user experience, and broader clinical potential. Mobile AR titles have leveraged exploration-driven and stealth-health mechanics to subtly increase steps and promote general physical activity, offering exceptional accessibility but largely supporting light to moderate movement. In contrast, mixed reality headsets enable vigorous, full-body exercise and more complex motor tasks, achieving substantially higher intensity levels while also introducing ergonomic challenges related to device weight and session-induced fatigue. Key game mechanics, including exploration structures, goal-setting systems, narrative immersion, and social play, vary across platforms and shape user motivation in distinct ways. Emerging clinical applications further demonstrate the potential of AR in rehabilitation contexts, supporting balance improvement, fall-prevention training, and gait enhancement through spatial guidance and contextual cues. Advancements in generative AI and computer vision are poised to enrich these experiences with adaptive coaching and real-time movement correction, though meaningful human oversight remains essential. The synthesis of these factors points toward an ideal AR exergaming ecosystem that integrates cross-platform accessibility, adaptive AI-driven challenges, cooperative social features, ergonomic session structuring, and clinically grounded movement design to support sustained engagement and measurable health benefits.

*IEEE Keywords:* Augmented Reality; Exergaming; Mixed Reality; Head-Mounted Displays; Mobile Health (mHealth); Gamification; Rehabilitation; Physiological Monitoring; Computer Vision; Artificial Intelligence.

#### **1. Introduction**

The latest stage in the evolution of exergames as exercises related types of digital games is the development of advanced systems of AR, combining virtual activities with the real world of physical activity, which early step counters and easy movement prompts have turned into the last century [1]. Augmented reality does not shut the user off as virtual reality does entirely

by substituting the natural vision with a simulated world, but instead, the real world is visible with the interactive virtual objects superimposed on top of it. By enabling the user to stay in touch with space, work around the absence of barriers and incorporating exercise into daily life more naturally, this hybrid method provides the user with the safety benefits of full immersion without its associated safety drawbacks. An in-depth analysis of exergaming studies between 2010 and 2025 has shown that despite the fact that VR-based systems have historically monopolized the field of research, AR exergames have gained momentum of interest in the past years [1]. Some of the other effects of immersive exercise technologies that the review finds as consistent are those related to physical, cognitive, and emotional well-being, yet the overrepresentation of VR-centered studies demonstrates the necessity of more systematic research on the advantages and disadvantages of AR technologies [1].

Current AR exergames are usually based on broadly available consumer hardware. Mobile games like Pokemon GO and Pikmin Bloom are also based on smartphones and use GPS and camera tracking, as well as lightweight interactions to encourage walking and routine movement without any specialized tools. Mixed reality head-mounted displays, such as HoloLens 2 or Meta Quest 3, allow full body interaction by means of spatial anchoring, passthrough cameras, and map of the environment. Identifying the differences in accessibility, usability, intensity of exercise and potential therapy avenue of these platforms is important in designing suitable interventions. Generally speaking, mobile AR is concerned with convenience, low cost, and mass coverage whereas HMD-based AR is concerned with more gameful, intense workouts at the cost of hardware complexity and ergonomic strain. The comparative analysis of these systems basing on the empirical results of the literature in the exergaming domain [1]-[33] depicts that smartphone AR is able to achieve the movement in the sedentary population whereas wearable mixed reality devices may offer an intensive exercise and specific motor training [3]. Collectively, all these technologies create complementary measures of preventive health, rehabilitation, and adherence to exercise.

## **2. Comparative Architectures: Mobile vs. Head-Mounted Displays.**

The selection of hardware has a primary impact on motion patterns, exercise intensity, biomechanical participation, and experience in AR exergaming. The subsequent parts analyze mobile AR and the HMD-based mixed reality individually and then provide a direct comparison between physiological requirements of both.

### **2.1 Mobile Handheld AR: Availability vs. Intensity.**

Mobile AR exergames are interactions that present simple but effective interaction loops by placing virtual content on top of a smartphone camera feed and using the handheld device as a viewport. Most popular implementations include gps location-based exploration, object picking, and simple camera-based gesture detection. The main benefit of this design is that it is accessible; smartphones are virtually ubiquitous and the lack of dedicated hardware is a huge cost reduction, required setup and learning curves are minimal. The studies on usability continue to show that mobile AR is highly accepted, and especially in the case of such a population as older adults who indicated that mobile AR fitness apps were entertaining, easy to master, and comfortable to use [14]. Similar motivation research indicates that mobile AR

minimizes the psychological and logistical distance between participation and lets a user participate in an exercise in a comfortable environment with minimal effort [10].

This comfort is however normally at the cost of the intensity of the exercise. Comparative controlled trials of the same active game being played on a VR headset and a smartphone indicate that in all the variables measured, VR was more likely to induce higher physiological demand, such as average heart rate, maximum heart rate, and cumulative beats [2]. The participants also dedicated significantly longer minutes in moderate to vigorous heart rate ranges (more than 60% HRmax) when using VR sessions, but when using mobile AR games, the gameplay was still in the sedentary or very light intensive category [2].

These results are consistent with other greater observations that smartphone AR typically involves little motion, most usually through finger swipes, slight stepping, or periodic locomotion. Therefore, mobile AR hardly ever goes to metabolic levels necessary to address exercise recommendations [2].

Patterns of gameplay in the real world support this restriction. An example is Pokemon GO which elevates the number of steps per day by about 1,400 steps in less active users [25] but its intermittent stop and go nature rarely allows it to maintain cardiovascular workload. Pikmin Bloom is a gamified pedometer, which encourages a person to walk continuously by means of reward system though it does not require high physical activity or high metabolic rate [10]. Even exergames on mobile based on camera tracking tend to be of moderate intensity, such as the case with camera-based exergames, which use computer-vision tracking, which have been found to produce moderate heart rate and light perceived exertion.

The accuracy of sensors is another limitation to the exercise capabilities of mobile AR. Pose estimation systems like MediaPipe have been found to have more than 90 percent accuracy on major limb landmarks of simple motions [30], and have lower accuracy than depth sensors or controllers or specialized tracking systems, on complex or subtle motions. Consequently, although mobile AR can be used to enhance the adoption of regular movement and lower the level of sedentary behaviour, in most cases the patterns of interaction and limitations of hardware will limit the user to the level of light or very light activity [2][30].

## **2.2 Mixed Reality using HMD: Immersion or Ergonomics.**

Mixed reality glasses like Meta Quest 3 and HoloLens 2 provide a much more different experience with exergaming allowing hands-free interaction, room-scale movement, and spatial anchored virtual overlays. The tasks done by the users are full body tasks like squatting, reaching, stepping, swinging, and dodging, courtesy of the spatial audio and visual stimuli. These mechanics are a great way of increasing energy consumption. The results of the indirect calorimetry assessments of the fitness-based MR titles indicate high metabolic output and the reported intensities are as high as 8 METs in some game modes which is comparable to conventional aerobic exercise programs. Other exergames that utilize HMD regularly take participants to moderate and high heart rate ranges comparable or exceeding many traditional gym-based exercises [2][3]. Passive resistance is also added by the headset itself since putting

on a 500g device raises the amount of neck, shoulder, and core involvement during movement and increases the energy cost even more [2].

Irrespective of these benefits, HMDs pose significant ergonomic problems. The headsets used now have a weight of about 500 g to 600 g, and a prolonged wearing may cause a strain on the neck, upper back, and the muscles around them [7]. Lacking a thorough examination of the use issue, user tests on non-adult and adult users have shown that neck pain most often begins after 15-20 minutes of play, and it occurs particularly in devices of greater mass or poor weight distribution [7]. Other sources suggest that heavier headsets may produce major effects of subjective workload and physical discomfort; e.g. comparative evaluations indicate that NASA-TLX workload scales tend to be very high in heavier mixed reality devices than in lighter ones [13]. These results highlight the compromise between immersive and high-intensity exercise and physiological load due to existing headset form factors. Although the AR presented using HMDs allows more productive exercises, the duration of the sessions, and their accessibility are inaccessible to children, elderly adults, and those with musculoskeletal sensitivity [7][13].

In general, AR exergames based on HMDs are constantly able to reach or surpass fitness criteria in terms of exercise intensities [2]. Nevertheless, the cost involved, the time required to set-up, weight and physical exhaustion pose pragmatic constraints. The usage patterns used in the commercial aspect reveal that even motivated consumers tend to limit their choice of the session to 10-20 minutes in order to prevent discomfort [7]. Therefore, as much as HMD AR benefits the provision of rigorous training and multifaceted motor involvement, its ergonomic and economic limitations are restraining its use.

### **2.3 Face-to-face Comparison of Physiological Load.**

Comparisons made directly between mobile AR and the HMD-based AR show that the intensity difference between the two is significant. In a controlled trial in which respondents were required to play the same game on an Oculus Quest 2 and on a smartphone, all observed heart rate variables were elevated in the VR condition, such as the mean heart rate, the highest heart rate, and the total number of beats [2]. High-intensity activities (above 60 percent of HRmax) were greatly increased during the use of the headset as opposed to mobile AR games, which were still characterized by very light activities [2]. This suggests that the AR that is most reliable in reaching the physiological levels needed to create cardiovascular training is HMD-based.

This shows that, in mobile AR, the sedentary behavior is turned into light movement, which is efficient in the formation of habits, but not in organized fitness objectives. In the meantime, AR based on HMD can be used as a valid cardio alternative, which promotes the use of calories, cardiovascular training, and specific motor skill development [25][3]. All the evidence points to a hybrid ecosystem when evaluated in conjunction: smartphones as a means of high availability and low-intensity engagement throughout the day and headsets as a means of high-focus, high-effort engagements where vigorous intensity is required.

### **3. Game Rules and Motivational Dynamics.**

Hardware defines the type of movements one can make but game mechanics define why users want to move and how long they maintain the movement. The various AR genres form various motivational loops that influence exercise behaviour much more than the hardware does. The subsequent sections make comparisons of the major models of AR exergames to show how certain model design patterns affect physical activity, interest and sustained compliance.

#### **3.1 Niantic Trio: Spectrum of Ambulatory AR.**

The key location-based AR games of Niantic, namely Pokemon GO, Pikmon Bloom, and Monster Hunter Now, incorporate various incentive designs with the same hardware and generate various movement patterns [5][10]. Notwithstanding the fact that all three are based on GPS, map exploration, and the occasional use of cameras, each of them is a good way to get moving.

##### **3.1.1 Pokemon GO: The Search and Find Model.**

Pokemon GO follows the Search and Find pattern (P1) in which the players walk until virtual creatures appear on the map after which they stop to interact with them [5]. This architecture turns regular walking paths into scavenger hunts, and that is why longitudinal data is always recorded with great uptakes in the number of steps taken by hitherto dormant users [25]. The game is rather successful in encouraging light movement through rewarding the players in their exploration.

Nonetheless, its exercising mode is intermittent in nature. Motion occurs in bursts: the players either walk to a spawn point, pause and attack a creature, and continue walking. The intensity of the cardio does not run as long as the game does since it has to stop every now and then. Pokemon GO stimulates overall movement, according to internal play data, as well as external research, but seldom has a lasting effect on heart-rate elevation. It has the advantage of cumulative step count, rather than aerobic conditioning [25].

##### **3.1.2 Pikmin Bloom: The Never-ending Stroll Model.**

Pikmin Bloom eliminates much of the stop and start friction. Its Change of Distance pattern (P4) gives

rewards to continuous walking by planting virtual flowers and growing Pikmin with each step taken [10]. The design will make the phone look like a lightweight feedback pedometer whereby the gamer will just walk around with the app uncovered.

It has been demonstrated through qualitative studies that Pikmin Bloom is habit-forming, particularly in those who are sedentary and thus gain active benefits with low-pressure activity [10]. Emotional involvement is enhanced by social interaction through elements like joint garden construction that makes users keep coming back. Although it has been successful in developing steady walk routines, it is a low-intensity system; it seldom gets the heart rate out of the light activity levels.

### **3.1.3 Monster Hunter Now: The Interval-Style Augmented Reality Workout.**

Monster Hunter Now is an exploration game with brief, high-adrenaline battle scenarios. Gamers are walking to the position of a monster (Search-and-Find, P1), and then they are involved in quick and brutal battles that last approximately 75 seconds with quick taps and swipes. It produces a pattern of sprint-stop which puts users into a temporary state of moderate exercise and then decelerates them once more [5].

Although action scenes increase heart rate more than GO or Pikmin Bloom, the regular distractions of the aerobic activity. The game is also encouraging when one is into action intensive sessions rather than long-term cardio. It is a high-resistance anaerobic mechanic, very active, and not the best in a regular cardiovascular work-out.

### **3.2 Summary of the Niantic Spectrum.**

In the titles of Niantic, the exercise regime is continuous low intensity (Pikmin Bloom) through intermittent light-to-moderate intensity (Pokemon GO) to brief spurts of moderate intensity (Monster Hunter Now). Each of the three enhances the total movement compared with the baseline level [25], though there is a different physiological effect of each one:

- Pikmin Bloom - regular strolling.
- Pokemon GO - number of steps with a lot of breaks.
- Monster Hunter Now - infrequent moderate surges.

These distinctions demonstrate the extent to which mechanics can influence the exercise style: exploration games can be seen as promoting cardio exercise, whereas mechanics based on combat are like interval training with obvious trade-offs.

## **4. Games, Indoor vision-based: Active Arcade, and Plaicise.**

AR exergames do not necessarily rely on exploration outside. There are mobile apps that employ on-device cameras to monitor the movements of the player within the building. Games such as Active Arcade and Plaicise show virtual targets and the players have to strike, kick or avoid them by using full body movements. This installation enables one to do lunges, punches, sidesteps and jumps without having to move out of a small room.

Such studies have been conducted on older adults, where feasibility studies reveal that the games can be played safely and yet achieve moderate-intensity exercise, with participants indicating that they were becoming truly engaged in a physical activity [14]. Motivation is more effectively increased through the instant feedback gained by computer vision systems - which may be based on frameworks like MediaPipe -making real exercise appear to be a challenge of a videogame.

The games lie between extremes of AR. They provide greater exercise than outdoor smartphone games, as they use significantly bigger and more energetic motions, however they are not as intense as a full-body workout that head-mounted displays could provide. Their

benefits are based on availability, affordability and the fact that they can be used by the individuals that cannot travel outside or like to exercise in their own comfort.

There are still some limitations on tracking. Lack of adequate lighting or sub-par fields of view may lead to temporary failure on pose detection, yet since the moves are big (punching huge targets, moving through open spaces), even minor tracking errors do not matter much. In general, indoor AR games show that active movement with the use of meaningful gamified games does not require sophisticated and expensive hardware; smartphones only can serve an active activity of a large number of users.

### **5 Audio-Augmented Narrative: Zombies, Run!**

Zombies, Run! is an audio-augmented narrative that utilizes audio to depict the storyline of the game and facilitate navigation through the world.

Another model of AR exergaming involves audio but not visuals. Zombies, Run! combines a robust sound storytelling: radio communications, task briefings, and sound effects of zombie chases with actual running. Rather than viewing a screen, the users listen via headphones but their eyes are directed at the environment.

Interviews and behavioural studies show that players often run further and more regularly due to the fact that the story-line distracts with exercises and brings some urgency [17]. It has been observed that users find the story helpful in letting them forget the physical pain of running. Suspense, episodic missions, and character-driven narration make otherwise mundane cardio have more appreciation as a psychological experience.

The audio AR does not present many safety concerns that the visual AR poses, including hitting objects because it is screen-free and lightweight. It is also compatible with cheap earbuds, and therefore is available to almost everybody. Physiologically, it allows authentic sustained cardio, and players control the pace themselves and work extra hard on narrative ones.

This model proves that graphics are not necessary to make a digital augmentation effective, and the sound is enough to motivate the exercise, which is a strong substitution in case a person is distracted by a screen or not safe during running.

### **6. Social Mechanics: Cooperation vs. Competition.**

The influence of social systems on user motivation in exergames is enormous. Two major types of dynamics are identified in research: cooperative, and competitive.

Systems that are competitive (leaderboards, races, rewards based on rank, etc.) may enhance temporary intensity by motivating users to compete well with others. Nevertheless, they may cause stress, demoralize weaker players and bring in negativity of frustration or anxiety [11]. Competition may lead to spurts of peak performance, but it is a danger to longevity of performance among users who have no preference to high pressure or rough competition.

On the other hand, cooperative mechanics focus on teamwork, common objectives and support. The research has always indicated that cooperative exergaming produces positive

effects on enjoyment, perceived social support, and exercise persistence [11]. Elements such as team raids in Pokemon GO or team flower-planting in Pikmin Bloom promote constructive social bonding and offer a feeling of "social flow" wherein the user feels that they are connected to other users, and will more readily keep playing routinely.

The new AR-related research supports the idea that the collaborative forms are particularly helpful in maintaining the engagement in the long run [11]. Players also note that they are more motivated, experience reduced pressure, and that there is a stronger sense of collective achievement when they play as a team than when they play against each other.

In general, social mechanics are motivation modulators:

- Competition - more acute in the short term, more chance of dropout.
- Cooperation - increased enjoyment, increased chances of long-term compliance.

An effective AR exergame usually incorporates both, although it tends to follow cooperative frameworks to be able to remain inclusive and engage various levels of fitness.

## **7. Clinical and Therapeutic Implementations.**

Along with entertainment and fitness, augmented reality exergaming is also being researched in clinical and therapeutic areas. The fact that it enables real-time visual feedback, increases motivation, and aims to gamify repetitive activities puts AR as a helpful supplement to rehabilitation, balance training, neurological care, and preventive health in the long term. The clinical areas that are using AR largely in the following sections are based on systematic reviews and empirical trials.

Therefore, stroke recovery involves the involvement of motor recovery. Stroke survivors have frequent motor impairments, lack of balance and problems in making coordinated movements. AR-based intervention adds provisional visual overlays, direction, and interactive exercises that may complement conventional rehabilitation by promoting repetition, precision, and patient activity. A previous meta-analysis of over twenty AR stroke rehabilitation trials found that there were indeed significant differences in change on the Berg Balance Scale (BBS) between AR-assisted and traditional exercise programs [6]. This evidence indicates that the combination of AR as a visual feedback, task gamification, and repetition at a greater rate can lead to the attainment of measurable positive outcomes in the field of postural control.

AR-supported mirror therapy is one of the modalities that have been used commonly, where the patient is shown a virtual image of a healthy limb that has been overlaid on the affected limb. The approach is based on well-known neurorehabilitation concepts, such as activation of mirror neurons or visuomotor feedback. Such systems as A2Mirror operated on the AR smart glasses enable patients to observe a virtual arm making movements over their damaged part. Initial results show that the method is easy to use, interactive, and inspiring to users and there is a possibility that this method could improve upper-limb motor recovery [24].

Even with these advantages, AR is more likely to be used as an addition and not a complete substitute of conventional physiotherapy. Gait-related outcomes, including ten-meter walk speed, show that there are no significant differences between AR-assisted and standard rehabilitation groups, and that AR should be most useful to improve involvement and dosage instead of radically changing gait outcomes [6]. Clinical interpretations indicate that AR enhances the level of training by ensuring that exercise becomes more enjoyable and patients engage in practicing it at home, though it still takes physical therapists to monitor them.

On the whole, AR has the potential to promote early gains, enhance the motivation of the user, and promote remote care monitoring, although the ultimate results tend to align with standard treatment. The emerging practical model in clinics is hybrid rehabilitation where AR exergames can be used to carry therapy hours into the home environment and provide clinicians with remote monitoring of performance and intervention modification.

### **7.1 Geriatrics: Fall Prevention and Osteoporosis.**

Balance training is also very important to the older adults and fall risk is one of the key health issues in this category. AR, in contrast to VR, does not interfere with the perception of the real world by making users blind, but instead allows them to be aware of their surroundings when interacting with superimposed cues. This is why AR is uniquely qualified to simulate real world challenges at a safe level. According to a recent network meta-analysis, AR-based fall-prevention interventions, i.e., stepping over virtual obstacles projected onto the screen or stepping over simulated trip hazards, significantly outperformed passive control groups in terms of their balance outcomes [12]. AR can be used to teach older adults reactive balance strategies using real but controlled environments by superimposing puddles, blocks, or uneven surfaces on the real surface.

AR-enhanced supervision has also been suggested to be helpful to osteoporosis patients in strength and balance training. The people should be cautious about the form control so that no injury takes place. It is suggested by a 2024 clinical protocol that an AR exergame system, which displays real-time posture feedback as targets (spinal alignment indicators or movement instructions) on the field of view of the patient during training, could be implemented [19]. This will enable individuals to exercise their bodies in a safer and more proper alignment to minimize the chances of strain and allow them to have more intensive workouts at home. Pilot testing results are preliminarily positive and indicate that the feedback systems of AR can enhance compliance by making exercises more interactive and less repetitive.

To conclude, AR provides a layer of intelligent supervision that facilitates safe, realistic and cognitively challenging training of older adults. Integrating environmental awareness and visual directions, AR-based systems have the possibility to help decrease the risk of falls, build confidence, and increase compliance with long-term exercise programs.

### **7.2 Parkinson disease and cognitive-motor training.**

Gait freezing, balance instability, and impaired motor coordination are the characteristics of Parkinson disease (PD). The idea of augmented reality has already demonstrated potential to

help solve the previously stated problems with the help of external hints and systematic movement directions. Reality DTx is a home-based AR program with a wearable pair of glasses that displays lines and stepping markers over the floor in order to assist patients to follow stride length and prevent gait freezing. A 2024 feasibility study also discovered that PD patients were accepting of AR-based gait and balance exercises, and they felt safer, more confident, and more motivated using virtual sessions at home [23]. The remote prescription of exercises and performance monitoring capacity of therapists is a major move towards tele-rehabilitation, which may increase the reach of therapy to languid or transport-impaired patients.

There is also the potential of clinical AR exergames in children with neurodevelopmental conditions. First attempts at mixed reality experiences through games based on HoloLenses 2 were attempts to combine cognitive tasks with spatial navigation, which stimulates the growth of both motor and working memory. Pilot studies on healthy children were found to be highly usable and enjoyed with high scores and had demonstrated preliminary physical and cognitive benefits, which was a first step in validation before applying similar systems to other populations, such as children with cerebral palsy. These results suggest that AR is capable of facilitating dual-task training, combining motor and cognitive aspects in a manner that is not tedious and goal-oriented.

One such problem that has continually haunted neurological populations is cognitive load. AR with too intense visual or cognitive experience can enhance fatigue, especially in a person with neurological deficits. Research indicates that although AR exergames are effective in enhancing the engagement, the cognitive load should be well matched to prevent user overload. It is aimed at giving a person that level of challenge without causing an undue mental stress.

AR has proven to be effective in stroke, geriatric care, Parkinsonism, and cognitive-motor rehabilitation, with a consistent feature improvement in engageability, repetition, remote monitoring, and multimodal feedback. AR does not supplant therapists and is a powerful addition to their practices, which increases the reach of a therapist, motivates them stronger, and makes therapy more flexible and responsive to the home environment.

## **8. Generative Coaching and Vision the AI Frontier.**

The future of AR exergaming is driven by the achievements of artificial intelligence (especially generative dialogue systems and motion analysis based on computer vision). These technologies enable AR platforms to change dynamically to user performance, customize training content, and provide real-time guidance. The two of them bring a change in the form of statistical, pre-programmed exercise experiences to context-responsive coaching systems that can be scaled to extensive and diverse user bases.

### **8.1 Generative AI Coaching Personalized Coaching.**

Digital fitness design is starting to be affected by the Large Language Models (LLM) like GPT-4. Recent experiments assessing AI-generated workout plans have determined that LLM models tend to be helpful in generating safe recommendation plans, and are not capable of

decision making sophisticated enough to produce individualized programming, particularly when sensitive medical or contextual factors are taken into account [27]. The most significant changes were made in the hybrid configurations, where human coaches took AI-generated plans as a base and then optimized them according to the observations of the real world. Hybrid users in that research lost more weight than those who used AI-only plans, thus indicating that, although AI can help speed up the creation of the content, human supervision is essential to maximize the results [27].

In AR ecosystems, real-time coaching can be assisted by generative AI in the form of virtual trainers or non-player characters (NPCs). Such AI-driven avatars may offer active verbal feedback, responsive encouragement and adjustable pacing depending on constant sensor information like heart rate, motion quality, or user expression. With early experiments in related areas, including generative models creating responsible and emotionally sensitive virtual agents in language education platforms, it is clear that generative models can be trained to produce responsive and emotive virtual agents [29]. In applied to fitness, comparable systems might provide session instructions (Slow down, it is time to have a recovery), technique instructions (Keep your guard up), or motivational speech based on user effort. Despite the experimental nature of generative AI, it is projected that in the coming years, it can help dramatically increase the AR exergame engagement through offering conversational, emotionally supportive, and context-aware coaching experiences.

## **8.2 Form Correction through Computer Vision.**

Details in analyzing movements are also being enabled by computer vision (CV) on both smartphones and AR headsets. Frameworks like MediaPipe are capable of identifying an extensive image of body landmarks at real-time rates (about 30 fps) on consumer hardware with high accuracy of common fitness-motions like squats and lunges and proper lighting and placement [22]. This helps AR systems to observe form, repetitions, joint angles and deviations in safe movement patterns. In the case of an AR application, a tone of excess knee valgus in a squat can be detected and corrective markers can be overlaid or verbal feedback can be issued to correct posture.

Mobile AR pose estimation has been shown to be robust enough to support home-based coaching, without the use of depth sensors, through studies of mobile AR exercise monitoring [22]. The comparisons between 2D landmark detection based on RGB-only and the more complex depth-based techniques show that LiDAR and depth cameras are also able to provide higher precision, but modern 2D landmark detection can be good enough to deliver meaningful corrective feedback. The prototype AR systems, as experimented in controlled settings, have already shown that it is possible to provide angle-based instructions like lift your knee higher or straighten your spine, to enable a user perform perfect technique with the simplest hardware, a phone camera [22].

With further additions of cameras and computational power to the AR glasses, CV feedback will have an increased level of detail and context. New AR exercise games can consist of real-time skeletal overlay, fatigue prediction algorithms that operate on the basis of form degradation, and adaptive exercise sessions that are prompted by joint kinematic movements.

These features can successfully service the transition between house training and trained training, and formal training is more reachable and scalable.

### **9. The Ideal AR Exergame.**

By synthesizing the findings in the fields of hardware, mechanics, social interactions, clinical use, and artificial intelligence, one can provide a list of requirements of a perfect AR exergame that can address the needs of various users.

A perfect solution would embrace a hybrid hardware solution where the user can switch between a lightweight mobile experience and a more intense head-mounted experience. As an example, the walking-based exploration game mechanics can be done both outdoors via smartphones and inside via an impressive workout like boxing, rhythm exercises, or a mixed reality obstacle course can be done on an HMD without disrupting the overall flow of the game [10]. The cross-platform integration is a continuity, which allows the user to be active in any case of either environment or equipment available.

The conceptual AR exergame would be based on adaptive AI and utilize computer vision and generative coaching models to make the experience adaptive in difficulty, feedback, and progression. The data on heart rate can be used to increase the intensity of the task, whereas the pose-tracking would help point out unsafe form or inadequate range of motion. This type of system may add difficulty during the times of low exertion, provide recovery patterns in the event of fatigue, and provide real-time alerting to ensure safe and efficient movement patterns.

The people should have social structures that focus on cooperative interaction, which the research indicates are better in creating enjoyment, retention, and perceived social support compared to the individual competitive modes [11]. The long-term engagement can be fostered by group quests, collective challenges, and puzzles, and team-oriented missions involving users of different levels of fitness. Competitive aspects can be added to ensure variety like a challenge a day or a challenge a week but the essence must be on collective advancement as opposed to serious competition.

Ergonomics should also be taken into account. Sessions based on HMDs are to be structured on the basis of shorter, intensive sessions, which range between 15-20 minutes to reduce physical discomfort related to the weight of headsets and excessive loading of the neck [7]. These sessions can be bridged by mobile modes, which offer lighter activities or cooling-down activities. The optimal mechanism would provide the participants with pacing guidance with regular reminders to have a rest, stretch, or drink, which is safe and sustainable.

Lastly, the perfect AR exergame would include the use of clinically informed movement design, which will entail the application of tested exercise strategies into play-based interaction patterns. The step-ups, lunges, balance exercises or sit-to-stand transition could be integrated into the narratives of a game-like simulation, i.e. to climb up a virtual hill, to jump between platforms, to walk a simulated terrain, etc., and the user can get the benefits of the exercises approved by the physiotherapist without realizing that they are being used as a health intervention. Computer vision-based pre-session motion testing could determine the

baseline range of motion or the balance in order to provide individualized difficulty levels that can be modified throughout the session.

## **10. Future Directions, Key Challenges, and Conclusion**

The trends in the future of augmented reality (AR) exergaming are becoming more geared towards hybrid and adaptable ecosystems that involve the incorporation of smartphones, tablets and head mounted displays into a linear developmental model. The model allows users to move between light outdoor activities, indoor activities with structure, and workouts of high intensity with mixed reality without affecting continuity. This progress is expected to be facilitated by development of generative artificial intelligence and computer vision, allowing systems to provide personalized coaching, automatically increase or decrease difficulty, and provide real-time form correction with respect to heart rates, joint angles, and performance history. The capabilities have the potential of redefining the concept of consumer fitness, as well as clinical rehabilitation, by making it instant, engaging, and extensible. With AR gadgets growing smaller and larger in feature set, the line between entertainment, health tracking, and treatment will be further unstablized, which will contribute to long-term compliance through the use of narrative, group goals, and evidence-based adjustment.

Despite these opportunities, a number of issues should be discussed to address all the potential of AR exergaming. The ergonomic limitations of existing head-mounted displays still restrict the session time and make the high-intensity usage painful to most populations, especially older ones and those with musculoskeletal susceptibility. The accuracy, reliability, and interpretability of AI-based systems are also limited and are particularly susceptible to a wide variety of environments, body types, lighting requirements or movement speeds. There are still digital disparities because not every user has access to AR-enabled devices or an uninterrupted network presence, which can continue to increase disparities in adoption of health technology. Another issue is cognitive overload where an interface full of visual content or too challenging to use can be more exhaustive or unsafe during movement. Lastly, the fact that such a large amount of biometric and behavioral data, as well as location data, poses significant privacy and ethical concerns, and as such may warrant a well-developed governance structure to guarantee user trust and sustainability.

To sum up, AR exergaming is in a strategic position of changing the way people live and how patients can recover following illness due to its peculiar combination of immersion, adaptivity and accessibility. Mobile AR leads to habit formation and locomotion in low-resistance situations whereas head-mounted systems provide strenuous exercise and compound motor activities that compete with more conventional forms of fitness training. The clinical evidence in the fields of stroke-rehabilitation, gait and balance disorders, fall prevention, and cognitive-motor training has proven that AR has the ability to improve motivation, training dosage and remote care models, thus acting as an effective supplement of traditional treatment. As AI continues to develop, ergonomic design enhancements, development of broader social and co-operative systems, and incorporation of scientifically-proven exercises, AR exergaming can become an error-changing value-added to the health of the population. Through the advancement of the field, not only it can make interesting, but also in the most basic form, it

can completely transform the way people live in relation to movement, rehabilitation, and well-being in the long term.

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