Research Article

Computer Vision-Augmented Exergaming for Spine Health

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Citation Jayasree Th, Pragathi P, Premkumar S, Krishna SRS. Computer Vision-Augmented Exergaming for Spine Health. Journal of Modern Rehabilitation. 2026; 20(2):211-224. http://dx.doi.org/10.18502/jmr.v20i2.21716

http://dx.doi.org/10.18502/jmr.v20i2.21716

Article info:
Received: 10 Oct 2025
Accepted: 10 Feb 2026
Available Online: 01 Apr 2026

ABSTRACT

Introduction: Back pain remains a prevalent musculoskeletal condition with significant implications for quality of life and long-term spinal health. Conventional rehabilitation approaches often suffer from low patient adherence and limited engagement, highlighting the need for innovative, technology-driven solutions that motivate sustained therapeutic participation.

Materials and Methods: A real-time pose detection system was integrated with a Unity-based gaming platform to deliver personalized exercise regimens targeting flexibility, strength, and postural correction. The system incorporated computer vision algorithms for real-time biomechanical analysis and immediate performance feedback. Three therapeutic exercises were evaluated: the knee-to-chest stretch (cross crunches), side bend, and forward and backward bends. Exercise performance was gamified within the Unity engine to enhance user motivation and adherence.

Results: The system successfully detected and analysed user performance across all three target exercises in real time. A measurable improvement in user scoring patterns was observed over successive sessions, indicating enhanced engagement and more effective exercise execution. The gamified framework demonstrated reliable performance analysis and responsiveness to individual rehabilitation needs.

Conclusion: Integrating real-time pose detection with interactive game-based environments represents a viable and scalable approach to back pain rehabilitation. By transforming therapeutic exercises into engaging gameplay, the proposed system promotes greater adherence to treatment protocols and supports superior long-term spinal health outcomes. The framework's adaptability positions it as a promising tool for individuals with diverse rehabilitation requirements.

Keywords:

Back pain; Pose detection technology; Rehabilitation; Unity; Spinal health; Gaming exercise

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Introduction

Back pain is a prevalent global health issue affecting millions of people, leading to significant morbidity, reduced quality of life (QoL), and substantial healthcare costs. Traditional methods of back pain management often involve physical therapy, medication, and lifestyle changes. However, adherence to these treatments can be challenging due to factors, such as monotony, discomfort, and lack of engagement. The need for innovative, engaging, and accessible rehabilitation strategies is therefore critical for improving long-term patient outcomes [1].

The integration of technology in healthcare has opened new avenues for improving the efficacy and accessibility of rehabilitation programs. Specifically, pose detection technology, powered by advanced computer vision algorithms, such as OpenCV and MediaPipe, enables real-time analysis of users' movements and postures. By leveraging this technology, clinicians can gain objective insights into patient performance. Moreover, incorporating interactive gaming elements into rehabilitation protocols has shown promise for enhancing patient engagement and adherence. Gamification strategies, such as rewards, challenges, and progress tracking, have been effective in motivating individuals to participate consistently in their programs. Many recent studies have focused on at-home recovery using serious games and advanced technologies.

While existing systems have demonstrated the potential of these technologies, a critical gap remains in developing integrated, user-centric frameworks that specifically target the form-critical exercises required for back pain rehabilitation and demonstrably link real-time pose analysis to quantifiable improvements in performance and therapeutic scoring. Effective rehabilitation requires precise monitoring of movement patterns to target specific muscle groups and movement impairments, a level of flexibility and engagement often missing in current applications [2]

In direct response to these challenges and the identified gap, this study introduces a pioneering framework that integrates pose-detection technology with interactive gaming experiences to enhance back pain rehabilitation. By transforming traditional exercises into interactive and engaging games, this study aims to increase user satisfaction, encourage active participation, and ultimately improve treatment outcomes for individuals with chronic back pain. This work serves as a proof-of-concept for optimizing therapeutic outcomes through real-time feedback and gamified adherence.

Studies indicate that games are an effective tool for back pain rehabilitation, notably by increasing patient motivation and engagement [3] and providing viable support where traditional in-person care is restricted [4]. Despite this evidence, a key challenge is the lack of uniform guidelines for the design and development of these rehabilitation games.

Devices, such as Microsoft Kinect and Nintendo Wii, are often used to deliver fun, interactive exercises, largely because these commercially available systems are an alternative to specialized clinical equipment. For example, a Kinect-based system was created for children with cerebral palsy [5], using games to guide and track their arm movements. However, newer, more advanced systems can involve a higher initial investment. Another setup combines virtual reality (VR) games with specialized smart gloves and wearable sensors [6] to support intricate hand and finger exercises. This system records movement data and helps doctors track progress using a mobile app. However, the cost of such customized hardware introduces a potential barrier to widespread home use.

A review of past studies [7] showed that video games using motion capture can help stroke patients improve balance and walking. However, further research is needed to determine the best game type, timing, and frequency of use.

Other researchers have created hand-motion-controlled games, such as the popular game 2048 [8], making rehabilitation more fun and engaging. Hand gestures can also control robotic arms using image processing [9], and new methods for calculating joint angles improve posture tracking accuracy [10, 11]. These tools are especially useful for elderly people who require regular monitoring of their movement.

Artificial intelligence is also used to track posture and suggest better exercise routines, ensuring people follow safe, effective movements. Systems, such as the Home-based Immersive Lower Limb Exergame System [12], combine VR and motion sensors to support leg exercises while keeping the experience fun.

Game platforms, such as Unity, are used to create rehabilitation games for hand injuries. These games track hand movements in 3D and help patients improve without a therapist. Video analysis tools [13] using camera footage can accurately detect and classify exercises, thereby improving therapy monitoring precision.

Computer vision is widely used to study human motion, especially to estimate joint positions during rehabilitation [14]. Games that provide real-time feedback are also used to keep patients motivated [15], and many are safe and cost-effective [16].

For chronic pain, serious games with full-body tracking and sensors have been used to teach real-world coping and therapy skills [17]. Early studies have shown that game-based feedback can improve movement and reduce pain in individuals with long-term back problems [18]. VR games are being tested to safely expose patients to pain-related movements and help them overcome fear [19].

Some VR systems are designed especially for older adults with back pain, using simple designs and feedback suitable for their age [20]. Projects, such as virtual immersive gaming to optimize recovery [21], are testing how VR can improve rehabilitation results in people with chronic pain. One study in Nigeria [22] found VR games for back exercises were cheaper and more effective than regular clinic treatments.

Games, such as "playMancer," help people with chronic pain improve their motor skills and stay engaged in therapy [23]. Motion sensor-based remote rehabilitation for chronic low back pain showed significant pain reduction, improved mobility, and high adherence rates, with gamification and real-time biofeedback enhancing patient engagement and compliance [24], demonstrating that such technology can be equally useful. Finally, exercise games that use motion tracking have been shown to reduce pain and improve mobility in older adults [25].

Overall, this growing field shows how combining games, computer vision, and artificial intelligence can create powerful new methods to support physical rehabilitation. New research is also exploring non-contact, real-time pose-tracking systems [26], deep learning for recognizing therapy poses [27], and mobile applications that help people continue therapy at home [28]. Camera-based tools for remote tracking [29] and large datasets for posture and movement [30] are helping make these systems more accurate and effective. These studies collectively underline the advancement toward more accessible, efficient, and technology-driven rehabilitation solutions. Although interactive games offer a promising, low-cost solution for enhancing back pain recovery and overcoming limitations in in-person care, the field lacks standardized design and practical evidence, particularly regarding the use of off-the-shelf development tools. Building on this recognized gap, this study aimed to investigate the practical application and efficacy of interactive games for home-based back pain rehabilitation. Specifically, this study describes the development and implementation of three distinct rehabilitation games for spine health using the Unity engine and assesses their impact on key user outcomes.

Materials and Methods

This section outlines the systematic approach to developing and implementing the back pain rehabilitation system, which integrates pose-detection technology with interactive gaming experiences. This section outlines the key steps involved in creating a personalized, engaging platform to enhance flexibility, strength, and posture and alleviate back pain. Figure 1 shows a block diagram of the back pain rehabilitation module [31]. The Unity Engine, developed by Unity Technologies, is used on the host computer to create games for rehabilitation training and assessment. These games are specifically designed to support individuals in their recovery, offering immersive, interactive experiences. By incorporating gamification principles and engaging in gameplay mechanics, therapy sessions become more enjoyable and effective. Moreover, Unity's flexibility allows developers to customize experiences according to the unique needs and progress of each patient, enhancing the benefits of rehabilitation efforts.

PyCharm was the primary tool for detecting body postures and mapping landmarks via a webcam. The system calculates joint angles based on these landmarks. When a joint angle exceeds a predefined threshold, PyCharm triggers the corresponding arrow key press. These keyboard inputs are then sent to the Unity engine, which executes the corresponding movement for the in-game elements. This integration between PyCharm and Unity enables real-time interaction between the user's body movements and the game environment.

Game development process

Bunny Dodge, Road Rush, and Space Run are innovative games developed that combine physical therapy with interactive gaming. These games engage players in exercises targeting core muscles and improving flexibility, while offering an enjoyable, immersive experience. By utilizing pose detection technology, they track players' movements in real time, ensuring accurate integration between physical exercises and virtual gameplay. These games provide a fun and motivating way for individuals to engage in rehabilitation while enjoying gaming.

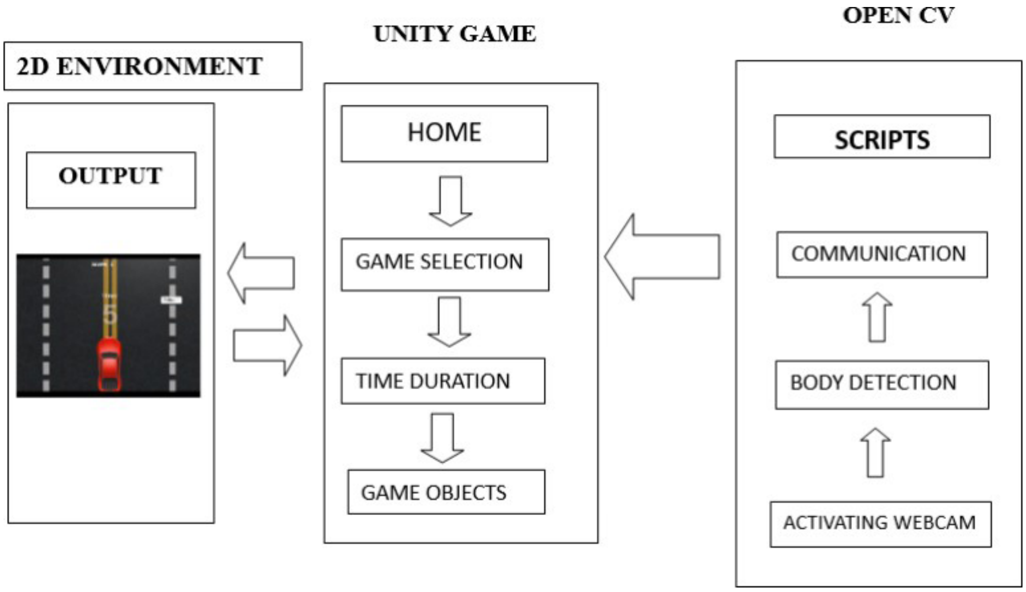


Figure 1. Block diagram of the assessment system

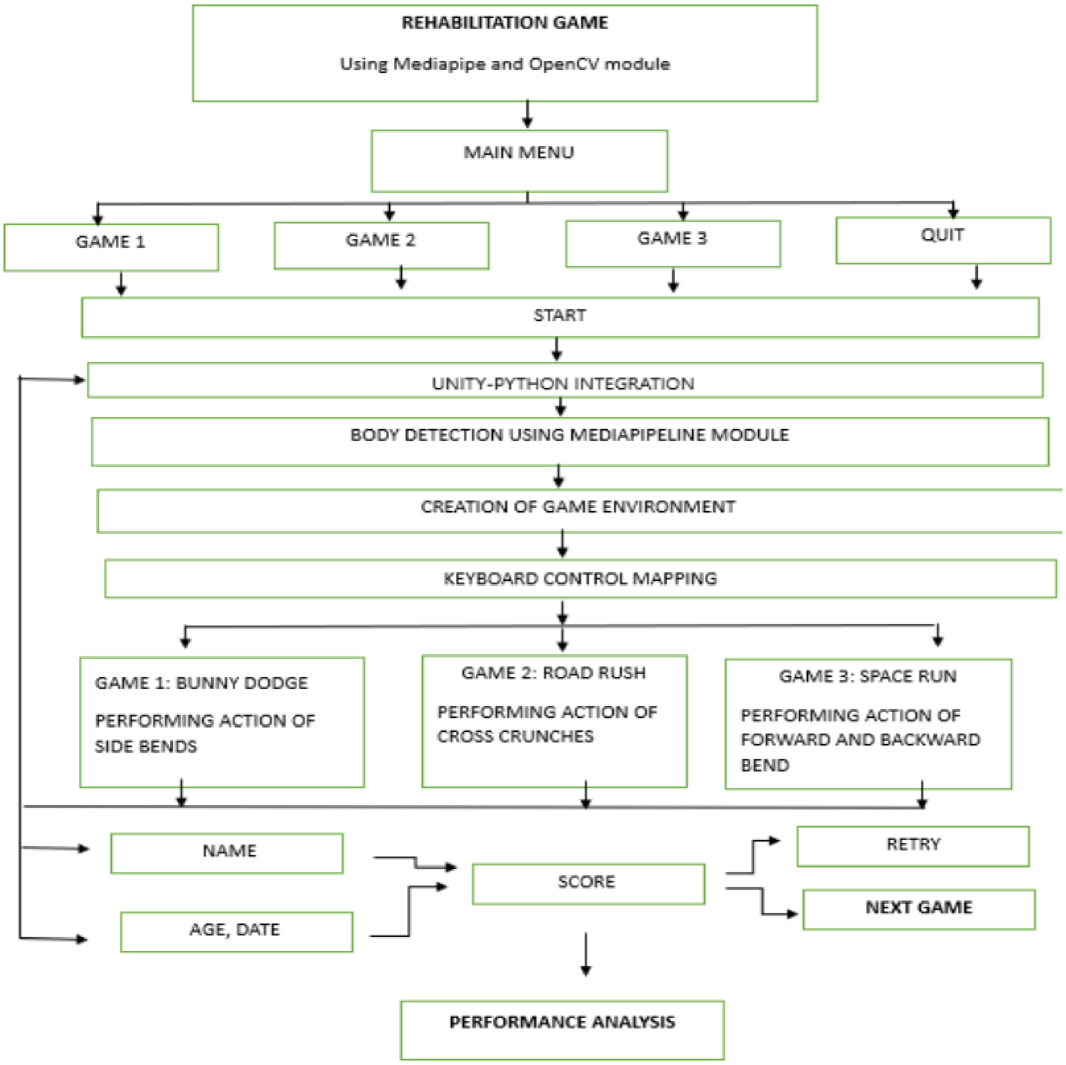


Figure 2. Game menu screen

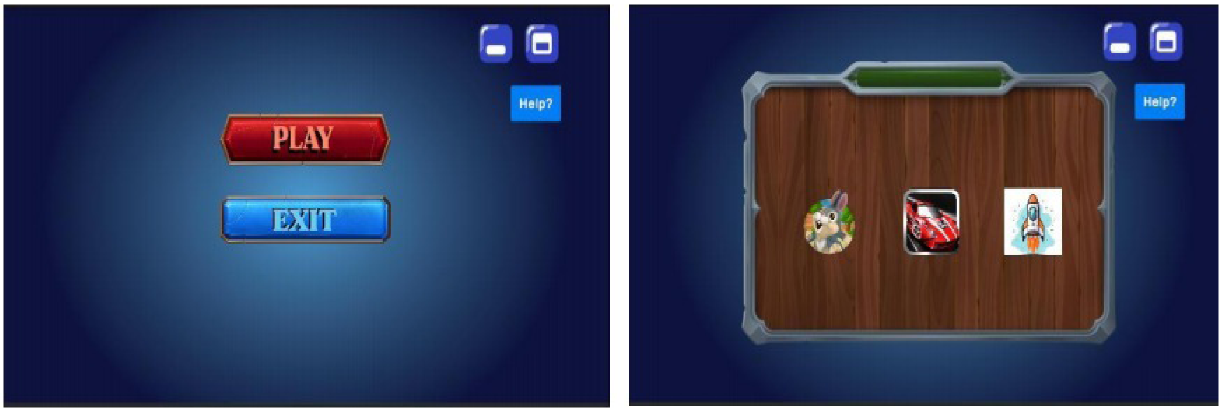


Figure 3. Game architecture

As shown in Figure 2, the rehabilitation gaming system's user interface features three buttons for the games Bunny Dodge, Road Rush, and Space Run. Upon launching the application, users can select their preferred game by clicking the corresponding button, seamlessly transitioning to the game environment.

A prominently displayed "Help" button provides essential guidance for interacting with each game. Clicking the "Help" button offers detailed explanations of the required poses and their associated in-game movements, ensuring that users have clear instructions for a smooth and engaging rehabilitation experience.

Figure 3 shows the detailed architecture of the module, which combines three rehabilitation games: Bunny Dodge, Road Rush, and Space Run. The menu offers users a choice among these games, each designed to target specific muscle groups and movements (side bends, cross crunches, and forward/backward bends). The system integrates Unity and Python, utilizing Mediapipe and OpenCV for accurate, real-time body movement detection and tracking, allowing seamless interaction between physical exercises and virtual gameplay. The rehabilitation game features personalized information displays (name, score, age, date), retry options, and performance analysis tools, enhancing motivation and progress tracking. This holistic approach makes rehabilitation enjoyable, engaging, and effective.

Pose detection algorithm

Pose detection and classification form the core functionality of the script, enabling it to analyze and interpret human body poses from images or video frames. Using the MediaPipe library, the script employs pre-trained machine learning models to accurately detect key landmarks on a person's body, such as joints and body parts. Functions, such as detectPose(), identify these landmarks, whereas classifyPose() analyzes their spatial relationships and angles to classify specific poses, such as left and right bends (side bends), left knees and right knees up (cross crunches), and forward and backward bends (Figure 4). This allows for real-time feedback, facilitating applications such as fitness tracking or motion-controlled gaming [13].

Video capture via openCV

The Python script used OpenCV for video capture. It initializes a video capture object to access the default webcam and continuously reads frames in a loop. Each frame was processed for resizing and pose detection/classification. The loop exits when the 'ESC' key is pressed, releasing resources and closing all the open CV windows. This setup enabled real-time video capture and pose detection for each frame, resulting in a graphical interface.

Body landmark detection

Figure 5 shows that body landmark detection was achieved via the MediaPipe library. The script initializes the MediaPipe pose detection model using mppose.Pose(), configuring it with specific parameters, such as static-image mode and minimum detection confidence. Within the video processing loop, each frame is passed to the detectPose() function, which detects and returns landmarks representing key body points. Optionally, detected landmarks can be visualized on the frame via OpenCV drawing functions for debugging or user feedback.

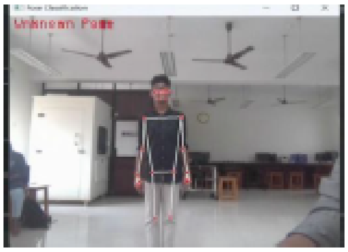


Fig. 4A Unknown Pose

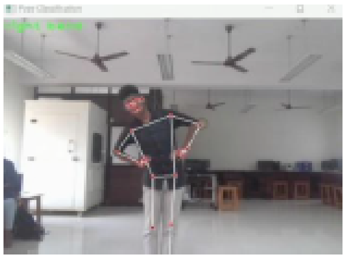


Fig. 4B Right Bend

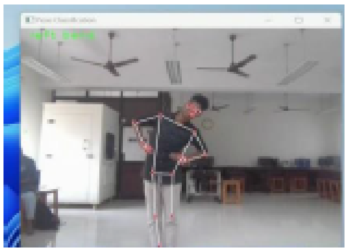


Fig. 4C Left Bend

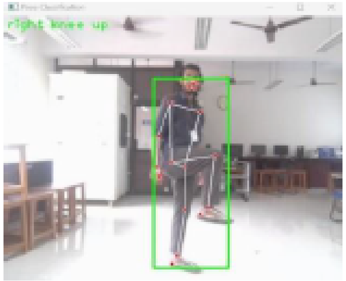


Fig. 4D Right Knee up

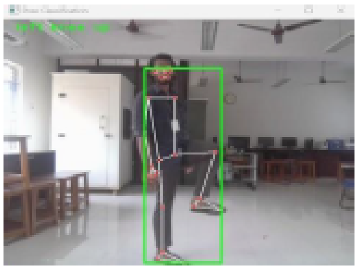


Fig. 4E Left Knee up

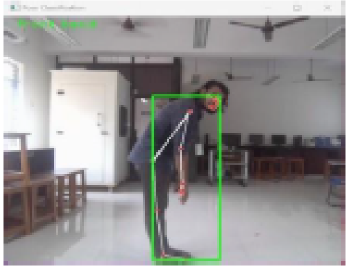


Fig. 4F Front Bend

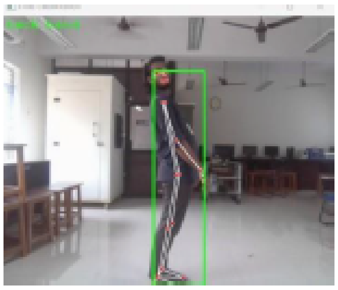
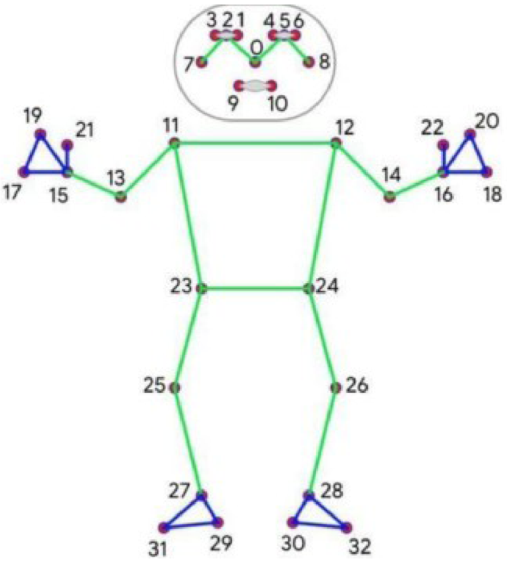


Fig. 4G Back Bend

Figure 4. Exercise for pose detection



0. nose
1. right eye inner
2. right eye
3. right eye outer
4. left eye inner
5. left eye
6. left eye outer
7. right ear
8. left ear
9. mouth right
10. mouth left
11. right shoulder
12. left shoulder
13. right elbow
14. left elbow
15. right wrist
16. left wrist
17. right pinky knuckle #1
18. left pinky knuckle #1
19. right index knuclke #1
20. left index knuckle #1
21. right thumb knuckle #2
22. left thumb knuckle #2
23. right hip
24. left hip
25. right knee
26. left knee
27. right ankle
28. left ankle
29. right heel
30. left heel
31. right foot index
32. left foot index

Figure 5. Biomarkers - 33 landmarks

Joint angle calculation

In the Python script, calculating joint angles is crucial for pose analysis. The 'calculate angle ()' function determines the angle formed by three specified landmarks (joints or body parts) via trigonometric principles. It computes the angle between vectors formed by the landmarks on the basis of their x and y coordinates. This angle, expressed in degrees, provides insights into the spatial orientation of the joints, aiding in understanding body posture. After detecting landmarks in each frame, the script uses 'calculate angle ()' to compute angles between landmarks representing key joints such as shoulders, elbows, hips, knees, and ankles via Equation 1. By comparing these computed angles against predefined thresholds, the script can classify various body movements. This classification enables the script to provide user feedback or trigger actions such as displaying messages, playing audio cues, or controlling interactive applications.

The formula used to calculate the angle between vectors AB and BC is expressed as:

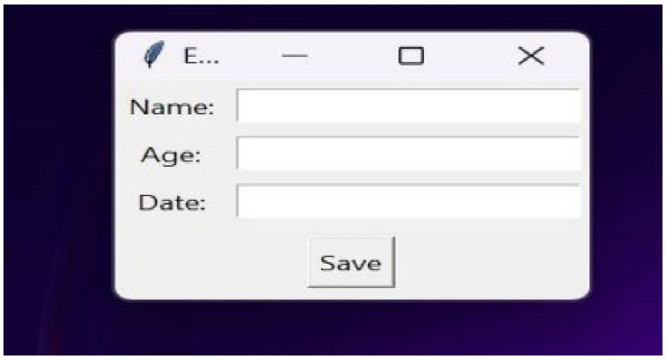
1. degrees (arctan 2[yc−yb, xc−xb]−arctan 2[ya−yb, xa−xb])

Where (xa, ya), (xb, yb), and (xc, yc) are the coordinates of the three specified landmarks.

degrees () converts the angle from radians to degrees arctan2() computes the arctangent of the ratio of the differences in the y-coordinates and x-coordinates of the vectors.

User feedback and data logging

The rehabilitation script enhances user engagement through audio feedback, data logging, and a gaming experience questionnaire. With the pygame.mixer module, the script provides immediate auditory cues based on

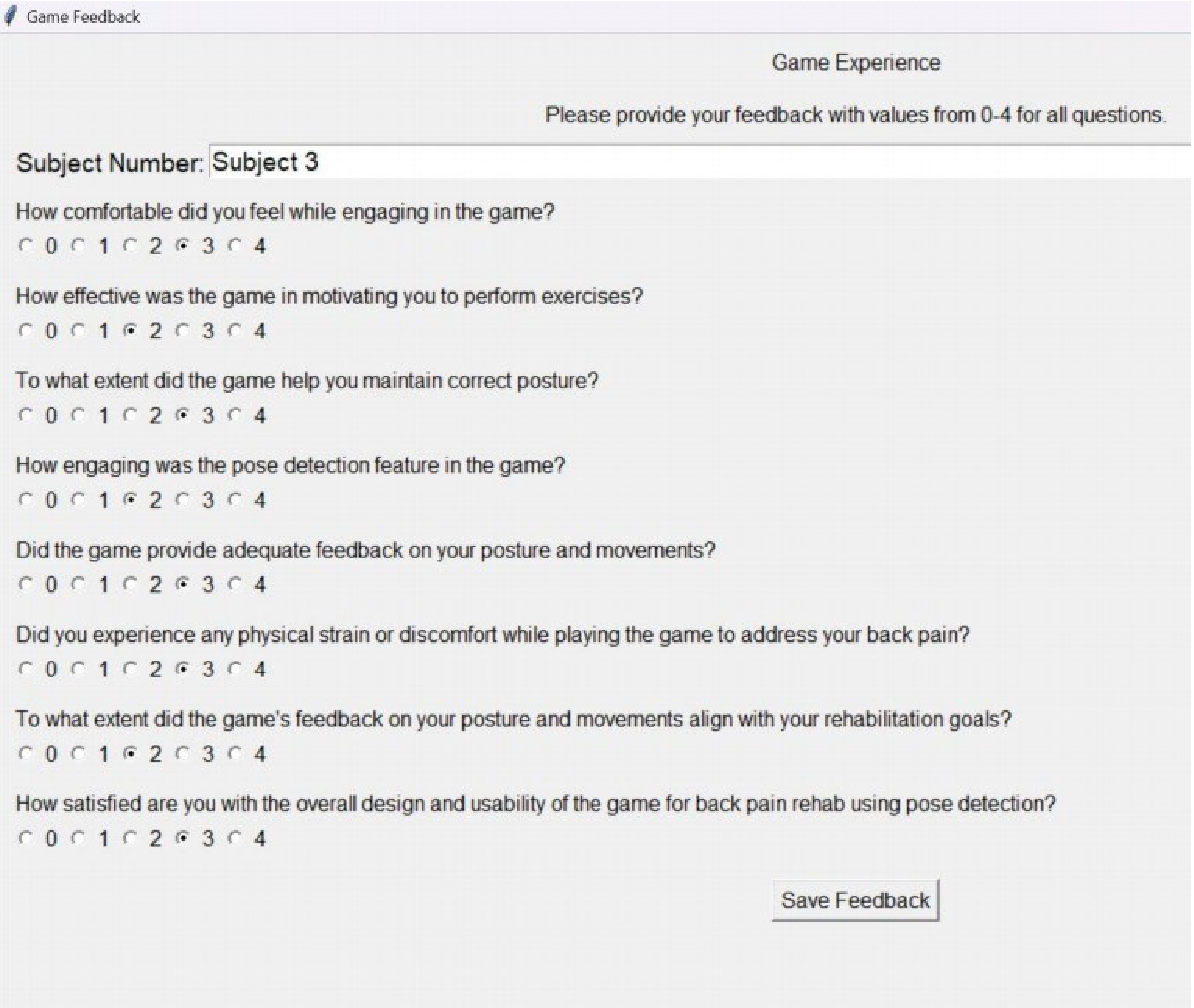


Name:

Age:

Date:

Figure 6. Data entry form



Game Experience

Please provide your feedback with values from 0-4 for all questions.

Subject Number: Subject 3

How comfortable did you feel while engaging in the game?
○ 0 ○ 1 ○ 2 ● 3 ○ 4

How effective was the game in motivating you to perform exercises?
○ 0 ○ 1 ● 2 ○ 3 ○ 4

To what extent did the game help you maintain correct posture?
○ 0 ○ 1 ○ 2 ● 3 ○ 4

How engaging was the pose detection feature in the game?
○ 0 ○ 1 ● 2 ○ 3 ○ 4

Did the game provide adequate feedback on your posture and movements?
○ 0 ○ 1 ○ 2 ● 3 ○ 4

Did you experience any physical strain or discomfort while playing the game to address your back pain?
○ 0 ○ 1 ○ 2 ● 3 ○ 4

To what extent did the game's feedback on your posture and movements align with your rehabilitation goals?
○ 0 ○ 1 ● 2 ○ 3 ○ 4

How satisfied are you with the overall design and usability of the game for back pain rehab using pose detection?
○ 0 ○ 1 ○ 2 ● 3 ○ 4

Figure 7. Game experience questionnaire

the pose classification results, such as positive sounds for correct poses and warning sounds for incorrect ones, thus offering additional guidance and encouragement. Data logging allows users to input personal information via a Tkinter GUI, capturing details, such as name, age, and date, as shown in Figure 6, along with performance metrics. These data are stored in a Pandas DataFrame and saved in an Excel file, enabling personalized fitness tracking and performance analysis. After each game session, users complete a questionnaire (Figure 7) with eight questions, rating their experience and the effectiveness of the exercises on a scale from 0 (not at all) to 4 (extremely). This feedback is vital for refining the rehabilitation module to better meet user needs and expectations.

Results

The implementation of the back pain rehabilitation module showed promising results, highlighting the benefits of integrating technology and gamification into traditional rehabilitation. Rigorous testing revealed significant improvements in user engagement, exercise adherence, and overall rehabilitation outcomes. Gamification notably boosted user motivation and adherence by turning exercise into interactive, enjoyable games. This approach increased user satisfaction and encouraged consistent participation, leading to better treatment outcomes.

Game development

Bunny Dodge focuses on improving flexibility and coordination by having players control a bunny that dodges obstacles through side bends (Figure 8). The pose detection algorithm uses a webcam to track movements, translating them into in-game actions: bending right moves the bunny right, and vice versa. A scoring system encourages correct and continuous side bends. A total of 21 participants (12 males and 9 females) were recruited for

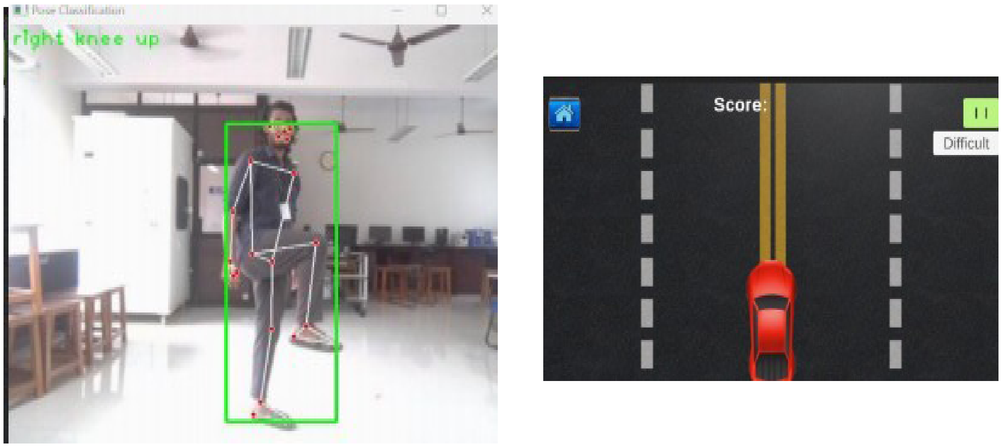


Figure 8. User testing of bunny dodge game

this study. The inclusion criteria required participants to be of any age group and present with non-specific chronic low back pain (LBP) lasting more than 3 months. Patients with specific pain etiologies or recent surgical history were excluded. Within the final cohort, the age range observed was 22-45 years. The developed exercise plan was checked and approved by a physical therapist. This was done before any participants started the study to ensure that the exercises were safe and medically sound for people with back pain. Significant improvements in flexibility and side-bending movements, with high levels of satisfaction and engagement are reported. Road Rush targets overall back flexibility and endurance through cross crunches. In this game, players steer a car left or right by performing cross crunches to avoid obstacles (Figure 9). The pose detection system accurately tracks the cross crunches, ensuring that the car's steering responds to the player's movements. Real-time scores and progress trackers provide instant feedback, making the exercise engaging and rewarding. The subjects who were tested on Road Rush showed improvements in core strength and endurance. The Participants appreciated the fun and challenging aspects of the gameplay.

Space Run enhances the core strength and balance through forward and backward bends. Players navigate a spaceship by performing these bends (Figure 10), with the pose detection algorithm tracking their movements. The spaceship's movement mirrors the player's bends, supported by visual and auditory feedback for better performance. Testing with subjects revealed significant improvements in the bending range and control. The game's interactive nature maintained high motivation and adherence to the exercise regimen. Data were successfully collected from all participants with mechanical LBP, attributed to prolonged activities such as bike and car riding. The rehabilitation protocol spanned ten sessions delivered over 25 days. Participants engaged with the developed module. Careful analysis of the results revealed a noticeable improvement in patient performance across 10 sessions, indicating the module's positive effect.

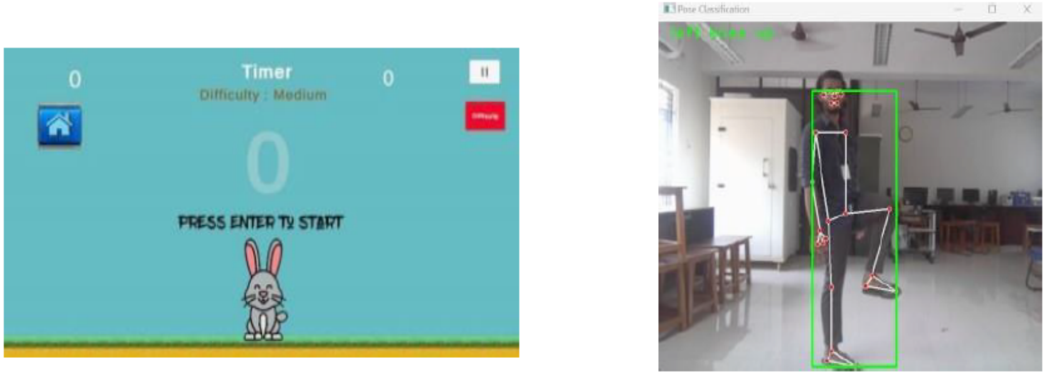


Figure 9. User testing of the road rush game

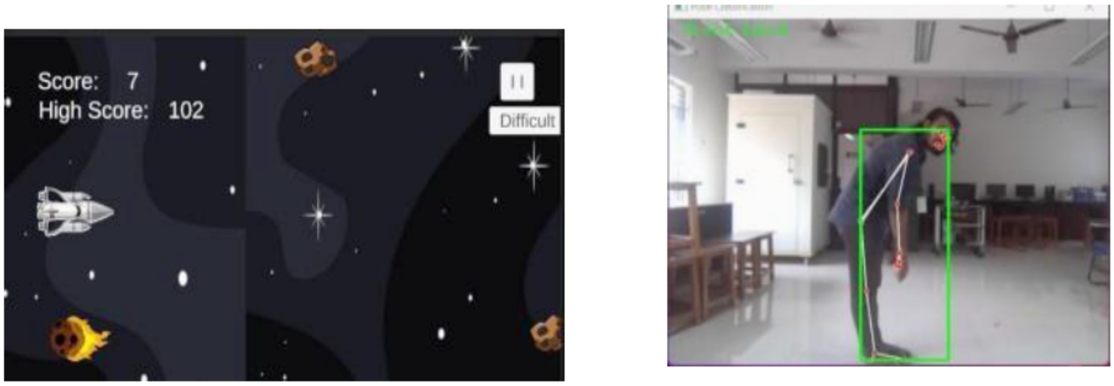
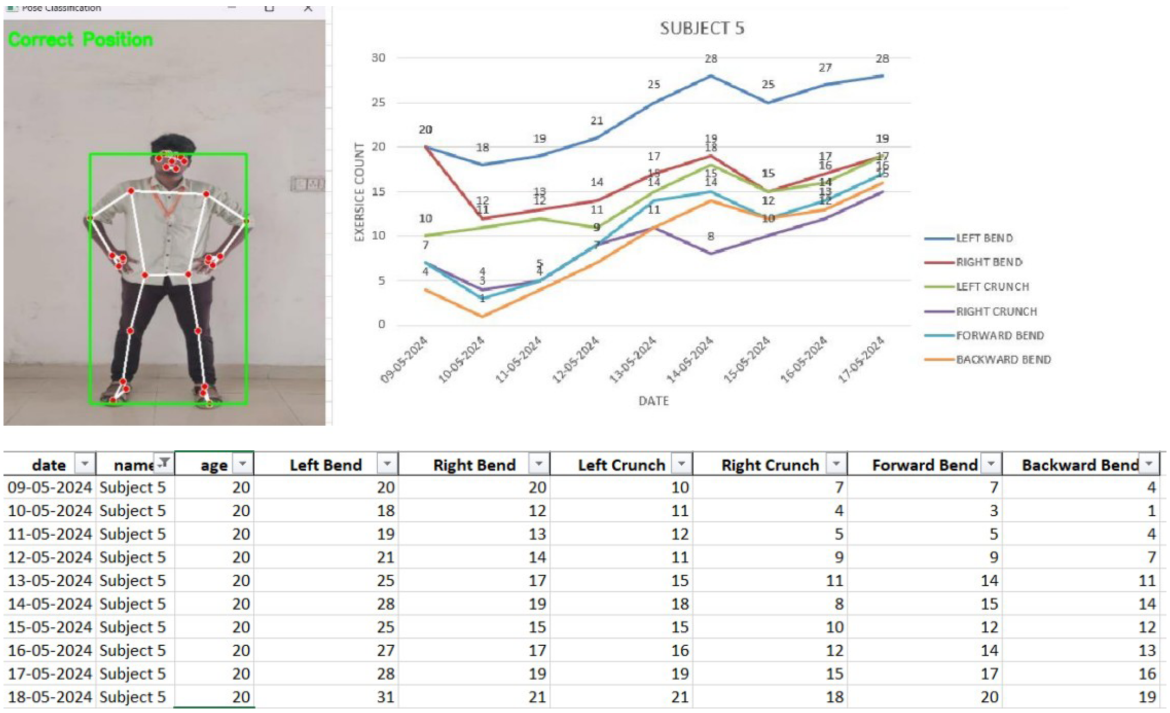


Figure 10. User testing of the space run game

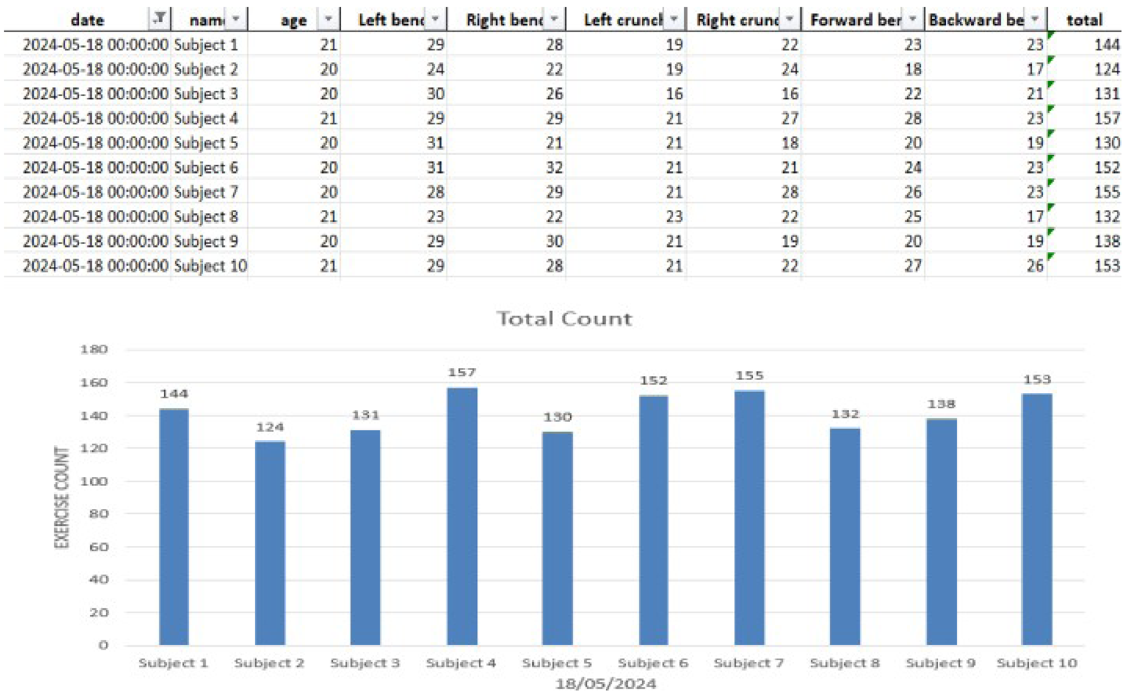
Consistent improvement in the scores of the physical exercise measurements was observed for most subjects. The scores obtained in the sequential days increased in the exercises. For example, in subject 1, the “left bend” it increased from 16-29, “right bend” from 12-28, “left crunch” from 10-19, “right crunch” from 9 -22, “forward bend” from 7-23, and “backward bend” from 6 -23 as depicted in. Figure 11 records “subject 5’s” physical exercise measurements, showing a general improvement in repetitions over the 10 days. The “left bend” increased from 20 to 31 repetitions, with the most significant gain in “forward bend,” which rose from 7 to 20 repetitions. These increases in scores indicate enhanced flexibility, core strength, and endurance. The data showed steady daily progress, with the highest measurements occurring on the final day, highlighting effective and progressive training.

To evaluate each subject’s progress in the rehabilitation module, exercise repetition counts were recorded each day during the 25-day intervention. The total counts for each subject were summed for days 1 and 10, and the improvement in counts over this period for 10 subjects is presented in Figure 12. Throughout the rehabilitation program, each subject’s exercise repetition count was



date	name	age	Left Bend	Right Bend	Left Crunch	Right Crunch	Forward Bend	Backward Bend
09-05-2024	Subject 5	20	20	20	10	7	7	4
10-05-2024	Subject 5	20	18	12	11	4	3	1
11-05-2024	Subject 5	20	19	13	12	5	5	4
12-05-2024	Subject 5	20	21	14	11	9	9	7
13-05-2024	Subject 5	20	25	17	15	11	14	11
14-05-2024	Subject 5	20	28	19	18	8	15	14
15-05-2024	Subject 5	20	25	15	15	10	12	12
16-05-2024	Subject 5	20	27	17	16	12	14	13
17-05-2024	Subject 5	20	28	19	19	15	17	16
18-05-2024	Subject 5	20	31	21	21	18	20	19

Figure 11. Readings acquired from subject 5



date	nam	age	Left ben	Right ben	Left crunc	Right crun	Forward be	Backward be	total
2024-05-18 00:00:00	Subject 1	21	29	28	19	22	23	23	144
2024-05-18 00:00:00	Subject 2	20	24	22	19	24	18	17	124
2024-05-18 00:00:00	Subject 3	20	30	26	16	16	22	21	131
2024-05-18 00:00:00	Subject 4	21	29	29	21	27	28	23	157
2024-05-18 00:00:00	Subject 5	20	31	21	21	18	20	19	130
2024-05-18 00:00:00	Subject 6	20	31	32	21	21	24	23	152
2024-05-18 00:00:00	Subject 7	20	28	29	21	28	26	23	155
2024-05-18 00:00:00	Subject 8	21	23	22	23	22	25	17	132
2024-05-18 00:00:00	Subject 9	20	29	30	21	19	20	19	138
2024-05-18 00:00:00	Subject 10	21	29	28	21	22	27	26	153

Figure 12. Day 10 overall repetitions of 10 subjects

carefully recorded to assess their progress. The results revealed significant improvements in exercise performance from day 1 to day 25. For example, subject 10 increased their exercise count from 55 on day 1 to 153 on day 10 and 213 on day 25, demonstrating substantial progress in their rehabilitation journey. This improvement underscores the effectiveness of the rehabilitation module in enhancing exercise engagement and adherence among participants. Overall, the recorded data highlighted the program's positive impact, supporting its potential to contribute to the management and treatment of back pain through personalized exercise regimens. This study introduces a novel approach to back pain rehabilitation by combining pose detection technology with interactive gaming experiences in Unity. Utilizing real-time pose tracking, it provides personalized exercise routines focused on improving flexibility, strength, and posture, ultimately supporting spinal health and relieving back pain. By incorporating gamification into rehabilitation exercises, the framework increases user engagement and adherence to treatment plans, resulting in better long-term outcomes. The module's performance was evaluated using a structured scoring system [32], in which subjects rated each question on a scale of 0 (minimum) to 4 (maximum) (Figure 7). Data collected on the final trial day indicated universal satisfaction, with all volunteers assigning the maximum score of 4 points across the entire questionnaire. The tabulated day 3 results (Tables 1 and 2) highlight an initial minimum score for question 6, which pertained to pain during the gaming exercise. Importantly, this feedback improved as the practice continued. These questionnaires are crucial for gathering direct patient feedback on usability, engagement, and efficacy, enabling the refinement of the pose-detection-based rehabilitation games to optimize user experience, comfort, and motivation.

Discussion

This study introduces a novel approach to back pain rehabilitation by combining pose detection technology with interactive gaming experiences in Unity. Utilizing real-time pose tracking, it provides personalized exercise routines focused on improving flexibility, strength, and posture, ultimately supporting spinal health and relieving back pain. By incorporating gamification into rehabilitation exercises, the framework increases user engagement and adherence to treatment plans, resulting in better long-term outcomes.

The use of pose detection in combination with gaming not only boosts user involvement but also enhances the system's scalability and accessibility, making it adaptable for individuals with varying mobility and rehabilitation requirements. By encouraging active participation in the recovery process, the framework offers a flexible, dynamic solution to the complex challenges of back pain rehabilitation.

Table 1. Questionnaire feedback

Questions	Sub 1	Sub 2	Sub 3	Sub 4	Sub 5	Sub 6	Sub 7	Sub 8	Sub 9	Sub 10	Average
1	3	3	4	3	4	3	4	4	4	3	3.5
2	3	3	4	4	4	3	3	3	4	3	3.4
3	2	4	4	4	3	4	4	4	4	2	3.5
4	3	3	3	3	4	4	3	3	3	3	3.4
5	3	4	4	3	3	3	0	3	0	2	3.1
6	2	0	0	0	0	1	3	0	4	2	0.5
7	3	4	4	4	4	3	3	3	4	3	3.6
8	2	4	4	4	4	4	4	4	4	4	3.8

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Table 2. Game experience questionnaires (GEQ): core module component scoring

GEQ Scores: Core Module	
Component	**Value**
Competence	3.5
Flow	3.25
Tension/Annoyance	0.5
Challenge	3.6
Positive effect	3.8

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Moreover, the project's innovative approach holds great potential as a versatile platform for future research and development in this field. With continued refinement and validation, this framework could have a significant positive impact on the lives of those affected by back pain, enhancing their overall well-being and QoL.

These three Unity-based games utilize common, low-impact back-strengthening and flexibility exercises widely recommended by physiotherapists. The movements are foundational and can be safely performed by most adults with non-specific back pain, ensuring that the developed system is broadly accessible for home-based rehabilitation. To achieve a deeper understanding and better control of patient movement, the system could be upgraded by adding wearable motion sensors. These devices would capture highly precise, three-dimensional kinematic data, enabling more detailed analysis of a user's range of motion, movement quality, and posture. Ultimately, this leads to a more sophisticated and personalized therapeutic feedback loop embedded in the game mechanics. However, the interpretation of the current findings requires careful consideration, as the study's preliminary nature means the cohort size (n=21) and the 25-day intervention period may constrain the generalizability and long-term sustainability of the observed effects. Furthermore, while the pose classification system provides reliable feedback, its reliance on predetermined, fixed thresholds suggests an opportunity for enhancement, as this approach may not fully accommodate the subtle, personalized movement variability inherent to patients with chronic pain. Moving forward, the research focus will shift to a larger, multi-site randomized controlled trial comparing the module against established standard care. Concurrently, an advanced, adaptive tracking system that utilizes user-calibrated thresholds can be developed to tailor rehabilitation feedback precisely to each individual's unique biomechanics and progression.

Conclusion

By gamifying rehabilitation exercises, user engagement and adherence to treatment protocols are enhanced, thereby improving long-term outcomes. The proposed framework not only enhances user engagement but also promotes scalability and accessibility, making it suitable for individuals with varying rehabilitation needs. This technology-driven solution offers a dynamic, adaptable approach to address the challenges of back pain, with the potential to significantly impact the QoL of affected individuals.

Ethical Considerations

Compliance with ethical guidelines

The research is conducted using noninvasive, recording of movement patterns while performing the exercise. Since the study design involved no interaction, intervention, or contact with individuals, and all data was captured, stored, and analyzed in an entirely with the knowledge of the volunteers, the study can be exempted from full ethical review, proper consent was collected from the participants

Funding

This research did not receive any grant from funding agencies in the public, commercial, or non-profit sectors.

Authors' contributions

Conceptualization: Thandavamurthy Jayasree; Methodology and experiments: Palchamy Pragathi, Saravanan Premkumar, and Senthilkumar Revathi Sree Krishna; Writing: All authors.

Conflict of interest

The authors declared no conflict of interest.

Acknowledgments

The authors extend their sincere appreciation to Rebalance Physiotherapy and Rehabilitation Centre. During their visit, they had the privilege of engaging with a renowned physiotherapist and a dedicated team of junior practitioners. They took the time to carefully listen to our presentation, which detailed the project's objectives, methodologies, and technical complexities. They are incredibly grateful for their insightful observations and constructive feedback, which played a crucial role in refining and enhancing the effectiveness of our rehabilitation module. Their expertise and recommendations were invaluable in advancing the project's impact.

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