AN INTELLIGENT REMOTE EXERGAME SYSTEM FOR KNEE OSTEOARTHRITIS REHABILITATION TRAINING

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ABSTRACT

Exercise therapy is a specialized and long-term process, and home exercise is an essential approach to treating knee osteoarthritis (KOA). We propose an intelligent remote exercise game system to assist the patients with correct and effective rehabilitation training. This system includes the knee assessment, the Kinect-based exergame, the system server, and the Web program. The physical therapist gives the patient an exercise prescription that specifies the patient's exercise tasks at home through the knee assessment. The exercise tasks are transformed into game tasks through the exergame, and the patient is guided to perform the exercise tasks correctly. The Kinect is used to obtain real-time joint position data of the KOA patient and calculate the joint movement angle to determine whether the patient has completed the exercise movements required by the exercise task. Exercise data is recorded for the patient's exercise and transferred to the system server for the physical therapist to view. The physical therapist reviews the patient's exercise data by the Web program, then evaluates the exercise and provides feedback to adjust the exercise prescription. The system allows the KOA patient to perform the rehabilitation exercises at home enjoyable and allows the physical therapist to achieve remote process evaluation and rehabilitation guidance. This approach can improve the effectiveness of KOA rehabilitation training and reduce the burden of traditional hospital follow-up visits.

Keywords: *Exercise therapy, home exercise, knee osteoarthritis, kinect, exercise game, process evaluation.*

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Introduction

Exercise therapy is an important intervention in knee osteoarthritis rehabilitation and health care(1). All major international guidelines recommend Exercise therapy for KOA management, and its effectiveness has been verified(2-4). An appropriate exercise can improve the patients' knee muscle strength, reduce pain and improve knee function. However, exercise therapy is a long-term rehabilitation process. Most KOA patients cannot afford the burden of prolonged in-hospital rehabilitation instruction from a physical therapist. Then KOA rehabilitation is mainly based on home exercise. The patients with KOA have differences in the type and intensity of exercise due to the degree of disease and exercise progress, and therefore exercise therapy requires proper process guidance(5-6). However, the home exercise does not achieve better therapeutic effects for the patients due to the lack of accurate rehabilitation exercise guidance and process interventions and low adherence. Exergame programmed the exercise movements into the game, allowing the patients to complete the exercise in an enjoyable game and increasing their active training willingness.

Many studies have proved that the gamification approach can increase the patients' motivation and improve their execution(7-9). Note that ordinary Exergame cannot obtain information about the patient's joint motion, which is a necessary part of the joint disease rehabilitation for better exercise feedback and guidance. Therefore Kinect-based Exergame is an excellent solution to this problem(10-11). Shih Y H et al. designed a flight game to help the patients exercise their neck and shoulder muscles. Using the Kinect, they acquire human neck and shoulder joint position information and transform it into control commands for a flight simulation game(12).

Chen M et al. designed an augmented reality game system to obtain the patients' movement information through Kinect. Then, they use the information to control games and movement assessment to promote the exercise of lower limb muscles and reduce the risk of falls in the elderly(13). Su C H et al. designed a 3D game-based rehabilitation system for the total knee replacement rehabilitation patients, which proved that the exercise motivation and system feasibility could significantly improve the effectiveness of rehabilitation training(14).

We developed a Kinect-based Exergame for KOA rehabilitation training. The system allows the KOA patients to be guided and supervised remotely for rehabilitation exercises. The physical therapist only needs to assess the patients' rehabilitation progress and formulate an exercise program by viewing the patients' remote exercise data. The system could guide the KOA patients to perform scientific rehabilitation training accurately, improve the patients' compliance, reduce the burden of the traditional hospitals follow-up visits, etc.

Problems and countermeasures of knee rehabilitation therapy

Although the effectiveness of knee KOA exercise therapy has been proven, it is still difficult for most KOA patients to receive effective exercise therapy guidance.

The current problems in the application of KOA exercise therapy and the countermeasures of this system were analyzed as follows.

Exercise prescription could promote the safety and effectiveness of KOA exercise therapy

The knee is one of the most complex joint structures in the human body and has a variety of diseases.

The KOA patients often have meniscal tears and ligament damage(15). Different disease states and degrees have significant differences in the type and intensity of exercise. Proper exercise can promote functional recovery, while improper training can easily cause more damage(16). Therefore, an individualized exercise program based on the patient information is needed to guide the patients to exercise correctly.

Exercise prescription is an exercise program formulated by physical therapists based on a joint assessment that involves the exercise's type, frequency, duration, and intensity(17). The knee assessment includes the diagnosis of knee disease, physical examination, and functional testing. Disease diagnosis and physical examination determine the type and extent of the patients' disease and whether other complications accompany it. Functional testing further assesses information about the patient's muscle strength and endurance.

The physical therapist formulates exercise prescriptions based on the patients' knee assessment information in conjunction with exercise rehabilitation guidelines to ensure the safety and effectiveness of exercise therapy(18-19).

Kinect could facilitate the accuracy of KOA exercise prescription execution

Rehabilitation training often requires physician guidance and demonstration.

The patients can perform simple movements and programs on their own.

Complex exercises, especially rehabilitation training movements with specific angles and time requirements, are challenging for the patients to grasp independently.

It is difficult for the KOA patients to exercise at home independently and receive accurate exercise instructions. Kinect can evaluate the patients' primary human joint position data in real-time through 3D depth images(20). The angles of the hip and knee joints can be calculated and obtained, and it can determine whether the patients meet or exceed the angular requirements of the movement.

At the same time, the Angle judgment can guide the patients to adjust the Angle of action to ensure the accuracy of the exercise prescription.

Kinect-based Exergame can facilitate the process assessment of KOA treatment

Process assessment is the focus and difficulty of exercise therapy. Exercise therapy is generally a long-term and gradual process, and the exercise program will be adjusted according to the progress of exercise, so the exercise process needs to be evaluated in time[21]. Exercise rehabilitation for the KOA patients is typically 8-12 weeks and requires long-term execution[22]. It is difficult for the physicians to know in time whether there is inaccurate exercise movement or uncomfortable feeling in the process of home-based self-rehabilitation training, and they cannot adjust in time, which will cause adverse effects. Therefore, process assessment of exercise in the KOA patients is also an essential part of rehabilitation training.

The Kinect-based Exergame system can obtain exercise data from the user's workout and provide timely feedback to the physical therapists on the exercise data through Internet technology. The physiotherapists can view the exercise prescription execution on time and realize the process assessment of exercise prescription. The exercise data includes the accurate execution rate of movement execution, the curve of joint angle change, and subjective feelings such as pain and fatigue after exercise. The physical therapists can use the exercise data to evaluate the patients' execution process and make prescription adjustments to feedback to the user of the Exergame system.

Exergame

For many patients, exercise is boring or even distasteful, and the patients cannot keep exercising for long without supervision. One study showed that only 31% of rehabilitated individuals performed the exercise routine recommended by their therapists[23]. The patients have difficulty in adhering to the exercise routine as requested by their physicians due to forgetfulness and lack of interest in repetitive movements, thus failing to achieve the effects of exercise therapy. Therefore, improving the patients' compliance with rehabilitation training is important.

Exergame is a game format to enhance the enjoyment of the patients' rehabilitation training and improve compliance[24]. Targeted user-centered game design is carried out for the elderly population, meeting users' needs and motivating them to complete their exercise. The system sets up message reminders to monitor the patients' exercise prescriptions to avoid forgetting to exercise. At the same time, the patients are supervised to perform the exercise on time through remote viewing and feedback by the physical therapists. The patient's exercise prescription is guaranteed to be executed consistently through these measures.

Materials and methods

Hydrothermal method

By analyzing the problems of KOA exercise therapy and the corresponding strategies, this paper designs Kinect-based Exergame to assist the KOA patients' rehabilitation training. The Kinect-based Exergame system consists of three parts: the Exergame at the home end, the hospital server, and the Web program at the physical therapist's end, respectively. The home end is mainly the Exergame executive part, which is composed of a Kinect device and a computer. The Kinect device, used for optical skeletal tracking; a computer with Windows 10, used to run the Exergame system.

The hospital server, a secure server dedicated to the hospital, is used to receive, store and manage the patients' exercise data. The physical therapist uses Web programs to index, view, and analyze the patient's exercise data. The remote exergame system architecture is shown in Figure 1.

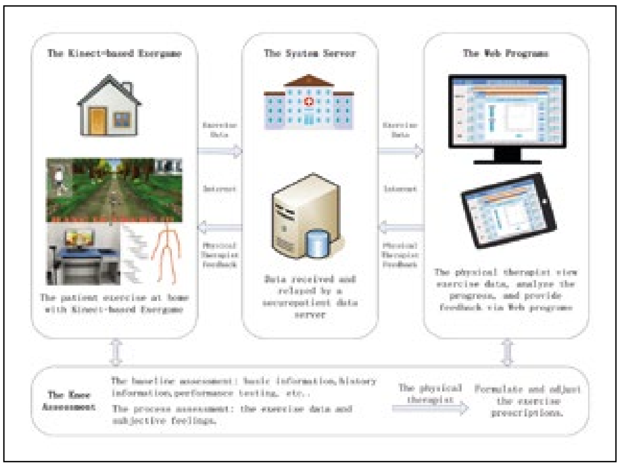

Figure 1: Remote exergame system architecture.

Since the KOA patient population are predominantly elderly, convenience and ease of use are essential features of the system[25]. The Kinect-based Exergame remote system operates completely autonomously in the home environment. The patients do not need to wear any sensors and train only within the appropriate field of view of the Kinect, performing the exercises set by the exercise prescription under the guidance of Exergame. During the workout, the system automatically measures and records the active flexion angles of the knee and hip joints, connecting to a secure hospital-based server by the Internet. The physical therapists can view and provide feedback from any computer with access to the hospital's intranet using a Web-based program. The clinicians can assess the progress or fade of the patients' rehabilitation and adjust the exercise program based on the patients' outcome feedback to ensure the safety and effectiveness of the patients' exercise. The KOA patients perform a knee assessment through the system's assessment module. The physical therapist then develops an exercise prescription based on the knee assessment, generates a personalized Exergame, and guides the patients through the rehabilitation process while providing feedback on the exercise data at the same time.

The physiotherapists analyze the patients' progress based on the exercise data and adjust the exercise program. We describe the knee assessment module, the Exergame module, and the Web program module, respectively.

The Knee assessment module

There are differences in exercise prescriptions depending on the status of the KOA patients. Due to the lack of other assessments during the face-to-face interview, the remote system makes it even more important to accurately assess the knee status of the KOA patients to develop an exercise prescription. In this system, the knee assessment involves the baseline and process assessments.

The baseline assessment refers to assessing the functional status of the patient's knee joint before using the system. Since this system is based on the physical therapist developing the patient's exercise prescription, the patient's baseline assessment is critical for the knee exercise prescription and the comparison of treatment outcomes. The baseline assessment includes basic information about the KOA patients, knee history information, subjective symptoms, performance testing, and pre-training movement assessment. Table 1 shows the Knee evaluation information.

Process assessment refers to the evaluation of the KOA patients during the exergame process, which mainly includes recording exercise data and subjective feelings. Exercise data consists of the execution accuracy rate of each training movement and joint angle data. Subjective perception refers to the subjective feelings after rating the rehabilitation training task of the day, mainly including pain and fatigue, both of which were recorded using VAS (visual analog scale). Based on the process assessment, the physical therapists can keep track of the patients' execution of the exercise prescriptions.

Type	Content
Basic information	Age, Gender, Body mass index (BMI), Co-morbidities, Labour intensity, Exercise intensity
Diagnosis information	Diagnostic information, hospital examination information (MRI, X-ray, etc.), treatment information
Subjective symptoms	Pain limb, Pain site, Pain degree, Locking, Instability, Knee misalignment, Patella misalignment, History of knee trauma, Other typical symptoms
Physical examination (PE)	Lachman's, Posterior Sag, Varus at 30°, Valgus at 0/30°, McMurray's, Apley's (distraction and compression), Waldron Sign, Grind Test, Vastus Medialis Oblique Test
Performance tests	The timed 20-m (m) walk test, The 6-min walk test, The chair-stand test, The Berg Balance Scale
Pre-training auction evaluation	Stepping, Straight leg raises forward or backward, Leg raises and knee bend, Squat, Up and downstairs

Table 1: The Knee evaluation information.

The Kinect-based exergame

Exercise prescriptions are formulated by physical therapists who are familiar with exercise prescriptions. The exercise components of the prescription, including the type and dosage of exercise, are based on clinical guidelines and the choices made by a panel of orthopedic surgeons, rheumatologists, and physical therapists.

Based on the exercise prescription's type and intensity of exercise, we designed the Kinect-based Exergame to guide the patients through rehabilitation training. This system is based on more than two years of user-centered design and testing to finalize the best game mode. We designed a wilderness adventure game with corresponding game levels for each exercise type and created the exercise intensity as the related game parameters, as shown in Table 2.

The system uses the skeleton tracking function of Azure Kinect to track the user's action in real-time for cognitive and rehabilitation training. Azure Kinect is a new generation of depth sensors released by Microsoft in 2019(26). Azure Kinect can obtain 32-joint of the human, and the acquisition accuracy is higher than Kinect 2.0 (25-joint) and Kinect 1.0 (20-joint)(27). When the user appears in Kinect's field of vision, Kinect can quickly detect the human body and track its bones in real-time, obtain the position information of the user's hip, knee, and ankle joints, and then calculate the joint angles for action recognition. Therefore, users can interact with the computer through various gestures and postures without wearing a sensor. Kinect simplifies the interaction and allows more natural mapping, making it easier for older people who lack gaming experience to enter the game. The Azure Kinect sensor deployment and skeleton tracking structure are shown in Figure 2.

Exercise	Exergame level Description
T-Pose	The user stands in the designated Kinect field of view area to ensure that the Kinect can fully obtain the user's whole-body joints, and according to the screen prompts, poses a T-Pose motion to execute system data calibration. Successful action recognition indicates the start of the game. Each group of training can leave the position to rest, so each group of exercise needs to be recalibrated.
Warm-up Exercise	Kinect obtains the user's joint data in real-time to drive the game character (virtual person) to execute an action display. Follow the instructions to complete the warm-up.
Stepping	The user's stepping action drives the game character to step in real-time and calculates the user's stepping frequency to give the game character a moving speed to walk or run forward.
Straight leg raises forward or backward	Design the monster corresponding to the straight leg raising action, and defeat the monster by recognizing the action to generate an attacking object. The number of attack objects that defeat the monster matches the number of training sessions in each group, and the number of monsters corresponds to the number of action training groups. Within a specified time, the monster attacks the protagonist at a set frequency. It also requires the user to complete each set of exercise training within the specified time.
Leg raises and knee bend	Rock instructs users to Leg raises and knee bend through. In a specified time, given the initial speed and set the appearance frequency of the rock, the user is also required to complete each set of exercise training within the specified time.
Squat	The fallen tree guides the user to squat through, and the height of the fall guides the user to complete the squatting action. In a specified time, given the initial speed and set the appearance frequency of the big tree, the user is also required to complete each set of exercise training within the specified time.
Up and downstairs	Set traps (puddles, etc.) in the path to instruct users to move up and down the steps, and by recognizing the actions of going up and down steps, it means crossing the traps (puddles, etc.). The number of traps matches the number of training sessions for each group, and the number of consecutive trap groups corresponds to the number of action training groups.

Table 1: Exergame levels based on exercise prescription.

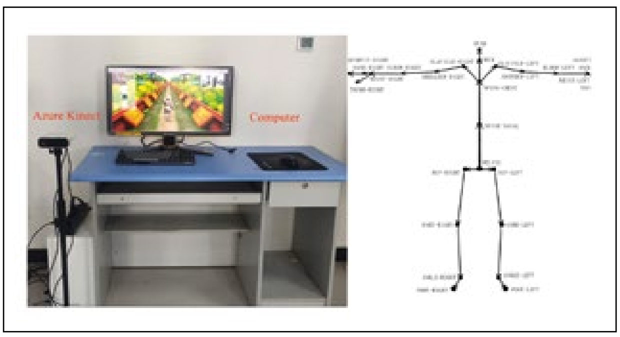

Figure 2: The azure kinect sensor deployment and skeleton tracking structure.

For each movement, the system calculates the angles of hip and knee joints by acquiring joint data in real-time, as shown in Figure 3.

Then, for each action, the joint angle threshold discrimination method determines whether the patients complete the action or not[28]. The result of movement recognition controls the gameplay and serves as a record of movement completion. Some of the running effects of the Kinect-based Exergame exercise performed by the KOA patients are shown in Figure 4. The usability test of the exercise game module of the system has been completed, the accuracy of joint data acquisition is high, and the user experience is satisfactory[29-30].

The final prototype version of the KOA Exergame system has been tested and initially implemented.

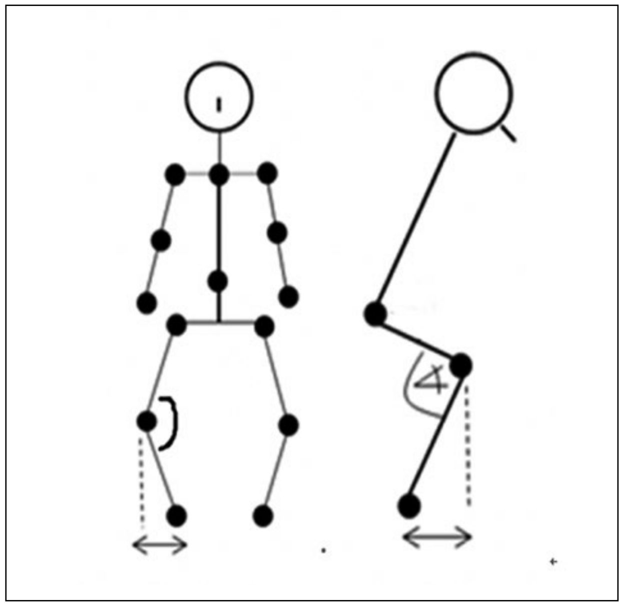

Figure 3: Schematic diagram of knee angle calculation.

Figure 4: The running effects of the Kinect-based exergame.

The system server and the web programs

The system server can securely receive and store exercise data at the hospital site. Because it is Internet-based, clinicians can access the system data from their computer or tablet from any location via the physical therapist Web program. Physical therapists supervise and evaluate the patient workouts based on the patient workout data presented in the Web program. The system server is used to receive, store and manage the user's exercise data. The exercise data recorded by the patient-side Exergame system is transmitted to the system server via the Internet.

The system server is placed in the hospital, and access rights are set to secure the data. Physiotherapists are authorized to access the patient data from a computer or smartphone connected to the hospital's internal network.

The physical therapist views the patients' exercise data and subjective feelings through the Web program and analyzes and adjusts the exercise program. The feedback exercise prescription parameters will be fed back to the patients' home end via the Internet to update the Exergame parameters.

The main functions of the Web program on the physiotherapist side are as follows:

• The main screen of the physical therapist web program lists the name and basic information of each patient. This interface includes both adding new patients and deleting the patient information. The patient's status, such as emergency status, is highlighted by color and flashing markers. The main screen of the physical therapist web program is shown in Figure 5.

Figure 5: The main screen of the physical therapist web program.

• The main interface of each patient display shows the patient information. Click any patient button on the main interface to enter the main patient interface. The patient interface includes basic patient information, the patient exercise prescription information, and the patient exercise data. The main interface of each patient is shown in Figure 6.

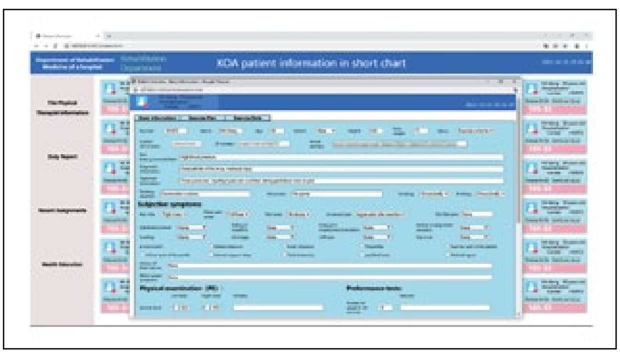

Figure 6: The basic information of each patient.

• The patient exercise data. The patient's daily Exergame execution is displayed in the form of a daily list, recording the correct execution rate and joint angle curve of each movement. The physical therapist can analyze the patient exercise data and view the patient's subjective feelings and messages. The patient exercise data is shown in Figure 7.

Figure 7: The patient exercise data.

A visual map of the patient's joint angle of exercise movements can also be displayed. A visual map of the patient's joint angle is shown in Figure 8.

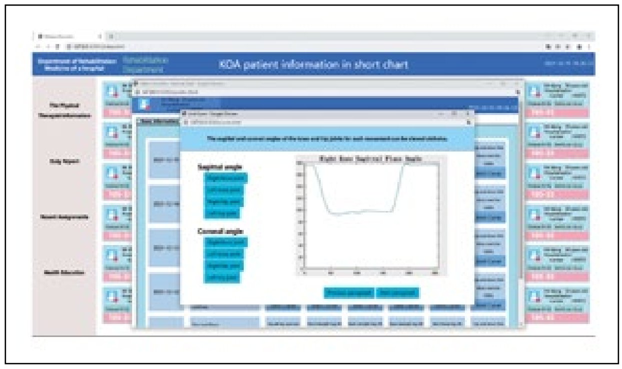

Figure 8: A visual map of the patient's joint angle.

• The feedback adjustment of the physical therapist. According to the patient's exercise data, the exercise prescription can be improved, and by publishing it, it can be fed back to the user side, and Exergame will adjust accordingly according to the exercise prescription to better promote the user's exercise.

Conclusion

This paper introduces a Kinect-Based Exergame system to guide KOA patients to perform the correct rehabilitation training. The system enables physical therapists to remotely view patients' exercise data, analyze and adjust patients' Exergame, and realize the process evaluation of patients' rehabilitation training, which ensures the safety and effectiveness of patients' rehabilitation training. At the same time, it enhances the fun of patients during rehabilitation training through the form of games and improves patients' exercise compliance.

The usability test of the exercise game module of the system has been completed, the accuracy of joint data acquisition is high, and the user experience is satisfactory. The final prototype version of the KOA Exergame system has been tested and initially implemented. However, the system is complex, and system application and trials require the cooperation of multiple parties, including KOA patients, hospitals, and physical therapists. There are many challenges to clinical trials and exercise validation, such as patient recruitment and support in the home environment and interference of non-exercise fac-tors on exercise effectiveness. We will recruit suitable patients who can meet the time requirements for long-term exercise in the future. We can set up an exercise game system in the community to facilitate more patients to perform the exercise, compensate for the lack of home conditions, and improve the convenience of patients' participation in training.

In conclusion, this system provides an excellent remote assistance system for joint rehabilitation training and provides an example for other joint rehabilitation and fitness exercises.

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