Intelligent Frozen Shoulder Rehabilitation

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Frozen shoulder is a common condition characterized by painful and limited range of motion. Using interactive technologies can help patients complete the exercises crucial to their rehabilitation.

Frozen shoulder, or *adhesive capsulitis*, is a condition caused by impaired soft tissues and the articular capsule of the shoulder. It commonly occurs in people aged 40 to 65 years, and it's more likely to appear in females than in males.[1] Frozen shoulder is characterized by painful and limited active and passive range of motion. The main treatment involves proper shoulder exercises and joint mobilization to break up adhesions at the joint capsules and improve joint mobility and functions. However, due to a lack of persistence, not all patients complete rehabilitation.

To address this, we created a virtual reality game-based treatment system that encourages patients to participate in regular rehabilitation. Using our system, patients can inquire freely about their rehabilitation progress through real-time sensing and game-based feedback. Six progressive and hierarchical training tasks make each training step adjustable based on the patient's physical condition. To test our system, we used randomized clinical trial criterion to recruit 40 patients for a sequence of trials over a four-week period. Here, we describe our system and the study, as well as our results, which show that patient shoulder joint mobility and muscle strength significantly improved for those using our system compared to those using the traditional rehabilitation method.

Frozen Shoulder Disease

Frozen shoulder severity is categorized in four stages: preadhesive, adhesive,

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maturation, and chronic. At the preadhesive stage (0–3 months), a fibrinous synovial inflammatory reaction is detectable only by using arthroscopy. Patients typically present with signs and symptoms of impingement syndrome, in which the primary patient complaint is a limited range of motion (ROM) and the secondary complaint is pain. In clinical practice, these two common complaints occur and change depending on the disease's course.[2]

At the adhesive stage (4–9 months), acute synovial inflammation is apparent on physical evaluation. Arthroscopic findings demonstrate that the normal spacing between the capsular fold, humeral head, and biceps tendon, glenoid, and humeral head diminish significantly. The patient experiences severe pain and loss of motion.

Patients at the maturation (10–15 months) and chronic (16–24 months) stages require treatment for frozen shoulder. Both stages are identified according to the maturation of the inflammatory process. The dependent fold is only half of its original size, and adherence occurs between various structures. Eventually, capsular adhesions become fully mature and markedly restricted; thus, the shoulder is clinically frozen.[3] For diagnosing frozen shoulder in clinics, doctors examine the ROM limitation of flexion, abduction, external flexion, and internal flexion to determine whether any ROM is less than those in healthy persons (that is, flexion: 155.8 degrees; abduction, 167.6 degrees; external flexion, 48.7 degrees; and internal flexion, 83.6 degrees).[4]

Treatment Strategies

Frozen shoulder is typically accompanied by a limited range of shoulder motion and pain. Therefore, the treatment strategy must include multiple, sequential goals to restore the ROM in the shoulder, alleviate pain, enhance muscle strength, and regain functionality.[5] Panadol and antiphlogistic medicine or a steroid injection can alleviate pain; however, the effect is limited in patients with severe frozen shoulder. Surgery might be necessary for such patients, but both the medicine and surgery treatments require continued physical shoulder rehabilitation to retain original functionality.

Common rehabilitation exercises that include shoulder joint stretching and rotating exercises—such as Codman's exercise, pulley therapy, finger-crawling exercises, and joint mobilization—should be applied to stretch the adhesive capsulitis to restore the shoulder joint's original mobility. Our primary goal in this study was to restore shoulder ROM in patients through a game-based training system.

Game-Based Treatment

Studies have reported that when rehabilitation exercises are modified to include interactive and entertaining games, patients pay attention to the games and ignore the tedious training repetitions and pain during rehabilitative exercises.[6,7] By interacting with virtual reality (VR) game exercises, patients can complete standard rehabilitation tasks naturally.[8]

To create an interactive and effective rehabilitation environment for frozen shoulder patients, we include four common rehabilitative exercises: flexion, abduction, internal rotation, and external rotation.[9] The design of our proposed VR game-based treatment incorporates these crucial exercises with muscle-strength enhancement practices into three game types: forearm extension training, shoulder-elbow interconnection training, and shoulder joint rotation training. Each VR task targets a main action, despite requiring composite actions. The level and number of main actions are higher than those of other minor actions. We matched the design with daily routine activities, which are generally composite actions.

In this study, we focused on providing interactive treatments to encourage patient participation in rehabilitation and to provide a quantifiable monitoring and guiding system for assisting physical therapists in tracking, designing, and adjusting training materials. The objective of our research was to combine VR technology with wireless sensor technology to develop assessment instruments for self-measurement of shoulder joint mobility using a situated frozen shoulder rehabilitation system. The proposed real-time interaction and feedback design accurately depicts the progress made by individual patients in real-time; thus, patients can inquire freely about their rehabilitation progress to understand their goals.[10]

System Design

The system architecture comprises a VR game-based training task, real-time sensor system, and assisted daily objects. Patients are required to complete standard training tasks—flexion, abduction, external rotation, and internal rotation—by interacting with designed VR rehabilitative training games.

As Figure 1 shows, we designed six VR training tasks and categorized them into three major exercises: forearm extension, shoulder-elbow coordination, and joint rotation. Using vision and inertial sensors, the sensor system (Figure 2) collects patient ROM data during the game tasks. Collected data are stored in a cloud repository for further analysis.

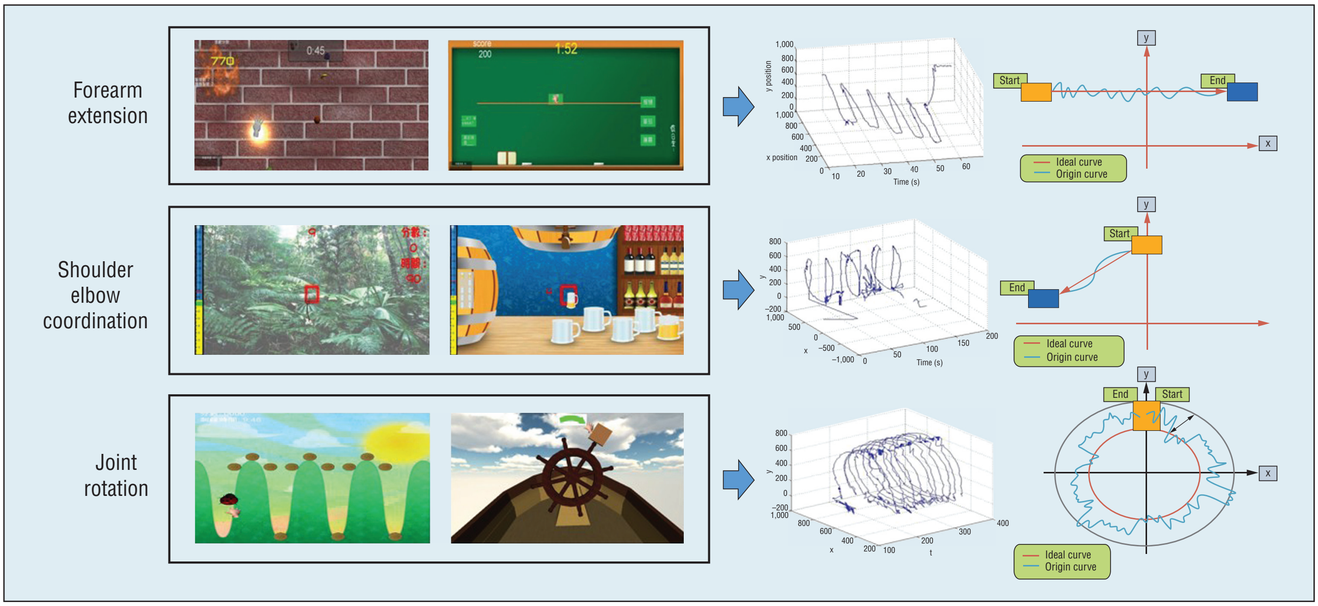

Figure 1. Six virtual reality training tasks grouped based on rehabilitation targets. User motions are recorded as trajectories, projected onto a 2D plane, and compared with the ideal path of the corresponding training task's ideal path. The yellow box indicates motion start, and the blue box indicates the endpoint, while the blue curve indicates the projected trajectories and the red curve shows the ideal path.

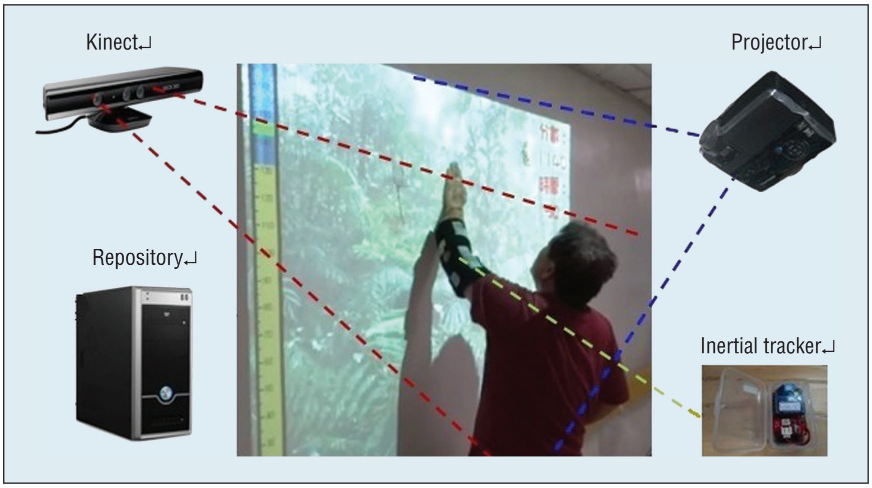

Figure 2. Overview of the system architecture. During game tasks, the sensor system collects a patient's range-of-motion (ROM) data, which are stored in a cloud repository for further analysis.

Physical therapists can use this system to track, design, and adjust training materials for individual patients. Moreover, they can adjust each training step based on a patient's physical condition. For instance, a simple adjustment involves selecting an appropriate game level based on the target patient's current shoulder flexion and abduction condition. To estimate flexion, a patient must face a wall and raise his or her hand to the maximum height on the wall. For estimating shoulder abduction, the patient performs the same movement, but stands on his or her side against the wall. The game level can be adjusted based on these initial measurements.

As we now describe, we designed three types of VR game-based training tasks that offer participants various types of feedback.

Forearm Extension

The forearm extension exercise comprises two tasks designed for training the patient's flexion and abduction ability.

The first task is called *tracing*. In it, patients must use the palm of their affected shoulder to link the targeted object on the screen's left side to the object on the right. The trajectory from the left to right might be horizontal and move upward from the left and downward to the right, or move downward from the left and upward to the right. The design lets patients with frozen shoulders stretch and extend their affected shoulder slowly.

In the second task, *reaching fruit*, patients must control a virtual palm using their affected shoulder to reach all fruits that appear continuously on the screen. This lets patients lift their shoulder as high as possible and stretch or extend it up and down as well as in the left and right directions.

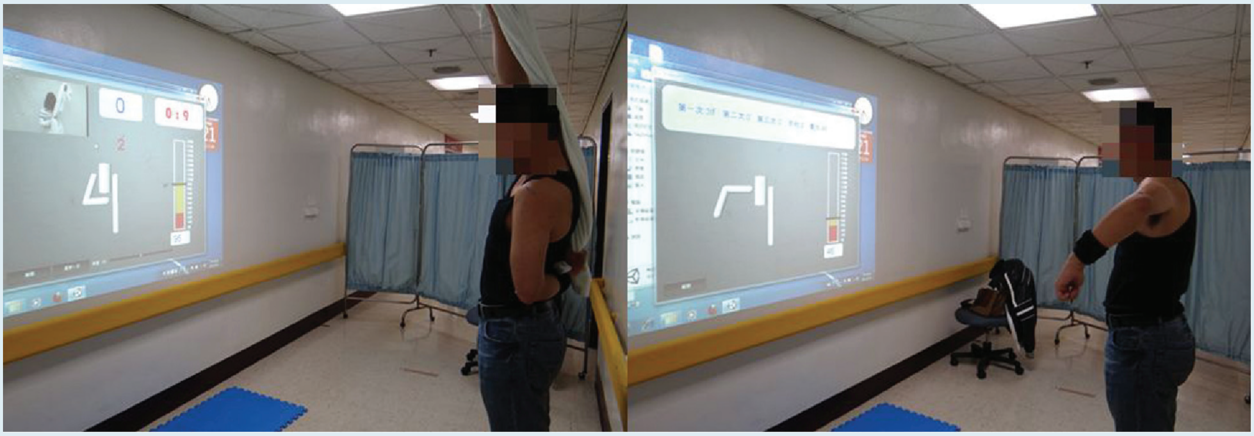

Figure 3. Video guidance and a virtual tutor are used in the treatment process. Quantified progress results motivate patients to improve.

Shoulder-Elbow Exercise

The shoulder-elbow exercise mode involves three game designs for enhancing a patient's flexion and abduction angles. When this game mode begins, patients lean their affected shoulder against a white wall, stretch it, and hold for 10 seconds.

Two of the three game tasks are related to Spiderman and Jungle Adventure. In these tasks, players move their palm to the targeted object; as they advance to a higher difficulty level, they must lift their hand higher to complete the task. The higher the difficulty level, the higher their potential score.

The third game is called the Barman. In it, players control a bartender's hand on the VR screen and must complete tasks such as taking a glass, filling it, and placing it on the bar. The task lets patients stretch their affected arm against the white wall for 10 seconds.

Shoulder Joint Internal/External Rotation

The shoulder joint internal/external rotation exercise mode comprises two games designed for stretching the shoulder. including internal rotation, external rotation, and circumduction.

The first task is called the *lady bug game*. In it, patients must straighten their elbow to trace the motion trail of a lady bug. The second task is called *ship driving*. Here, the patient must straighten their elbow and turn the rudder clockwise or counterclockwise for one full circle, as instructed.

Virtual Tutor

Real-time sensing technology allows patients to observe their performance in real time. Quantified progress results motivate patients to improve, helping them understand how much work they have accomplished and which goals remain (see Figure 3).

Research has shown that score feedback in VR can positively affect patient motivation and has a positive relationship with disease improvement,[11,12] because the patient is actively involved in the self-measurement process and can understand their body condition more clearly. In addition, the virtual tutor design lets patients quickly examine themselves to determine whether they're following the video guidance correctly.

Virtual tutor works as a mirror in front of users, showing quantified numbers and visualizing differences between the current progress and the desired goal. Video guidance and the virtual tutor provide patients with self-training capability. Daily life objects, such as a tower and a wall, assist patients in completing game tasks without human intervention. Patients learn to retain their body control through their own effort.

In Figure 2, for example, the VR game-based training task is projected on a wall and guides the patient to exploit a reacting counterforce from the wall to move his extremities. As this example shows, patients require no external assistance from therapists to stretch or rotate the joints of their extremities. Physical therapists need only demonstrate or video record the correct way to use common daily life objects, such as stretching out a tower to play the ship-driving game. Hence, a limited number of therapists can handle more patients than before.

Real-Time Interaction

We collected quantified skeletal data using the Microsoft Kinect sensor, and acceleration and orientation data using inertial sensors. By combining sensor data from Kinect and IMU, the sensor accuracy is ±2.2 degrees. The sensor accuracy in this study didn't affect the system evaluation results, because the patients' joint mobility was measured using standard protractors during pretest and post-test processes. In addition, we

Table 1. Demographics of study participants.

Demographic criteria	Study group	Control group
Case number	20	20
Average age	60.65 (±11.84)	61.45 (±12.84)
Male/Female	5/15	9/11
Course of disease (in months)	12.2 (±6.2)	10.4 (±7.3)

expected patients in both the control and study groups to have achieved improvement by more than 20 degrees after rehabilitation treatment. Therefore, the ±2.2 degree sensor accuracy wasn't the main concern in this research.

In our proposed system, user motions are recorded as time-indexed trajectories. Patients can immediately adjust their reaction based on the real-time fused kinematics feedback. Physical therapists can adjust the game's difficulty levels and design detailed parameters based on the statistical analysis results, which can provide them with a quantifiable measurement for each patient's training and suggest a direction for future adjustment for individual patients. For example, some patients use elastic ribbons to further enhance their muscle strength when they generate acceleration in manipulating virtual objects in the games.

Experiments

We recruited a total of 40 patients, diagnosed with frozen shoulder by an attending physician, for a prospective, interventional, randomized controlled, and single-blind study (Table 1). To diagnose frozen shoulder, the attending physician used parameters such as ROM limitation[4] and symptoms. Magnetic resonance imaging was required in some complex cases.

The experiment ran for four weeks. The study included subjects who

- were more than 20 years old,
- had never undergone a physical therapy,
- had frozen shoulder symptoms for more than three months, and
- were capable of participating in frozen shoulder rehabilitation based on VR.

We excluded patients from the study if they

- had weakness or paralysis in the lower limbs,
- were under active treatment with drugs for ototoxicity,
- would undergo medical or surgical vestibular ablation treatment during the study period, or
- were suffering from cognitive dysfunction.

We randomly grouped the patients into control and study groups following standard randomized clinical trials criterion to evaluate the therapeutic effects and system feasibility. All of the training tasks and balance test were conducted and designed by a currently practicing licensed physical or occupational therapist.

Experimental procedures included rehabilitation exercise training and hot pack and ultrasonic treatment.[13] The study group started on the VR-based immersed training program, while the control group did traditional rehabilitation exercises. Both groups' exercises were similar, but study group members had the privilege of receiving real-time quantified motion feedback and VR game-based training. The duration of the full training program was 20 minutes per visit, and the patients had to visit the rehabilitation center twice a week for a total of four weeks. The study group patients were required to finish a series of rehabilitative exercises with/without physical objects, depending on the physical therapist's judgment. Exercise parameters were adjusted according to the participant's condition and the therapist's judgment. The rule of thumb was to avoid excessive pain for a patient during the exercises.

Results and Discussion

The dropout rate was zero, showing that patients were highly compliant with the therapy involved in the proposed system. Figure 1 shows the sample motion-tracking data. Motion trajectories are extracted from the tracing, barman, and ship driving games. The right-most plots present the 2D projection of the time-index trajectory data, with two boxes (orange and blue) indicating the motion's start and endpoint. Each game includes an ideal path that represents the expected motion trajectory. The difference between the ideal path and the projected motion trajectory represents patients' game-playing performance.

To evaluate the VR system's efficacy, patients from both the study and control groups were evaluated by the authorized physical therapist using standard protractors. For each participant, both shoulders' ROM were tested in four basic exercises: flexion, abduction, internal rotation, and external rotation.

As Table 2 shows, we performed midspread estimation (interquartile range) of the joint angle analysis to quantify the efficacy of VR-based and traditional rehabilitation methods. Members of the study group achieved 26 percent improvement after the four-week VR rehabilitative training, but members of the control group achieved only 18 percent improvement during the same four-week period. In fact, the study group outperformed the control group in all four exercises.

Table 2. Shoulder joint angle test.

Motion angle (Degree)	Pretest			Post test		
	Study group	Control group	P-value	Study group	Control group	P-value
Flexion	149.1 (129.2–162.7)	149.0 (131.7–157.5)	.904	171.6 (153.2–174.0)	166.0 (154.7–171.2)	*
Abduction	145.8 (104.4–163.5)	144.0 (100.7–163.9)	.947	168.0 (1510.3–171.3)	157.7 (127.7–169.9)	*
External rotation	62.1 (55.7–83.9)	60.0 (39.7–71.6)	.076	83.65 (71.5–88.2)	74.3 (56.5–81.2)	*
Internal rotation	40.5 (36.4–64.2)	37.1 (21.9–53.7)	.051	65.5 (54.0–71.9)	50.65 (40.2–59.0)	**
CMS assessment	63.5 (45.5–70.7)	63.0 (50.0–71.2)	.738	85.0 (72.5–89.0)	76.0 (68.2–84.7)	*

Significance level = 0.05;* p-value ‘0.05; **p-value ‘0.01

To determine whether a significant difference exists in outcome between the study and control groups, we conducted the Wilcoxon rank sum test because the normality test indicated that all datasets had an abnormal distribution. Examining the pretest data collected before the rehabilitation training indicated that the shoulder joint dexterity between the study and control groups was small. Patients in both groups demonstrated similar ability to manipulate their shoulders. However, the study group's post test result revealed that the patients' shoulder joint mobility significantly improved compared with the control group treated using the traditional rehabilitative method.

We compared our study's novelty and contribution with previous studies and found participants are highly engaged with the game-like tasks and have strong intentions to continue using the proposed system for rehabilitation. This design is based on a user-centered design concept, provides hierarchical challenges that can be adapted to each individual's current status, and the integration between passive resistant force applications and VR tasks eliminates a number of interventions from medical professionals.

Pamela Kato[7] presented several video game-based treatments in various medical applications, but frozen shoulder rehabilitation wasn't included. Kato also reviewed and summarized game-based research that mainly used wearable sensor systems. Our system specifically targets frozen shoulder rehabilitation and includes various shoulder joint rehabilitation exercises, making our study a pioneering initiative in addressing frozen shoulder using video game-based treatments.

Although Yao-Jen Chang and his colleagues[6] used similar Kinect-based technologies, our system combines VR technologies with Kinect (vision) and motion sensors (wearable system) and integrates a mounted projector to create a self-rehabilitation environment for patients. In addition, our experiment followed a rigorous randomized clinical trial design with a larger sample size. Moreover, our study introduces the concept of a virtual tutor for increasing patients' motivation to train and passive haptics to help patients attempt self-rehabilitation. In contrast to common sensory system designs, in which patients simply wave their arms in the air, our design incorporates the real world (the wall) and provides patients with a self-rehabilitation environment.

Work is currently underway to further analyze the rich motion data measured during the training, to determine motor characteristics and develop new assessment methods for clinical purposes. Beyond that, an intelligent rehabilitation system that can automatically adapt to each individual is desirable. In the future, we'll further incorporate cloud computing services in the system so that telerehabilitation can be practiced and the system can be introduced into the homes of patients to establish home-based telerehabilitation. ■

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