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Interactive Media in Training and Therapeutic Intervention

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INTRODUCTION

Joint Pain is a Significant Health Issue

Joint pain is a leading cause of disability and, as our population ages, it will increasingly affect larger numbers of individuals and our national economy. Aging gradually reduces the physiologic reserve that is available to perform daily activities. When the physical impairments and chronic pain associated with joint pain (such as arthritis or adhesive capsulitis) are combined with age-related changes, the physiologic reserve is further compromised, which increases the risk of functional dependency and greater economic losses. Patients with joint disease commonly first consult a physician because of pain.

Adhesive capsulitis (AC) affects approximately two percent of the general population. Primary adhesive capsulitis is characterized by idiopathic, progressive, and painful loss of shoulder motion. The onset of pain causes many patients to limit the use of the arm. Due to the loss of motion, patients can find it increasingly difficult to perform everyday activities. AC patients also tend to develop pain compensating movements which, over time, result in less shoulder pain but side effects including a stiff shoulder and a significant limitation of function.

The root cause of AC is still not fully understood; however, there are two primary explanations for the underlying pathophysiology of the disease. There is disagreement as to whether the underlying pathologic process is an inflammatory or fibrosing condition. There is significant evidence that the underlying pathologic changes are due to synovial inflammation and subsequent reactive capsular fibrosis. However, the initial trigger of inflammation and fibrosis in most patients is still unknown.

Original Research

Virtual Reality-Enhanced Physical Therapy System

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Abstract: Joint disease is a significant health issue for a large portion of the general population and an even greater issue for the elderly. Pain associated with joint disease can be treated with pharmacological and non-pharmacological therapies. Currently, there are no pharmacological agents that are able to simultaneously provide relief from the pain and improve quality of life, without the risk of adverse side effects.

The specific aim of this project is to develop a non-pharmacological treatment option for chronic joint pain. We are working to achieve this by developing a system that combines virtual reality technology with hardware for physical therapy. Physical therapy (PT) has been shown to be an effective treatment for chronic joint pain, resulting in increased range-of-motion (ROM), greater strength, less dependence on pharmacological treatments, and improved quality of life. Virtual reality (VR) has been shown to distract patients from pain during treatment and therapy. By combining VR with a PT system, we expect to achieve more effective treatments with less discomfort in patients suffering from chronic joint pain.

The results of our pilot study confirmed our hypotheses. Of the eight subjects with adhesive capsulitis tested, all of those that were immersed in the virtual reality system were distracted from the pain associated with the therapy. Of all of the test subjects, 87.5% preferred using the VR-enhanced system and would have chosen to continue using the VR-enhanced system (if that were possible) in their continued physical therapy treatments.
Pharmacological Treatments for Joint Pain

The primary goals of treating patients with joint pain are pain management, minimizing disability, improving quality of life, and preventing progression of the disease. Of these goals, the most important is pain control, because pain has strong associations with disability and quality of life. Furthermore, since there are no causative treatments for joint pain, all therapeutic measures in joint pain treatment are designed to treat symptoms of the diseases (i.e. managing the pain).

The use of drugs for the treatment of pain associated with joint disease has significant drawbacks. Analgesics can cause strong adverse reactions and dependency; NSAIDs introduce significant gastrointestinal and renal toxicity; corticosteroids can cause cataracts, a vascular necrosis of bone, osteoporosis, thin skin, and muscle fiber atrophy; and immunosuppressive drugs may result in respiratory compromise, weakness, cognitive deficit, fatigue, sexual problems, and impaired balance.

Clearly, there is no single drug that is both completely effective and safe for treating joint pain. Furthermore, the significant risks from prolonged drug use have required the development of non-pharmacological treatments for joint pain.

Non-Pharmacological Treatments for Joint Pain

Significant effort has been expended in the development of non-pharmacological joint pain treatments. These efforts include heat, cold, electrical stimulation, light therapy, splints and orthoses, diet, weight loss, psychology, and exercise. Of all of the non-pharmacological pain treatments for joint pain, exercise has been one of the most rigorously studied and has shown significant beneficial effects. The proven benefits include increases in strength, range-of-motion (ROM), and aerobic capacity, as well as decreases in disease activity and pain level.

In AC, a supervised physical therapy program has been used effectively in many patients. Physical therapy is preferred because a major objective in treating AC patients is to restore function by decreasing the inflammation and pain, increasing ROM, and reestablishing normal shoulder mechanics. Research has shown that there are significant long-term benefits to physical therapy for AC patients. It has been observed that passive ROM significantly increased flexion, abduction, and internal and external rotation of the shoulder. Physical therapy also resulted in significant decreases in perceived pain between initial and final evaluations. A recent study showed the benefits of using anesthesia during physical therapy treatments for AC. The anesthesia enabled the patients to be distracted from the pain during therapy. It also enabled the anesthesized group to achieve greater benefits in shorter periods of time as compared to the group receiving the same physical therapy without anesthesia.

Virtual Reality Has Been Shown to Reduce Perceived Pain During Therapy

It has been recognized for some time now that virtual reality (VR) has the potential to be used to improve quality of life in the real world. Applications include treatment of phobias, eating disorders, post-traumatic stress, and pain management. VR allows individuals to become active participants in a computer-generated world that changes naturally (i.e. as our past physical experience would suggest) and responds to the individual’s motion.

One example of this has been a system developed to distract burn patients from pain during wound care. The system that was developed consisted of a virtual kitchen where patients could open drawers, pick up pots, touch other objects, and see three-dimensional images. Both reports concluded that VR can function as an effective nonpharmacological method for reducing perceived pain during wound care and physical therapy.

Based on evidence in the open literature discussed above, namely that (1) joint pain is a significant health care issue; (2) physical therapy is an effective nonpharmacological treatment for many of the symptoms of joint pain from a number of diseases; and (3) VR can be used to distract patients during painful therapy, Creare is developing a VR system for physical therapy that can be used to treat joint pain.
MATERIALS AND METHODS

System Overview

Figure 1 shows a picture of Creare’s Virtual Reality-Enhanced Physical Therapy System. Our system combines an immersive VR system with physical therapy hardware. The system is designed to enable patients with joint pain to undergo rigorous physical therapy treatments while being distracted by VR technology from pain that may be induced by the therapy. Our overall system consists of the following components:

Haptic Interface. The haptic interface is used to perform physical therapy on patients and to provide realistic force feedback for enhanced immersion in the VR system. Previous research has shown that physical therapy is one of the most effective nonpharmacological treatments for joint disease and that haptic interfaces greatly improve the immersion of VR systems. Our design for treating adhesive capsulitis is built around commercially-available devices originally developed for the computer gaming industry.

Visual Display. To provide a greater level of realism in the VR system, we use a head-mounted display (HMD) to present visual content to the user. By using an HMD, we try to fully immerse the user in the VR environment. We make use of off-the-shelf HMD hardware and use graphic rendering software that we have previously developed for a VR training application to render the

Figure 1. Creare’s Virtual Reality-Enhanced Physical Therapy System. Creare’s VR-enhanced PT system combines immersive VR technologies with physical therapy hardware. The immersive VR technology is used to distract patients from pain experienced during physical therapy treatments. By distracting patients from pain, the Creare system holds the promise of allowing patients to better tolerate existing therapy procedures or to enhance the provided therapy. In the long term it is reasonable to expect that the likely result will be less chronic pain and improved clinical outcomes for patients with joint pain/disease.
graphic content to the user. This software makes use of 3D Linx, a commercial off-the-shelf product for real-time display of visual content in games and training systems.

**Head-Tracker.** The system is designed to enable the user to wear an electromagnetic tracker mounted to the HMD. The measurement of head motion is used to compensate in real time for motion parallax and other display anomalies common in virtual reality visual displays. In addition, we can make use of the head-tracker measurements to present audio information to the user with proper three-dimensional sound content.

**Computation Engine.** The computation engine consists of hardware for real-time implementation of the signal processing algorithms. The hardware consists of off-the-shelf computer hardware. The inputs to the computation engine are the measurement of haptic display input, the head-tracking device, and the physics-based models used to determine the behavior of the virtual environment. The output from the computation engine includes the visual, auditory, and haptic displays. We have previously developed real-time software for proper timing and for analog-to-digital and digital-to-analog conversion while making use of off-the-shelf computer hardware that was modified for this application.

**Underlying Software.** The VR-enhanced physical therapy system is designed around a module architecture that permits each component of the system to be modified without affecting overall operation of the system. This approach facilitates incorporating new hardware, VR content, physics-based models, and physical therapy routines. This design allows our system to be easily modified for new and more challenging applications in chronic pain management that might require specific physical therapy routines or procedures.

**VR Graphical Content**

The graphical content of the original training system upon which our system is based consisted of city and country roads over which the user to follow with the virtual vehicle, and the steering wheel is used to provide resistance as part of the physical therapy.

![Figure 2. View of Graphical Content for Virtual Reality System. This figure shows the virtual city and landscape that is used for the virtual reality system. The purple balloons are used to define a path for the user to follow with the virtual vehicle, and the steering wheel is used to provide resistance as part of the physical therapy.](image-url)
patient could drive (shown in Figure 2), all the while feeling the interaction of the vehicle with the road and viewing the motion of the vehicle relative to the surrounding environment. The new design adds a well-defined task to the system and makes use of the existing graphical content. We added a “game” to the system such that the driver has a fixed amount of time to drive over markers placed on a number of the roads and part of the countryside. Each marker that is driven over is counted and the patient achieves a score based on the number of markers “collected” (much like the Pac Man video game).

**Non-Enhanced System**

In order to provide a method for direct comparison between our VR-enhanced physical therapy system and a non-enhanced system, we developed a non-enhanced system using the same hardware as the enhanced system. For this system, the task was to follow a moving round target by rotating the steering wheel to move a crosshair. A picture of the non-enhanced system screen is shown in Figure 3. While the user rotates the steering wheel, the wheel also applies torque so that the user is forced to apply retarding torque, and thereby exercise their shoulder muscles. The target position and torque applied to the steering wheel are “played back” from a data file which contains a time history of target positions and torque values. The data files can be recorded from previous interactions with the hardware, either during a familiarization session or during a VR-enhanced session.

**RESULTS**

Using the system described above, we performed a pilot human subject test designed to investigate the following hypothesis: An immersive VR system can be used to distract patients suffering from joint disease from pain during physical therapy treatment.

We performed the pilot human subject test at the Massachusetts General Hospital Physical Therapy Clinic with eight test volunteers. Dr. Michael Kane of the Massachusetts Institute of Technology performed the diagnosis of adhesive capsulitis, recruited all of the subjects, and obtained informed consent documents prior to
their first visit to the PT clinic. Once at the PT clinic, Katherine Breen, PT, DPT, performed a standard initial PT exam for all of the patients and reviewed the human subject test protocol. Afterwards, the volunteers were brought to the area where the hardware was set up and the testing began, following the approved protocol. All of the test results are summarized in Table 1. The table shows the sex and age of the subject, the subject’s responses to the questions that we asked, our qualitative assessment of level of immersion (based on the length of time required to familiarize with the hardware and score on achieving the goals of the task), and the calculated slope of the torque vs. angle curve generated by recording the data during the VR-enhanced session.

The test subjects ranged in age from 53 to 78, with four between the ages of 53 and 58 and four between the ages of 69 and 78. The test subject population consisted of five females and three males; two of the males were in the 69–78 age group.

**Pain Perception**

Overall, five of the eight participants ranked the relative level of pain experienced during the non-enhanced session as being greater than the pain experienced during the VR-enhanced session. Of the five, three ranked the pain as “a little more pain,” one ranked the pain as “more pain,” and one ranked the pain as “much more pain.” One test subject ranked the pain as being the same between the two systems, and two participants ranked the pain as being less during the non VR-enhanced session.

**Affective Results**

Seven of the eight participants found the VR-enhanced session to be more pleasurable, preferred to use the VR-enhanced system, and would choose to use the VR-enhanced system for continued therapy if that were possible. The one individual who found the non-enhanced session to be more pleasurable also found the non-enhanced session to generate less pain. This individual also complained of a headache that may have occurred because the HMD was probably not adjusted properly (it was too tight and he did not say anything until the session was over). We believe that this issue with the HMD contributed to this participant’s lack of immersion in the VR environment.

**DISCUSSION**

The results of our pilot study clearly demonstrated the feasibility of our VR system. We achieved our research objectives by developing an early prototype VR-enhanced physical therapy system for frozen shoulder, performing a pilot human subject test of the system, and designing a clinical system appropriate for use in long-term studies. Our test results confirm that VR-enhancement has the potential to distract individuals from pain during therapy, that patients enjoy using VR-enhanced hardware, and that patients would like to continue using a VR-enhanced system if that were possible.

<table>
<thead>
<tr>
<th>Subject</th>
<th>Sex</th>
<th>Age</th>
<th>Pain during</th>
<th>System to use</th>
<th>Immersion</th>
<th>Slope (torque/°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>F</td>
<td>76</td>
<td>a little more</td>
<td>VR-enhanced</td>
<td>moderate</td>
<td>-0.024</td>
</tr>
<tr>
<td>2</td>
<td>F</td>
<td>53</td>
<td>more</td>
<td>VR-enhanced</td>
<td>high</td>
<td>-0.074</td>
</tr>
<tr>
<td>3</td>
<td>M</td>
<td>78</td>
<td>much more</td>
<td>VR-enhanced</td>
<td>moderate</td>
<td>-0.155</td>
</tr>
<tr>
<td>4</td>
<td>F</td>
<td>75</td>
<td>less</td>
<td>VR-enhanced</td>
<td>low</td>
<td>-0.286</td>
</tr>
<tr>
<td>5</td>
<td>M</td>
<td>69</td>
<td>less</td>
<td>Non-enhanced</td>
<td>low</td>
<td>-0.350</td>
</tr>
<tr>
<td>6</td>
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<td>53</td>
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<td>VR-enhanced</td>
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<tr>
<td>8</td>
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<td>58</td>
<td>a little more</td>
<td>VR-enhanced</td>
<td>high</td>
<td>-0.162</td>
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</tbody>
</table>

Table 1. Summary of Pilot Human Subject Test Results.
The test subject who ranked the pain as the same used the VR-enhanced system second and may have suffered a bit from fatigue due to the buildup of exercise from the intake exam and first non VR-enhanced therapy session. This subject spontaneously said “This works; I am not even thinking about my shoulder,” during the VR-enhanced session. This comment indicates that the VR-enhanced system was performing as expected, even though the response to the specific question regarding pain did not clearly support our hypothesis.

Neither of the participants who ranked the relative level of pain in the non VR-enhanced session as “less” were completely immersed in the VR-enhanced system. Both of these participants were in the 69–78 age group and had a difficult time keeping the virtual vehicle near the path defined by the task. In retrospect, we could have recorded the number of balloons on the path that were “collected” by the participant and used this as an indication of immersion. The two subjects who experienced more pain obtained very low scores on the task as defined by “collection” of the balloons; whereas all those who scored well on the VR task reported more pain during the non VR-enhanced session.

Furthermore, the data recorded during the VR-enhanced sessions for these two individuals showed a very high slope of torque vs. steering wheel angle; almost twice as high as the next highest values. This slope is an indication of the “gain” of the force feedback or spring constant. This indicates that these subjects had to work very hard to move the steering wheel against a relatively large resistive force. This came about because both individuals were not able to control the speed of the virtual vehicle and kept it moving at a relatively high speed through the environment. This had the dual effect of making them score poorly on the task as well as increasing the level of work that they needed to perform during the session. Figure 4 shows a graph of the torque vs. angle data for Subjects 1 and 5. These data show the quantitative difference between the interaction that the subjects had with the system during the VR-enhanced session. Effectively, the data in Figure 4a show that the steering wheel resistance is much greater than that shown in Figure 4b, resulting in greater effort being expended by the participant and a greater feeling of pain during the VR-enhanced session.

We also noticed that the individuals in the 69–78 group were on average less familiar with computer technology (especially games) and required more familiarization time with the hardware than the individuals from the 53–58 group. Our evidence suggests that people who were more familiar with the hardware and computers were more likely to become immersed in the VR and were much more likely to be distracted from the pain.

![Figure 4. Torque vs. Angle Data Recorded During Two VR-Enhanced Sessions.](image-url)

(a) Data from Subject 5 whose effective steering wheel resistance was large compared to other subjects. (b) Data from Subject 1 whose steering wheel resistance was comparable to most of the other subjects.
ACKNOWLEDGEMENTS

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