A concept virtual harp with physical string vibrations using augmented reality for therapy

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A concept virtual harp with physical string vibrations using augmented reality for therapy

by

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A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Major: Human and Computer Interaction

Program of Study Committee:
Shana Smith, Major Professor
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Iowa State University
Ames, Iowa
2008

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ABSTRACT

This thesis presents a multimodal three-dimensional harp for interactive musical experiences for use in therapy for individuals with disabilities. A preliminary harp model in OpenGL with user interaction being a mouse and keyboard tested on special education children lead the Virtual Harp program on a new design approach to provide more interaction and stimuli. This system provides individuals with three forms of feedback visual, audio, and haptic during interaction using a Sensable Phantom Omni haptic device and immersion in a portable augmented reality-based system using a video see-through head mounted display. Modeled as a realistic harp, the virtual harp uses realistic harp string vibrations modeled from Fourier analysis physics equations. The individuals play the virtual harp with the Phantom Omni haptic device by plucking or strumming the strings of the harp. They have the freedom to move the harp around the environment giving the feeling of playing a traditional musical instrument. A virtual therapist feature was developed to allow a therapist without musical knowledge to observe the individual during therapy exercises and allow the individual to engage in a self-motivating therapy exercises outside the therapy room by following a simple sequence of notes by following the color-coded strings. User testing was performed to measure usability and therapeutic effectiveness: development of skills, improvement in range of motion, and entertainment value. Results showed that there were no major usability issues discovered and responses were positive with regards to using this technology for therapy.
CHAPTER 1. OVERVIEW

The United State has between thirty-four and forty-three million people who have some type of disability, with physical, sensory, mental, and self-care effects ranging from mild to severe. Nearly 13.9 million people or thirty-five percent of persons over the age of sixty-five have some level of disability [1]. According to the US Department of Commerce, a person has a disability when that person has difficulty with any of the following [1, 2]:

1. Normal body functions, such as seeing, hearing, talking, or walking
2. Activities of daily living (ADLs), such as bathing or dressing
3. Instrumental activities of daily living (IADLs), such as shopping or doing laundry
4. Certain expected roles, such as doing housework, schoolwork, or working at a job
5. Performing usual activities, such as driving or taking a bus

In the United States, an estimated 9.2 million or four percent of the non-institutionalized population at the age five and over need personal assistance with one or more activities. There are over 5.8 million people that need assistance in instrumental activities of daily living (IADL), which is independent living activities, while 3.4 million need assistance in activities of daily living (ADL), which is personal functioning activities [2]. Several different factors can contribute to getting some level of disability; to name a few factors, people can have strokes, arthritis, injuries, or congenital disabilities like cerebral palsy. Stroke is a leading cause of long-term, severe disability in Americans. Currently there are 5.5 million United States adults living with the effects from a stroke [1]. When a blood clot blocks or breaks an artery or a blood vessel in the brain it causes a decreased blood flow and lack of oxygen causing a person to have a stroke. There are two types of strokes: ischemic which is a
blockage of a blood vessel supplying the brain and hemorrhagic which is bleeding into or around the brain [3]. About eight out of ten strokes are ischemic strokes and are the most common type of stroke in older adults, while the hemorrhagic strokes are less common but more deadly than ischemic strokes [4]. A common disability that results from stroke is complete paralysis on one side of the body, called hemiplegia. A related disability that is not as debilitating as paralysis is one-sided weakness or hemiparesis [4]. Other conditions experienced by a person who have had a stroke are depression, memory loss, communication problems, difficulties in performing daily tasks, muscle tightness or spasticity, and pain [5].

Cerebral palsy could be caused by infections, birth injuries and poor oxygen supply to the brain before, during, and immediately after birth. The United Cerebral Palsy Association estimates that more than five hundred thousand Americans have cerebral palsy [6]. Common conditions experienced by a person who has cerebral palsy are paralysis or weakness to limbs, communication problems, seizures, muscle tightness or spasticity, and other disabilities with hearing, vision or learning.

Musculoskeletal disorders, including carpal tunnel syndrome, are among the most prevalent medical conditions in the U.S., affecting seven percent of the population accounting for fourteen percent of physician visits and nineteen percent of hospital stays. According to the National Institute for Occupational Safety and Health, sixty-two percent of the persons with musculoskeletal disorders report some degree of limitation on activity, compared with fourteen percent of the population at large [7]. Currently, carpal tunnel syndrome affects over eight million Americans being reported as the number one medical problem, which account for about fifty percent of all work-related injuries [7]. A work-
related musculoskeletal disorder known as repetitive motion or strain injuries is an injury to the muscles, tendons and/or nerves of the upper body either caused or aggravated by work.

There are many different methods to reduce or correct any conditions from disabilities. The first method involves taking medications; the most common conditions that use this method are muscle tightness or spasticity, depression, memory loss, and pain. Another method is having a surgical procedure to correct or reduce a disability condition such as injuries, pain, muscle tightness or weakness, and seizures. The most common method is having the individual registered in some type of therapy program such as physical, occupational, recreational, musical and speech therapy.

**THERAPY**

Many traditional therapeutic interventions used in a rehabilitation program promote functional recovery and have demonstrated that intensive massed and repeated practice may be necessary to modify neural organization and effect recovery of functional motor skills [8]. When traditional therapy is provided, individuals are usually seen for half hour sessions once or twice a day dropping to once or twice a week as outpatients. Access to therapy is terminated once the individual reaches a predetermined level of function even if residual deficits remain and while in sessions it has been reported that there are low interaction levels between the patient and environment from common problems including boredom, fatigue, lack of motivation and cooperation [9]. Music therapy goals and objectives are consistent with the treatment goals of other therapeutic modalities including counseling [10]. It not only helps to stimulate and motivate, but also provides opportunities to convey feelings without the use of words and can facilitate social interaction [11]. Humans are inborn with the ability
to appreciate and respond in terms of pulse, rhythm, breathing and movement, and the whole range of emotions to music, which can remain despite disability, illness, injury and does not depend on music training [10, 11]. Music therapy is a means of opening new channels of personal development and humanness, and opening paths for expression and learning for persons who are limited in their ability to relate to themselves, others, and their environment because of mental or physical disorders or limitations [10]. The Virtual Harp system is coupled with music to increase the therapeutic goals from music therapy and to help stimulate and motivate the use of therapy exercises.

VIRTUAL AND AUGMENTED REALITY REHABILITATION

Computer simulations have become more common over the last decade due to decreasing equipment costs and increasing processor speed. This technology is currently being explored for the potential benefit as a therapeutic intervention for retraining coordinated movement patterns [8]. Virtual reality provides the capability to create an environment in where the intensity of feedback and training can be systematically manipulated and enhanced in order to create the most appropriate, individualized treatment needs and training protocols [8, 9, 12]. In addition VR-based rehabilitation systems can be made similar to computer games providing a unique experience that is engaging, functional, and purposeful which is important in terms of patient motivation. Additionally, having precise feedback in real time increases the motivating effect for patients [12]. The sensor technology can also be used to fully quantify any progress made by the patient, especially in terms of motor control improvement [8]. Primarily most rehabilitation applications have used visual and auditory sensory input, less developed are haptic interface devices including gloves, pens, joysticks and exoskeletons
Haptics provide users with a sense of touch allowing the user to feel a variety of textures, weights, and forces. There is increasing evidence that haptic information is an effective addition towards the accomplishment of certain treatment objectives such as increasing joint range of motion and force, which can be used as assistive technology tools [9, 12].

The following paragraphs explain rehabilitation applications that are currently being developed and researched using this technology. To enhance spatial awareness and to successfully teach children with cerebral palsy to operate motorized wheelchairs a virtual reality training program using three virtual scenarios that progress in difficulty level and complexity allowed the children to be motivated to learn and subsequently improved their driving skills [8].

A PC based desktop Virtual Reality system was developed for rehabilitating hand function in stroke patients [8]. The system uses two hand input devices, a CyberGlove and a RMII force feedback glove where each exercise is designed to work on one specific parameter of hand movement on range, speed, fractionation, or strength. Each exercise takes the form of a simple interactive game to motivate the user to continue the exercise program where the patient performs a number of trials to reach a particular goal using target-based trials, and all the exercises are driven by the user’s own performance. The therapy program is semi-automated and personalized to each user using performance-based target levels that are adapted between sessions in order to induce the user to improve [8].

A haptic application used a virtual reality system to improve the training of blind and visually impaired people in the use of the white cane. The system was designed as an alternative method for training adding the value of studying various cases such as an outdoor test case and an indoors test in a controlled and safe environment before practicing in the real
environment. The virtual cane with parameters of size, grasping forces, collision forces adjusted so that it feels similar to a real cane was an extension of the user’s index finger with force feedback applied to the user’s hand depending on the virtual object collision. A force is applied to the thumb with collisions on its right side and to the middle ring and pinky fingers simultaneously on its left side. The user wears the CyberGrasp and a waistcoat for carrying the Force Control Unit (FCU) for the CyberGrasp have the type of forces applied to the users being a constant continuous force that simulates the force provided by grasping a real cane, a jolt effect force and buzzing [13].

VIRTUAL HARP PROJECT

In its initial implementation the Virtual Harp project was designed to be integrated into a children’s musical therapy program led by special education teachers or therapists. This project was an effort to make learning fun and motivational to help children become independent in remembering name of colors, musical instruments, and using the computer equipment along with developing physical, attentive, and listening skills. Through collaboration with an elementary special education classroom, it was determined that the most important aspect of our program was using both visual and audio sensory cues to keep the children engaged. This directed the Virtual Harp program to a new design approach to provide more interaction and stimuli. As new technologies and knowledge were implemented into the Virtual Harp program, this led to the implementation of the Virtual Harp system that could be applied towards interactive musical experiences and development of skills during therapy for individuals with disabilities as shown in Fig. 1.
This system uses a Sensable Phantom Omni haptic device and provides individuals with three forms of visual, audio, and haptic feedback during interaction. The individuals are immersed in an augmented reality environment using a video see-through head mounted display to provide the unique capabilities of having a portable augmented reality-based system. The virtual harp model was developed using a realistic harp guide, and it used realistic harp string vibrations modeled from Fourier analysis physics equations as a continuous system having multiple elements distributed continuously throughout the string. The individuals play the virtual harp with the Phantom Omni haptic device by plucking or strumming the strings of the harp. They have the freedom to move the harp around the environment with a feeling of playing a traditional musical instrument. A virtual therapist feature was developed to allow a therapist without musical knowledge to observe the individual during therapy exercises and allow the individual to engage in a self-motivating therapy exercises outside the therapy room. The virtual therapist feature allows individuals to follow a simple sequence of notes by following the color-coded strings to help the user
identify the notes. This thesis describes the development stages of the Virtual Harp system and includes user testing to evaluate the effectiveness of the implementation.

**THESIS ORGANIZATION**

This thesis includes one paper written during the initial development and testing of the virtual harp system. The first paper, published in the Proceedings of the ASME 2007 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2007, describes the initial system development and a pilot study that was performed with disabled children. The second paper, submitted to Proceedings of the ASME 2008 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference IDETC/CIE 2008, discusses the newest version of the virtual harp system as a therapy application which includes the modifications to the system, the new virtual therapist feature, and user study testing.
CHAPTER 2. A VIRTUAL HARP WITH PHYSICAL STRING VIBRATIONS IN AN AUGMENTED REALITY ENVIRONMENT

A paper published in the *Proceedings of the ASME 2007 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*

*IDETC/CIE 2007*

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**ABSTRACT**

This research provides a prototype of a computer-generated harp, using physical string vibrations with haptic feedback in an augmented reality environment. The individuals, immersed in an augmented reality environment using a head mounted display, play the virtual harp with the Phantom Omni haptic device receiving realistic interactions from the strings of the harp. Most previous musical instruments research only provides feedback in the form of visual and audio cues, but not haptic cues. The proposed project is designed to provide individuals with all three forms of cues for interacting with a computer-generated harp. This computer-generated harp is modeled as a realistic harp and includes physics for string vibrations to provide the individuals a traditional instrument-like interaction. This
prototype will be applied towards interactive musical experiences and development of skills during music therapy for individuals with disabilities.

**KEYWORDS:** VIRTUAL REALITY, HAPTICS, MUSICAL INSTRUMENT

**INTRODUCTION**

Computers are readily available to the public and have become a new way to produce music. The computer is becoming its own musical instrument for use in music therapy, virtual applications, education, and providing new ways to play traditional instruments. Humans are inborn with the ability to appreciate and respond in terms of pulse, rhythm, breathing and movement, and the whole range of emotions to music, which can remain despite disability, illness, injury and does not depend on music training [1, 2]. Since humans have this ability, music therapy can help individuals in a wide range of needs from causes such as disabilities, stress, abuse, illnesses, and developmental needs by providing interactive musical experiences [2]. Virtual reality can provide many different human senses to an individual by providing a computer generated object that can be interacted with. Individuals with special needs benefit from the use of virtual reality in cases such as training, education, gaining experience in real world situations, and developing communication, motor control, and cognitive skills [3, 4].

Mäki-Patola et al. [5] developed virtual reality interfaces for sound control using interfaces presented that are “instrument-like”. They used a variety of input devices such as data gloves, magnetic trackers, computer vision, and MIDI controllers with visual feedback in the forms of a 270-degree virtual reality view and stereoscopic computer graphics. They aimed at analyzing professional instruments based on efficiency and the learning curve. They found that familiarity with real-world instruments helps to grasp the concept and supports
playing in the beginning, but it is not easy to play the instrument in new ways such as using different input devices to interact with the instrument in a virtual environment. However, their research did not incorporate the use of haptic devices and the instruments were not modeled as a traditional instrument.

Gerard [6] designed a MIDI-based music player called Fakeplay to allow users with minimal training on musical instruments to actively appreciate and learn about music. This program allows users to express themselves through tempo and intensity of notes by tapping note by note with the keyboard to play the music. The tapping provides partial haptic feedback to the users in which they believe they are controlling the music. The visualizations provided are floating virtual notes in a score-reading format. This program is limited to following along the piece rhythmically and does not allow the user the ability to freely play any music outside the selected piece.

These articles only discuss applications for computer-generated musical instruments that provide a visual output on a computer monitor display or cave display. Their programs only provide to the individual visual and audio feedback cues during interactions but not any haptic feedback. Providing haptic feedback to users improves how they interact with the musical instrument. This prototype of a computer-generated harp will provide individuals use of a haptic device giving them all three forms of feedback during interaction.

A study conducted by O'Modhrain and Chafe [7] tests the hypothesis that adding haptic feedback to computer based musical instrument would improve the playability of these kinds of instruments using the musicians’ unconscious use of auditory and haptic cues. They made a simple feedback controller to model the performer and instrument interaction. They use a computer model of the theremin instrument and had twenty musicians play short melodies
using the haptic display device called the Moose for six different force feedback conditions. The study showed support for their hypothesis that adding haptic feedback improved the players’ ability to control the instrument and that force conditions correlated with auditory feedback resulted in a better performance.

Nichols [8] improved the violin MIDI musical controller for interactive computer music. There were difficulties to get an accurate or expressive translation from performance gesture to synthesized sound and latencies. He designed an expressive violin bow controller called the vBow to improve the expressiveness and playability of the bowed-string physical model by making an instrument with an array of sensors, which mapped physical bowing gestures to parameters of the bowed-string physical model. The vBow instrument was testing the expressiveness of the bowed-string physical model and the efficacy of adding haptic feedback to a musical controller system. This instrument can be used for interactive computer music performance as a versatile and expressive electronic musical instrument.

Wang et al. [9, 10] designed a real-time simulation of a thread for knot tying in use for virtual reality training in laparoscopy. The simulation provides a thread that has dynamic motion from physical equations and two haptic devices to manipulate the thread for knot tying. The thread is modeled as a spline of linear springs with self-collision handling. It uses second order dynamics with physically plausible stretch/compression, bending, twist, friction, gravity and contact forces to simulate thread motion and self-collision running at haptic speed. This thread model provides improved motion compared to the geometry model and a more realistic visual display. Other forces and thread properties can be used with this dynamic model.
The authors also created a preliminary harp model in OpenGL where the user interaction was with a mouse and keyboard. The sounds were produced using the software MIDIShare. During playing, the harp string would produce a certain harp sound starting from middle C to note B before the C an octave above. This harp model was placed into a virtual 3-D room where the user had to view the computer monitor for interactions. This preliminary program presented the users feedback in the form of audio cues and very little visual cues. These visual feedback cues were in the form of viewing the harp model moving around in the room and viewing the mouse cursor moving over the harp model strings. The preliminary program was tested on students that have severe disabilities classified at level three who are visual and active learners. Most of the students liked the program and could make the note sounds with the mouse with having a little help. The students only interacted with the program for short periods of time. The results influenced the study on a new design approach to provide more interaction and stimuli with the virtual harp.

Although a virtual musical instrument has many advantages, most prior research only renders the virtual instruments on a computer monitor. The virtual instruments are not portable and, thus, are not realistic compared to the physical instruments in the way of playing. The proposed study will use the unique capabilities of portable augmented reality-based systems to meet the unique requirements of certain musical instruments. Augmented reality technologies can mix or overlap computer generated 3D virtual objects with real-world scenes, unlike virtual reality, which totally replaces the physical world with a virtual world. Augmented reality technology simply attempts to enhance the existing physical world by integrating virtual objects into the physical environment, so that the virtual objects become, in a sense, an equal or integral part of the natural scene.
Most recent augmented reality applications use see-through head mounted displays (HMDs) to deliver 3D images to the users’ eyes. There are two types of see-through HMDs: video based and optical based. Since optical see-through HMDs are currently very expensive, in the project, video see-through HMDs will be used for augmenting real environments to create virtual musical instruments.

In order to provide users with force feedback while they are playing a virtual instrument, a haptic device will be used. Most applications for haptic feedback have not been used in conjunction with augmented reality environments. Brown and Vallino [11] have designed an alternative method for integrating haptics with augmented reality. Users use their finger on the Phantom to manipulate and feel the forces of the virtual object; their example was a globe. In addition, users could use the virtual object to interact with the real part of the display; their example was placing a virtual cube on top of the background wall.

This paper presents a prototype of a computer-generated harp, using the Sensable Phantom Omni haptic device to provide force feedback in an augmented reality environment. The harp model will use realistic harp string vibrations from physics equations after the release of the initial string pluck. The harp string is modeled as a continuous system in one dimension having multiple elements distributed continuously throughout the string. The individuals play the virtual harp with the Phantom Omni haptic device receiving realistic interactions from the strings of the harp immersed in an augmented reality environment using a head mounted display. The augmented reality environment enhances the interaction with the harp by providing freedom to move around with a feeling of playing a traditional musical instrument. This prototype will be applied towards interactive musical experiences and development of skills during music therapy for individuals with disabilities.
VIRTUAL HARP WITH HAPTIC INTERACTIONS

Most of the current research does not consider adding realistic interactive physical motion to computer animated virtual instruments. Here, a physics-based harp model is created to concurrently simulate the string vibrations of a harp while playing with force feedback. This program will allow users to play a virtual computer harp with the Sensable Phantom Omni haptic device as shown in Fig. 1.

Figure 1. Sensable Phantom Omni

A harp model using the open source program H3D was created. H3D uses Sensable’s OpenHaptics program to run the Phantom Omni’s haptics toolkits and OpenGL to display the graphics. The main H3D harp program is made using H3D’s nodes in a scene graph format. Drawing the harp and providing haptic effects used different types of Shape Nodes such as boxes, cylinders, and spheres. Figure 2. shows the individual shapes used for designing the harp.
Figure 2. Expended Harp Model

This program created the haptic feeling of touching the harp frame and the strings. Since the harp is in a 3D space, it is sometimes difficult to find the harp’s strings with the haptic device endpoint. The haptic effect from the MagneticSurface Node, makes the strings as magnetic lines, helps the user find the harp’s string by pulling the haptic device endpoint to the string’s location. The completed simple model of a concert harp with haptic effects is shown in Fig. 3.
This model is able to produce harp sounds when the harp string is touched with the Phantom haptic device. The sound output is programmed with Python to produce the MIDI harp sound. Assigned to each harp string is a particular note in the Python code, which the main program reads from the haptic touch to initiate the Python code. The users are able to play the harp by touching individual strings or doing a strumming motion on the strings with the haptic device. The force felt by the user from the haptic device are the small magnetic pulling force toward the strings.

Preliminary testing was performed where users tried to play the virtual harp with the haptics device. The users were having problems locating the harp string in the 3-D space. Most users were either too far into the screen of 3-D space (behind the string) or too far out of the screen (above the string). The stylus was made with a sphere for the contact point and a cylinder rod for pen orientation. The rod did not have any collision detection and confused the users when the rod went through the harp objects. The stylus was changed to a cone.
shape having collision detection for the whole shape and the ability to show the pen orientation. To help the users find the strings easier and faster, a hidden haptic plane was added inline with the strings with ridges around the string to know when the stylus is near the string. This plane was made using multiple box Shape Nodes in different positions and rotations. Using the ToggleGroup Node, the graphics and haptics properties could be turned on and off allowing the plane to be hidden with haptic feedback. In addition, the string’s line width was increased to see the strings better. Figure 4. shows these additions made with the plane shown and hidden.

**Figure 4.** View of Hidden Plane
STRING VIBRATION MODEL

The model for adding realistic string vibrations needs to have the vibration movement decease as the string length deceases. The model needs the harp strings to vibrate similar to sinusoidal waves and triangular waves. The use of physics equations on string vibrations and waves would be used to model the harp’s strings movements after the release of the initial string pluck. Considered are mechanical vibrations for the vibrations in a harp string. Based on Fletcher and Rossing [12] definition of mechanical vibrations, it needs two properties, “a stiffness or spring like quality to provide a restoring force when displaced and inertia, which causes the resulting motion to overshoot the equilibrium position.” This fits the string model since the string has a stiffness or spring like quality.

Considering the harp’s vibrating body will follow Hooke’s law; the restoring force should be proportional to the displacement from the equilibrium depending on the elasticity or compressibility of the harp string material. To provide a more realistic vibration motion in the harp string, a continuous system in one dimension is used. The harp string would have multiple elements distributed continuously throughout the string creating a system of composed discrete elements. The string can be modeled as a mass-spring system, as shown in Fig. 5.

**Figure 5.** Mass-spring system for continuous system [12]
Figure 6. Transverse oscillations of mass-spring system [12]

Figure 6. shows the transverse oscillations of three different mass-spring systems which can be considered for the motion of the string’s length. This figure illustrates three of the modes; since there are three masses there should only be three modes of transverse oscillations, but if there are N number of masses there would be N number of modes of transverse oscillations. The first mass-spring system follows the fundamental mode of oscillation. This mode follows the transverse oscillation motion of a half a sinusoidal wave, which occurs when the string is plucked from the center. The second mass-spring system follows the second mode of oscillation. This mode follows the transverse oscillation motion of a sinusoidal wave along the string’s length. The third mass-spring system follows the third mode of oscillation. This mode follows the transverse oscillation motion of a sinusoidal wave along the string’s length with a different period. The second and third modes of transverse oscillation motions can occur when the string is plucked away from the center of the string. In this prototype of a computer-generated harp the first six modes of oscillation are considered for the string vibration animation interaction.
Each mass-spring section will be considered as a mass point along the string and can only move in one plane. This motion creates a transverse wave, and as the number of mass points increases along the string, a wavelike appearance takes shape on the string as shown in Fig. 7.

![Figure 7. Transverse vibration for N masses of N modes [12]](image)

For each individual mass-spring mass point, the equation of motion would need to be found along the string. If the length of the string has N number of mass points along the string, there will be N number of equations to use to model the motion of each mass point. So instead of taking equations for each individual mass-spring mass points along the string the equations used to model the mass point’s motion will take the string as a whole. On a concert harp, the strings are fixed at both ends of the instrument and tension is applied to each string with different material properties. The vibration motion of the string depends on the tension applied, string properties like the linear density, the length of the string, and the end conditions. String damping will occur from internal, air, and support damping [12]. Since the string is modeled with many mass points along the line, each mass point on the line vibrates
harmonically with the same frequency [13]. The vibrations created are from standing waves. The vibration motion will be analyzed using a Fourier analysis for each point along the line. As shown in Fig. 8. to simulate the realistic pulling motion limit in the string Eq. (1) will provide the pulling limit along the string.

![Figure 8. String pulling limit diagram](image)

String pulling limit:

\[
h(x) = \begin{cases} 
  \frac{2H}{L} & 0 < x < \frac{L}{2} \\
  -\frac{2H}{L}(x-L), & \frac{L}{2} < x < L 
\end{cases}
\]  

(1)

Next the periodic function of the string needs to be defined based on the pluck location to use in the Fourier analysis. The fundamental frequency has a wavelength of 2L giving the limit on the z-axis of –L and L as shown in Fig. 9.
This diagram leads to three sets of equations based on the pluck location in the periodic function Eq. (2).

**Periodic Function:**

\[
y(z) = \begin{cases} 
  \left( \frac{h(x)}{x} \right) z, & -x < z < x \\
  \left( \frac{-h(x)}{(L-x)} \right) z + y_o, & x < z < L \\
  \left( \frac{-h(x)}{(L-x)} \right) z - y_o, & -L < z < -x 
\end{cases}
\]  

(2)

*Where: \( y_o = \frac{h(x) \cdot L}{(L-x)} \)*

The periodic function is then used to do the analysis of the Fourier coefficients in Eq. (3) for the first six modes of oscillation considered for the string vibration animation interaction. These Fourier coefficient values are then used in the Fourier analysis Eq. (4) to simulate the vibration motion for each time frame for each node along the string.

**Fourier coefficient:**
\[ C_n(x) = \frac{1}{2L} \int_{-L}^{L} y(z) \sin(nk_n z) \, dz \] 

Fourier analysis:

\[ y(z,t) = \sum_{n=1}^{N} C_n \sin(k_n z) \cos(2\pi \nu_n t)e^{-\gamma t} \] 

Where the string properties, speed Eq. (5), wavelength Eq. (6), wavenumber Eq. (7), and eigenfrequency Eq. (8) also known as harmonics would be defined in a table to use in the Python code.

Speed:

\[ c = \sqrt{\frac{T}{\mu}} \] 

Wavelength:

\[ \lambda_n = \frac{2\pi}{k_n} \] 

Wavenumber:

\[ k_n = \frac{n\pi}{L} \]
Eigenfrequency:

\[ v_n = \frac{n c}{2L} \]  \hspace{1cm} (8)

Here, a string was modeled by a vertical line with three points equally spaced in the direction of the y-axis. To manipulate the line’s points, a Python script was made to the Python code. In the Python code, it would run all the string animation for making the string vibrate and move during plucking. First, the haptic device knows if the IndexedLineSet was touched from a route in the X3D code and this starts the animation. The haptic device’s position is recorded to a variable, and this position point replaces the middle point in the line. This allows the user to touch the line and view the motion of the line moving during the touching in the x, y, and z directions with the haptic device as shown in Fig. 10. During the plucking of the string, there would be a spring effect to give the users the feeling of string tension that activates at the string position when the line is touched using the Phantom Omni’s haptic device.
Once the user reaches the defined pulling limit, the string would snap back to its original position removing the spring effect to a position away from the string and producing the appropriate MIDI harp note sound.

**AUGMENTED REALITY**

The ARToolKit allows a developer to overlay virtual objects on the marker detected in a real visual environment (http://www.hitl.washington.edu/artoolkit/download). Since the original 3D harp model for haptic application was written in an X3D format, it needed to be converted to VRML encoding .WRL file. One change was to put the rotation angle 90.0 degree toward x-axis 1.0, so that the harp body could be standing perpendicular to the floor, as shown in Fig. 11. In order to locate the harp in the center of the marker, translation information needs to be modified.
The augmented harp is interfaced with the haptic feedback to provide users with the feeling of forces while seeing the harp in a real scene. To enhance the interaction with the harp and to provide the user freedom to move around with a feeling of having an immersive environment, a head mounted display is used as shown in Figs. 12. and 13.
Using a head mounted display, the user will be able to play the harp similar to playing an actual concert harp. The marker to display the augmented harp on will need to be placed so that the maker will not be blocked from the camera. To work with this problem, the augmented harp will be displayed a distance away from the marker to minimize the blockage with the camera view.

**CONCLUSION AND FUTURE WORK**

The presented prototype of a computer-generated harp allows the individuals play the harp with the Omni Phantom haptic device by touching individual strings or doing a strumming motion on the strings. The virtual harp uses realistic harp string vibrations models and has sound after playing the strings. This provides individuals with three forms of feedback improving how they interact with the musical instrument by visually receiving realistic vibrations from the strings of the harp, hearing the harp sound afterward, and feeling the harp’s features. The augmented reality environment enhances the interaction with the
harp by providing freedom to move around with a feeling of playing a traditional musical instrument. There is still some future work to be done before the prototype of a computer-generated harp will be ready for use in testing.

The graphical display of the computer-generated harp will be redesigned to resemble a small sized concert harp. The harp would consist of thirty-six strings and the frame designed slim and semi-transparent to allow the users easy viewing of the strings. The strings would have the properties of the concert harp and be scaled down to a reasonable viewing and playing size. The animation of the vibrations on the string will be implemented on all thirty-six strings. The sound will still use MIDI as the output but the string properties will have effects on how the sound will be heard to the users. The users will have control over the loudness of the sound from the plucking of the string. The strings will have a limit for the distance of stretching the string based on their properties. The distance the users’ stretches the string will determine how loud the sound will be heard and the amount of time the sound will last. Other features such as musical songs, colored strings for a specific note and other needed features to help users play the harp will be implemented as users test playing the harp.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>Defined pulling limit value (m)</td>
</tr>
<tr>
<td>L</td>
<td>Length of string (m)</td>
</tr>
<tr>
<td>N</td>
<td>Number of mass points on string</td>
</tr>
<tr>
<td>T</td>
<td>Tension of string (N)</td>
</tr>
<tr>
<td>C</td>
<td>Speed of wave (m/s)</td>
</tr>
</tbody>
</table>
h(x) Pulling limit based from position (m)

n Number of mode

t Time (s)

x Position (m)

y(z) Node position along y and z-axis (m)

z Node position along z-axis (m)

Γ Damping term

μ Linear Density (kg/m)

ACKNOWLEDGMENTS

I would like to thank Robert McQueeney for his kind contributions with the physics equations and the string vibration model section.

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CHAPTER 3. A VIRTUAL HARP FOR THERAPY IN AN AUGMENTED REALITY ENVIRONMENT


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ABSTRACT

The goal of this research study was to develop a music therapy tool using a computer-generated harp, which could provide users with visual, audio, and haptic feedback during interaction with the virtual instrument. Realistic 3D visual and haptic feedback was provided through immersion in a portable augmented reality-based system composed of a video see-through head mounted display (HMD) and a Sensable Phantom Omni haptic device. Users play the virtual harp by using the Phantom Omni haptic device to pluck or strum the strings
of the harp. Users can also freely move the harp in the augmented reality environment to provide a more realistic experience, similar to that of playing a traditional musical instrument. The system will be used to provide interactive musical experiences and to develop motor skills among individuals with disabilities through music therapy. A virtual therapist feature was developed which can be used by a therapist without musical knowledge to observe a user during therapy exercises or by a user to engage in self-motivated therapy exercises outside the therapy room. With the virtual therapy feature, users can follow a simple pre-determined sequence of notes using color-coded strings. User testing was completed to measure usability and therapeutic effectiveness: development of skills, improvement in range of motion, and entertainment value.

**KEYWORDS:** VIRTUAL REALITY, HAPTICS, MUSICAL INSTRUMENT, THEARPY

**INTRODUCTION**

In the United States, between thirty-four and forty-three million people have some type of disability, with physical, sensory, mental, and self-care effects ranging from mild to severe. For people over age sixty-five, nearly 13.9 million people, or thirty-five percent, have some level of disability [1]. According to the U.S. Department of Commerce, a person is considered to have a disability when that person has difficulty with any of the following tasks [1, 2]:

1. Normal body functions, such as seeing, hearing, talking, or walking
2. Activities of daily living (ADLs), such as bathing or dressing
3. Instrumental activities of daily living (IADLs), such as shopping or doing laundry
4. Certain expected roles, such as doing housework, school work, or working at a job
5. Performing usual activities, such as driving or taking a bus
In the U.S., an estimated four percent of the non-institutionalized population age five and over, that is 9.2 million individuals, need personal assistance with one or more activities. People who need assistance with instrumental activities of daily living, also considered independent living activities, number over 5.8 million, while 3.4 million people need assistance in activities of daily living, which are personal functioning activities [2]. Several different factors can contribute to developing some level of disability, for example, strokes, arthritis, or injuries, or individuals may be born with disabilities such as cerebral palsy.

There are many different treatment methods to reduce or correct disabilities. The most common treatment method is to enrolling the disabled individual in some type of therapy program, such as physical, occupational, recreational, musical, or speech therapy.

Many traditional therapeutic interventions used in rehabilitation programs have demonstrated that intensive and repeated practice may be necessary to modify neural organization, effect recovery of functional motor skills, and promote functional recovery [3]. With traditional therapy, patients usually visit a therapist once or twice a day for half hour sessions. Their visit frequency drops to once or twice a week when they become outpatients. Finally, when they reach a predetermined level of function, their access to therapy is terminated even if residual deficits remain. It has been reported that while in sessions, common problems during therapy, such as boredom, fatigue, lack of motivation, or cooperation, result in low interaction function between the patient and the environment [4].

Due to decreasing equipment costs and increasing processor speed, computer simulations have become more common over the last decade. Such technology is currently being explored for potential benefits in therapeutic intervention for retraining coordinated movement patterns [3]. Virtual reality (VR) can create the most appropriate individualized
treatment needs and training protocols by providing an environment in which the intensity of feedback and training can be systematically manipulated and enhanced [3-5]. In addition, VR-based rehabilitation systems can provide a unique experience that is engaging, functional, and purposeful, in a manner similar to computer games, which is important for stimulating patient motivation. Additionally, VR systems can provide precise real-time feedback, which further increases the motivating effect for patients [5].

As an example, Todorov et al. used a VR system to create a computer animation of a table tennis task for training a difficult multi-joint movement [6]. The system had a virtual ball and virtual paddles which provided the teacher and the trainee the movement variables most relevant for successful performance of the task by the trainee. The system also used augmented feedback. Their results showed that virtual environment training provided better training for the task compared to a comparable amount of training in a real environment.

In a different virtual environment training study, two patients with hemiplegia were trained on an upper-extremity reaching task [7]. The two patients were evaluated pre- and post-VR training using motor recovery and functional ability tests and a real-world test. During the training, subjects practiced a virtual task similar to the real task, trying to imitate a virtual teacher’s performance. Post-training, reaching errors during real-world performance were reduced by 50%. Both subjects improved in the trained task, indicating transfer of skills from the virtual environment to real world performance. On the other hand, motor recovery and functional scores showed little to no change. However, one subject acquired the ability to perform several functional tasks. The results suggest that virtual environment training has a positive impact in stroke rehabilitation.
Reiss and Weghorst used augmented reality to help patients with akinesia Parkinson's disease overcome difficulties stepping over objects in their paths when initiating and sustaining walking. They found that a stable cue appearing about six inches in front of the toes was required to initiate the first step, while cues scrolling toward the feet were needed to sustain walking. In addition, the effectiveness of the visual cue was dependent on the degree and type of akinesia, showing that more realistic cues are needed as the severity of akinesia increases [8].

For individuals with spinal cord injuries, a VR-enhanced orthopedic appliance was developed linking a gait-inducing exoskeleton to a HUD. The exoskeleton used a semi-rigid sling to support the bust and lower limbs of the user and move the lower extremities to support and induce human gait. In preliminary study results, a 26-year old with complete paraplegia showed improvements in self confidence, increased relaxation, and activity scores, and higher levels of optimism and motivation [9].

VR assessment and intervention tools have also been developed. A hand system with force feedback was developed in a virtual environment to complete various tasks such as a virtual PegBoard and reach-to-grasp exercises. The system was useful for augmenting rehabilitation chronic-phase patients following strokes. Skills also transferred to a functional clinical outcome measure as well as improvement on a variety of movement parameters [10].

In our study, we created a prototype computer-generated harp to be used for interactive musical experiences and development of skills during music therapy for individuals with disabilities. A colored 36-stringed harp was designed and force feedback was provided using a Sensable Phantom Omni haptic device. Study participants played the virtual harp with the
haptic device and thereby experienced feeling string tension when pulling strings and heard appropriate harp note sounds afterward.

The virtual harp was modeled as a realistic harp using realistic harp string vibrations modeled from Fourier analysis physics equations. Users were provided the freedom to move the harp around the environment to simulate the feeling of playing a traditional musical instrument. A virtual therapist feature was developed to allow users to engage in self-motivated therapy exercises, and user testing was conducted to examine the effectiveness of the virtual harp, skills development, improvements in range of motion, and entertainment value.

**ARTOOLKIT INTEGRATION**

One challenge in the study was integrating ARToolkit features with an H3D program to provide users with the ability to position the harp freely for best use. A default viewpoint position and orientation was established so that the user was on the positive Z-axis looking in the negative Z-axis direction, as shown in Fig. 1.
Users of the prototype system wear a video-see-through type HMD, which produces the same image as a computer monitor image produced by a camera mounted on the HMD. When users interact with a marker, which represents the virtual harp, without head movement, the camera remains stationary, and movement between the marker object and camera creates the following virtual harp movements:

1. As the marker is moved away or towards the camera, the virtual harp decreases or increases in size, respectively, giving the user a zooming effect along the Z-axis.

2. As the marker is moved left, right, up, and down, the virtual harp moves left, right, up, and down, respectively, the virtual harp pans along the X and Y-axes.

3. As the marker rotates, the virtual harp rotates about its axis giving the user a method for exploring or examining the harp from different angles; for example, when the marker lies flat on the table and spins, the virtual harp rotates about the Y-axis.

When users move their heads and the marker remains stationary, head movements cause the following virtual harp movements:
1. When the camera moves away from or toward the marker, the virtual harp decreases or increases in size, respectively. As a result, users experience a zooming effect along the Z-axis.

2. When the camera moves left or right, the virtual harp moves right and left, respectively. When the camera moves up and down, the virtual harp moves down and up, respectively. The movement provides users with a navigation mode for viewing different parts of the harp.

3. Rotating the camera about the marker’s axes provides a rotation mode for viewing the virtual harp from different directions.

The interactions were taken into consideration when creating ARToolKit nodes in C++ for H3D. The design provides a bridge between the H3D API and ARToolKit, so that augmented reality applications can be easily built which take advantage of all the power provided by the H3D API. The ARToolKit portion of the program was developed as an independent library add-on for H3D that contains only a few nodes, which integrates the basic marker handling capability of ARToolKit.

ARToolKit has four stages that run in a loop. A node named ARToolkit was created as the main node which runs all of the ARToolKit’s functions in the H3D API. The ARToolkit node was designed as a bindable node. One instance is created at application initialization as a singleton which provides all communication with the ARToolKit.

ARToolKit uses computer vision algorithms to track the users’ viewpoint, using video tracking libraries to calculate, in real time, the real camera position and orientation relative to physical markers [11]. ARToolKit tracking works by capturing camera video of the real world allowing the computer to search through each video frame for any square shape. Then,
it calculates the position of the camera relative to a black square, which draws a computer graphics model from that position to render graphics overlaid on the real world.

The SeeThroughViewpoint node is a Viewpoint node that uses the marker to determine the position and orientation of the view. The users are able to interact with the virtual scene since they can translate and rotate the virtual harp based on marker movements. The SeeThroughBackground node is a background node that renders the ARToolKit camera image to the background to provide a see-through Augmented Reality environment. Using the SeeThroughViewpoint node together with the SeeThroughBackground node produces an augmented reality environment, as shown in Fig. 2.

**Figure 2.** Playing harp in augmented environment

**HARP STRING NODE AND VIBRATION MODEL**

A spring effect was activated at the string position when the line is touched using the Phantom Omni’s haptic device and deactivated when reaching the defined pulling limit, which causes the string to snap back to its original position and produces the appropriate
MIDI harp note sound. This allows the user to touch the line and view the motion of the line during the touching in the x, y, and z directions with the haptic device, providing the users the feeling of string tension during pulling the line with the Phantom Omni’s haptic device.

Originally a Python code was used to produce the string vibration animations. However, the first limitation was the code needed to have each string coded with all the necessary properties to do the animations and routed to the X3D file. The next limitation was caused by the fact that each string and their properties had to be written in the Python code; any change to the strings properties in the X3D file or movement to the harp’s placement on the screen would cause the haptic device to be unable to pluck the harp strings. This code did not have any of the vibration model equations implemented, and the code was limited in which mathematical functions it had to use. The final harp design required the use of thirty-six strings and realistic real-time vibrations. These limitations in Python would have made the code very long and confusing for using thirty-six strings, resulting in the loss of the ability to allow the users to move the harp in any position without providing the real-time vibrations. Therefore, a H3D node for the string animation was written in C++ to eliminate the limitations found in using the Python code.

The string is modeled as a mass-spring system where having N number of masses would produce N number of modes of transverse oscillations. For this computer-generated harp, the first six modes of oscillation are considered for the string vibration animation interaction to minimize the computation time. Each mass-spring section will be considered as a mass point along the string and can only move in one plane. On a harp, the strings are fixed at both ends of the instrument and since the string is modeled with many mass points along the line, the vibration motion will be analyzed using a Fourier analysis for each point along the line.
Since the strings on a realistic harp are not positioned on a starting base location, it was needed to take into account a starting position and an ending position in order to draw the strings in the proper location as a realistic harp. Using the y-axis starting point position (P2) and the y-axis ending point position (P1) the string length L will be P1-P2. As shown in Fig. 3, this simulates the realistic pulling motion limit variables in the string to provide the calculation of the pulling limit along the string.

![String pulling limit diagram](image)

**Figure 3.** String pulling limit diagram

The string pulling limit now needs to take into account the y-axis starting point position and the y-axis ending point position in order to use this equation for any string in any position on the harp model. The maximum pulling limit (H) is an arbitrary number based on half the distance between two strings along the x-axis, and the string pulling limit equation requires the use of two equations for the lower half and the upper half as in Eq. (1).
String pulling limit:

\[ h(y) = \begin{cases} 
\left( \frac{2H}{L} \right)y - P2, & P2 \leq y \leq \frac{L}{2} \\
-\left( \frac{2H}{L} \right)y - P1, & \frac{L}{2} \leq y \leq P1 
\end{cases} \quad (1) \]

The periodic function of the string was defined based on the pluck location with the fundamental frequency having a wavelength of 2L giving the limit on the y-axis of –L and L as shown in Fig. 4. This diagram leads to three sets of equations based on the pluck location in the periodic function used to do the analysis of the Fourier coefficient for the first six modes of oscillation, as shown in Eq. (2).
Figure 4. Periodic motion diagram

Fourier coefficient:

\[
C_n(y) = \frac{1}{2L} \int_{-L}^{L} y(z) \sin(nk_z z) dz = \\
\left\{ \\
\frac{1}{2L} \left[ h(y) \left( \frac{\sin(nk_z z)}{n^2 k_1^2} - z * \frac{\cos(nk_z z)}{nk_1} \right) \right]_{-L}^{L}, -y < z < y \\
\frac{1}{2L} \left[ \frac{h(y)}{L - y} \left( (z - L) * \frac{\cos(nk_z z)}{nk_1} - \frac{\sin(nk_z z)}{n^2 k_1^2} \right) \right]_{-L}^{L}, y < z < L \\
\frac{1}{2L} \left[ \frac{-h(y)}{L - y} \left( \frac{\sin(nk_z z)}{n^2 k_1^2} - (L + z) * \frac{\cos(nk_z z)}{nk_1} \right) \right]_{-L}^{L}, -L < z < -y \\
\right\} \tag{2}
\]
To simulate the vibration motion for each time frame for each node along the string, the Fourier coefficient values are calculated in the Fourier analysis Eq. (3). The string properties, wavenumber Eq. (4), and eigenfrequency Eq. (5), also known as harmonics would be defined as function calls to be used during the Fourier analysis calculation. The damping term ($\Gamma$) value was defined on a trial and error basis by matching the vibration decay to the sound decay, and the frequency ($f$) value in the eigenfrequency equation was defined using the midi note frequency definition for each string. The string’s note frequency is placed in a list and selected based on the user’s string number input.

Fourier analysis:

$$x(y,t) = \sum_{n=1}^{N} C_n(y) \sin(k_n z) \cos(2\pi v_n t)e^{-\Gamma t}$$  \hspace{1cm} (3)$$

Wavenumber:

$$k_n = \frac{n\pi}{L}$$  \hspace{1cm} (4)$$

Eigenfrequency:

$$v_n = n \ast f$$  \hspace{1cm} (5)$$
A flow chart for describing the process is shown in Fig. 5. The program can be divided into three sections with section one handling the line drawing for the string called Harpline, section two handling the forces for the string called Harpforce, and section three handling the sound for the string called Harpsound, all being place in the group node called Harp.

When the program starts Harpline, an IndexedLineSet node initially draws the string with a vertical line using two hundred points equally spaced from the line length equation being divided by the number of points in the direction of the y-axis. To manipulate the line’s points, the IndexedLineSet IsTouched feature is routed in the X3D code and is initially set to false, and the haptic device is informed if the line is touched which starts the animation for pulling the string. One example is shown in Fig. 6.

During the pulling of the string, Harpforce an H3DForceEffect node is activated. It creates a spring effect by using the distance difference from the initial position to the current position multiplied by the spring constant to give the users the feeling of string tension while the line is pulled within the pulling limit using the Phantom Omni’s haptic device. Once the user reaches the string’s calculated pulling limit, the string would start the vibration animation removing the spring effect and producing the appropriate MIDI harp note sound.

The vibrate function in Harpline starts a real-time timer loop for drawing each of the two hundred points along the string in the correct position from the Fourier analysis equations, for which the timer is reset every time the string is touched. The vibration damping term value was found by matching the MIDI sound decay to the visual string vibration decay.
REALISTIC HARP DESIGN AND SOUND

To model the realistic harp, SolidWorks 2001 was used, and it was able to convert the model file into an X3D file that H3D uses. Using Fig. 7 as a model guide, the harp frame was divided into four parts consisting of the column, base, soundboard, and string frame. This SolidWorks assembly file was then converted into an X3D file for which now the model is a series of IndexFaceSets points with a wood texture applied on the face. The strings were colored a light gray color to resemble the color of metal strings.
Figure 6. Plucking Harp String

Figure 7. Harp model guide
The Harpsound node created in C++ used MIDIShare for the sound output. The harp’s sound range is from C2 to C7 on the MIDI sound range scale. When the program starts Harpsound, an X3DChildNode node initially opens the MIDIShare system and changes the sound output to produce harp type MIDI sounds. When the string’s calculated pulling limit is reached, the MIDI pitch value of the string was sent to the playnote function in Harpsound. Once the vibration animation starts, there is a switch to activate the sound.

**VIRTUAL THERAPIST**

In most therapy sessions, the therapist would prompt the individual in therapy to perform an exercise and observe the individual during therapy exercises for errors and improvements. Once the individual leaves the therapy sessions, the therapist wants the individual in therapy to continue performing the exercises on their own. Therapy exercises are repetitive, causing the individual performing the therapy exercises to become bored and unmotivated to continue performing the exercises on their own. Therefore to allow the individual to engage in self-motivating therapy exercises outside the therapy sessions and have the therapist observe the individual during therapy exercises without musical knowledge, in this study, a virtual therapist feature was developed.

The virtual therapist feature includes a sequence of colored string. The patients can play a song by plucking the harp by following the colored string. Here, Python is used to create the virtual therapist guiding feature because Python allows the users to modify the sting sequence easily using a text editor and does not need to be compiled the program again.

The virtual scene uses a 3D sphere as a 3D button to active the virtual therapist feature. As shown in Fig. 6, touching this 3D sphere allows individuals to follow a sequence of notes
by following the colored strings to help the user identify the notes similar to playing the Simon game. In this study, the virtual therapist will highlight the strings and guide the users to play the song of “Joy to the World”.

USER STUDY

There were 20 participants in the user study. The requirement for our participants included having any upper limb limitations or disability effecting their arm and hand. The total age distributaries are shown in Fig. 8. There are 55% of participants in the age range of 18 and 30, 10% in the range of 31 and 40, 15% in the range of 41 and 50, and 20% in the range of 51 and 60. Fig. 9 shows the distribution of years of the participants had been in therapy. There are 80% of the participants have been in therapy.

In addition, 15 participants (75%) having some type of musical experience. Seventeen participants (85%) have not used any type of computer-aided music software or equipment, and the other users used software such as to write sheet music, keyboarding, and Guitar Hero.

![Age of Participants Pie Chart](image)

**Figure 8.** Participants Age Pie Chart
There were 12 females and 8 males that participated in the study. The user study testing procedure consisted of the four following sections:

1. Greeting and background questionnaire
2. Orientation
3. Performance test
4. Participant debriefing

The participants were greeted and made to feel comfortable while told about the study and asked to sign the informed consent form. During this time, the participants were informed on the issues of confidentiality and allowed an opportunity to ask any questions they might have concerning the test. Each participant was asked to fill out a short questionnaire gathering basic background information before using the system. Participants were given an explanation of the virtual harp therapy system equipment so that they would become familiar with the technology and understand how it is being used. This was followed by an informed

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**Figure 9. Years in Therapy Pie Chart**

![Pie Chart](image)

[52% for 1-2 years, 40% for 2-5 years, 5% for 5-10 years, 10% for 10+ years, 35% for None or Less than 1 year]
discussion about how the system will work and an explanation of the interface with the equipment. During the observed testing, the participants were be positioned in front of the virtual harp setup and asked to familiarize themselves with the harp and its interface to help in adjusting to the unique instrument.

After the familiarization time limit had expired, the participants were asked to freely play the virtual harp and then follow a simple sequence of notes using the virtual therapist feature by following the color-coded strings to help the user identify the notes, as shown in Fig. 10. After the testing tasks were complete, the participant were asked to fill out a brief questionnaire pertaining to the usability of the virtual harp, development of skills, improvement in range of motion, and entertainment value.

*Figure 10. User study participants playing virtual harp*
STUDY RESULTS

Based on the participants’ type of disability they were formed into two groups. There were 9 participants classified with long-term disability (cerebral palsy, arthritis) and 11 participants classified with short-term disability (pinched nerves, injuries). Statistical analysis was done using one sample t-test for the whole study group (20) and to compare the long-term disability and short-term disability. For users with either long-term disability or short-term disability the hypotheses are the following:

1. The virtual harp system would be easy and comfortable from using to the users
2. The users would improve their range of motion and skills
3. Users would be motivated to continue playing the system for therapy

The following questions are used as a composite result related to the ease and comfort from using for the first hypothesis.

1. How would you describe the level of difficulty in using the virtual harp?
   (1=very easy, 5= very difficult)
2. Did you find that the virtual harp acted in a predictable manner?
   (1=strongly agree, 5= strongly disagree)
3. How satisfying was the virtual harp to use?
   (1=very satisfying, very unsatisfying)
4. Was the virtual harp comfortable to use physically?
   (1=strongly agree, 5= strongly disagree)
5. Were you able to play notes or individual strings with little or no error?
   (1=strongly agree, 5= strongly disagree)
The following questions are used as a composite result related to the improvement in range of motion and skills for the second hypothesis.

6. Did you experience any improvement in your range of motion?
   (1=much improvement, 4=no improvement)

7. Did you experience any improvement in your skill level?
   (1=yes, 3=no)

The following questions are used as a composite result related to the user motivation from playing for the third hypothesis.

8. I felt motivated to continue playing this harp over traditional therapy exercises.
   (1=strongly agree, 5=strongly disagree)

9. I would recommend this along with traditional therapy.
   (1=strongly agree, 5=strongly disagree)

10. I would recommend this augmented reality format for other therapy.
    (1=strongly agree, 5=strongly disagree)

11. Would you like to play the virtual harp or another musical instrument presented in augmented reality again in the future?
    (1=yes, 3=no)

The composite result for questions 6-7 related to the improvement in range of motion and skills was calculated by Eq. (6). The composite result for questions 8-11 related to the user motivation from playing was calculated by Eq. (7). These composite result questions needed to use a weighted equation to change the scale from 0-1, since the questionnaire scale was different between the questions.
Composite result for questions 6-7:

\[ x_i = \frac{1}{2} \left( \frac{1}{4} x_n + \frac{1}{3} x_7 \right) \]  \hspace{1cm} (6)

Composite result for questions 8-11:

\[ x_i = \frac{1}{2} \left( \frac{1}{5} \left( \frac{x_8 + x_9 + x_{10}}{3} \right) + \frac{1}{3} x_{11} \right) \]  \hspace{1cm} (7)

Table 1 shows the results of the one sample t-test for the whole study group, the long-term disability, and short-term disability on the three hypotheses.

Users with either long-term disability or short-term disability felt the virtual harp system was neither easy nor difficult when using, so the first hypothesis is rejected. Short-term disability users gained improvement in their range of motion and skills. Long-term disability users did not show improvement. However, overall, as a group, users did show improvement, so the second hypothesis is accepted. Users with either long-term disability or short-term disability were motivated to continue playing the system for therapy, so the third hypothesis is accepted.
Table 1. One-sample T-test results

<table>
<thead>
<tr>
<th></th>
<th>Whole Group</th>
<th>Long Term</th>
<th>Short Term</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composite results for problems 1-5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ho: $\mu =3$</td>
<td>$\mu =3.21$</td>
<td>$\mu =3.13$</td>
<td>$\mu =3.27$</td>
</tr>
<tr>
<td>Ha: $\mu &lt;3$</td>
<td>$p=.9$</td>
<td>$p=.7$</td>
<td>$p=.88$</td>
</tr>
<tr>
<td></td>
<td>not sig.</td>
<td>not sig.</td>
<td>not sig.</td>
</tr>
<tr>
<td>Composite results for problems 6-7</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ho: $\mu =.875$</td>
<td>$\mu =.68$</td>
<td>$\mu =.73$</td>
<td>$\mu =.65$</td>
</tr>
<tr>
<td>Ha: $\mu &lt;.875$</td>
<td>$p=.0004$</td>
<td>$p=.036$</td>
<td>$p=.0034$</td>
</tr>
<tr>
<td></td>
<td>sig.</td>
<td>not sig.</td>
<td>sig.</td>
</tr>
<tr>
<td>Composite results for problems 8-11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ho: $\mu =.8$</td>
<td>$\mu =0.443$</td>
<td>$\mu =.44$</td>
<td>$\mu =.44$</td>
</tr>
<tr>
<td>Ha: $\mu &lt;.8$</td>
<td>$p=.0001$</td>
<td>$p=.0001$</td>
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<td></td>
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</table>

**CONCLUSION AND FUTURE WORK**

Some of the users’ comments mentioned that this will take awhile to get used to, but there could be good skills learned and that it was more interesting than traditional therapy because playing the harp gives an immediate reward for trying. Another comment mentioned with improvement the system would be versatile for use in therapy like hand/eye coordination.

Many users commented on the haptic device sinking through the harp, flashing background made it hard to see, and the headset was too heavy and big, making it hard to keep in place. Based on the results for the level of difficulty in using the virtual harp, the
users felt it was difficult using the system. However, since the equipment was new to them, this may have been the reason. Users expressed they experienced some improvement in their range of motion but really noticed improvement in their skills. In addition, users would recommend this along with traditional therapy and like to play the virtual harp or another musical instrument presented in augmented reality again in the future.

The virtual harp therapy system would benefit from a better method on the handling of the video image for the ARToolKit background in H3D to keep the background image from flashing while using the harp. The virtual therapist system could also be expanded to represent different difficulty levels of pieces of music by adding more three-dimensional buttons that provide different difficulty levels in therapy. Providing the virtual harp therapy system for use at a healthcare facility along with an individuals’ traditional therapy program would be a great benefit. Overall, the virtual harp system would be a beneficial addition to a therapy program.

**NOMENCLATURE**

- **H**  Defined pulling limit value (m)
- **L**  Length of string (m)
- **N**  Number of mass points on string
- **h(y)**  Pulling limit based from position (m)
- **n**  Number of mode
- **t**  Time (s)
- **x**  Position (m)
- **y(z)**  Node position along y and z-axis (m)
\[ z \] Node position along z-axis (m)
\[ \Gamma \] Damping term

**ACKNOWLEDGMENTS**

We would like to thank Dr. Robert McQueeney for his kind contributions with the physics part. We also would like to thank Mr. Jeremiah Still for his help in analyzing the data.

**REFERENCES**


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CHAPTER 4. SUMMARY AND DISCUSSION

The virtual harp system was an attempt to provide interactive musical experiences and development of skills during therapy for individuals with disabilities in a motivating and fun method. In the initial iteration, special education children were to have fun learning and be motivated in remembering name of colors, musical instruments, and using the computer equipment along with developing physical and attentive listening skills accompanied with teachers and therapists. While the children were interested in playing the virtual harp, it was determined that the most important information for children to gain from our program was using both visual and audio sensory cues to keep the children engaged with the program. For the final iteration the system moved to an approach to provide more interaction and stimuli allowing individuals to pluck or strum the virtual harp with the Phantom Omni haptic device in an immersive environment. This provides individuals a means to engage in a self-motivating therapy exercises outside the therapy room and therapists without musical knowledge to observe the individual during therapy exercises. Virtual reality technology is currently being explored for its potential benefit as a therapeutic intervention for retraining coordinated movement patterns since it has the unique capability to be engaging, functional, and purposeful for patient motivation. The virtual harp system is coupled with music to increase the therapeutic goals from music therapy and to help stimulate and motivate the use of therapy exercises. The users from the study did have some frustrations using the system but felt that they could improve with practice over time. They felt this system was more enjoyable, interesting, and a fun challenge over traditional therapy. It is hard to judge the therapy exercise this system would improve, but users had a great experience.
FUTURE WORK

The virtual harp therapy system would benefit being used at a healthcare facility such as the hospital or nursing home along with an individuals’ traditional therapy program. The virtual harp therapy system would benefit from an examination of how the video camera image is handled for the ARToolKit background image in H3D to keep the background image from flashing. While the current method worked better on the computer used for the user testing, users still had difficulties and frustrations with using the system. In addition, the head mounted display should be replaced with a lighter version to provide users with more comfort. The virtual harp therapy system could be expanded by adding more three-dimensional buttons that represent different difficulty levels in therapy by using different difficulty levels of pieces of music. In addition, this system could be expanded to include different type of instruments or different types of therapy scenarios such as lifting different weighted objects. The system could be updated to use the newest release of H3D and other programs. Although measuring improvement skills in therapy can be difficult, individuals cannot forget the experience and rewards they received using this system.
APPENDIX A. EVALUATION INSTRUMENTS

This section contains the background questionnaire that was used during the greeting and orientation period of the Virtual Harp Therapy User Study for gathering basic background information about the participants before using the system. Following that questionnaire is the user experience questionnaire that was used after the performance testing period of the Virtual Harp Therapy User Study for gathering information pertaining to the usability of the virtual harp, development of skills, improvement in range of motion, and entertainment value from the participants after using the system.
BACKGROUND QUESTIONNAIRE

1. Age: How old are you?  
(Please circle appropriate)  
18-30  31-40  41-50  51-60  61+  

2. Gender?  
(Please circle appropriate)  
Male  Female  

3. Disability cause? (Stoke, CP, Sport/Work Injury)  

4. How comfortable are you with using computer technology?  
(Please circle one)  
Very comfortable  Somewhat comfortable  Neutral  Somewhat uncomfortable  Uncomfortable  

5. Do you have musical experience? (Choir, Instrument, Dance, Composition)  
(Please circle one)  
Yes  No  

5.a If YES, how many years of experience do you have?  
(Please circle one)  
Less than 1  1-2  2-5  5-10  10-15  15+  

6. Have you used computer aided music instrumentation? (Virtual Instrument, Computer composing/mixing, Synthesizer)  
(Please circle one)  
Yes  No  

6.a If YES, please describe or explain.  

7. Have you ever been in therapy?  
(Please circle one)  
Yes  No  

7.a If YES, how many years?  
(Please circle one)  
Less than 1  1-2  2-5  5-10  10-15  15+  
(Please explain)  

8. How interested are you in interacting with a virtual musical instrument?  
(Please circle one)  
Very interested  Somewhat interested  Neutral  Not very interested  Not interested  

9. I think virtual musical instrumentation could benefit society.  
(Please circle one)  
Strongly agree  Agree  Neutral  Disagree  Strongly Disagree  
Why?
USER EXPERIENCE QUESTIONNAIRE

1. How would you describe the level of difficulty in using the virtual harp?
   \( \text{(Please circle one)} \)
   Very Easy  Easy  Neutral  Difficult  Very Difficult

2. Did you find that the virtual harp acted in a predictable manner?
   \( \text{(Please circle one)} \)
   Strongly Agree  Agree  Neutral  Disagree  Strongly Disagree
   Why?

3. How satisfying was the virtual harp to use?
   \( \text{(Please circle one)} \)
   Very satisfying  Satisfying  OK  Somewhat unsatisfying  Unsatisfying

4. Was the virtual harp comfortable to use physically?
   \( \text{(Please circle one)} \)
   Strongly Agree  Agree  Neutral  Disagree  Strongly Disagree
   Why?

5. Were you able to play notes or individual strings with little or no error?
   \( \text{(Please circle one)} \)
   Strongly Agree  Agree  Neutral  Disagree  Strongly Disagree

6. Did you experience any improvement in your range of motion?
   \( \text{(Please circle one)} \)
   Strong Improvement  Medium Improvement  Mild Improvement  No Improvement

7. Did you experience any improvement in your skill level?
   \( \text{(Please circle one)} \)
   Yes  No  Maybe
   (Please explain)

8. I felt motivated to continue playing this harp over traditional therapy exercises.
   \( \text{(Please circle one)} \)
   Strongly Agree  Agree  Neutral  Disagree  Strongly Disagree
   Why?

9. I would recommend this along with traditional therapy.
   \( \text{(Please circle one)} \)
   Strongly Agree  Agree  Neutral  Disagree  Strongly Disagree
   Why?
10. I would recommend this augmented reality format for other therapy.
(Please circle one)
Strongly Agree       Agree       Neutral       Disagree       Strongly Disagree
Why?

11. Would you like to play the virtual harp or another musical instrument presented in augmented reality again in the future?
(Please circle one)
Yes       No       Maybe
(Please explain)

12. Please explain any positive or negative aspects you experienced while using the virtual harp.
APPENDIX B. STATISTICAL RESULTS

This section contains the statistical analysis data using one sample T-test for the whole study group and the group divided into two disability types on the JMP 6.0 statistical software. The data is listed using this following order: whole study group, long term disability group, and short term disability group. The hypotheses were as follows:

Questions 1-11 and the composite results for questions 1-5 on ease and comfort

\( H_0: \mu = 3 \)
\( H_a: \mu < 3 \)
\( \alpha = 0.05 \)

The composite results for questions 6 & 7 on improvement

\( H_0: \mu = 0.875 \)
\( H_a: \mu < 0.875 \)
\( \alpha = 0.05 \)

The composite results for questions 8-11 on motivation

\( H_0: \mu = 0.8 \)
\( H_a: \mu < 0.8 \)
\( \alpha = 0.05 \)
JMP statistical software output for whole study group (N=20)

1. Level of Difficulty

Moments
Mean 3.9
Std Dev 0.967906
Std Err Mean 0.2164304
upper 95% Mean 4.352994
lower 95% Mean 3.447006
N 20

Test Mean=value
Hypothesized Value 3
Actual Estimate 3.9
df 19
Std Dev 0.96791
Test Statistic 4.1584
Prob > |t| 0.0005
Prob > t 0.0003
Prob < t 0.9997

2. Acted in predictable manner

Moments
Mean 3
Std Dev 1.0259784
Std Err Mean 0.2294157
upper 95% Mean 3.4801726
lower 95% Mean 2.5198274
N 20

Test Mean=value
Hypothesized Value 3
Actual Estimate 3
df 19
Std Dev 1.02598
Test Statistic 0.0000
Prob > |t| 1.0000
Prob > t 0.5000
Prob < t 0.5000

2.2
3. Satisfying to use virtual harp

Moments

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<tbody>
<tr>
<td>Mean</td>
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<tr>
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</tr>
<tr>
<td>Std Err Mean</td>
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<tr>
<td>upper 95% Mean</td>
<td>3.0595566</td>
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<tr>
<td>lower 95% Mean</td>
<td>2.2404434</td>
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Test Mean=3

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<tr>
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Test Statistic: -1.7887

Prob > |t|: 0.0896

Prob > t: 0.9552

Prob < t: 0.0448

4. Comfortable using physically

Moments

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<td>lower 95% Mean</td>
<td>2.7295288</td>
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Test Mean=3

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<tr>
<td>Std Dev</td>
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Test Statistic: 0.8898

Prob > |t|: 0.3847

Prob > t: 0.1924

Prob < t: 0.8076
5. Play notes or strings with little or no error

Moments

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<td>3.8058933</td>
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<td>2.7941067</td>
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Test Mean=value

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<td>Std Dev</td>
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<tr>
<td>Prob &lt; t</td>
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6. Improvement in range of motion

Moments

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Test Mean=value

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</table>
7. Improvement in skill level

**Moments**

- Mean: 1.7
- Std Dev: 0.8645047
- Std Err Mean: 0.1933091
- upper 95% Mean: 2.1046007
- lower 95% Mean: 1.2953993
- N: 20

**Test Mean=value**

- Hypothesized Value: 3
- Actual Estimate: 1.7
- df: 19
- Std Dev: 0.8645

- Test Statistic: -6.7250
- Prob > |t|: <.0001
- Prob > t: 1.0000
- Prob < t: <.0001

8. Motivation over traditional therapy

**Moments**

- Mean: 2.65
- Std Dev: 0.9880869
- Std Err Mean: 0.220943
- upper 95% Mean: 3.1124389
- lower 95% Mean: 2.1875611
- N: 20

**Test Mean=value**

- Hypothesized Value: 3
- Actual Estimate: 2.65
- df: 19
- Std Dev: 0.98809

- Test Statistic: -1.5841
- Prob > |t|: 0.1297
- Prob > t: 0.9352
- Prob < t: 0.0648
9. Use along with traditional therapy

Moments

Mean 2.05
Std Dev 0.6863327
Std Err Mean 0.1534687
upper 95% Mean 2.3712136
lower 95% Mean 1.7287864
N 20

Test Mean=value

Hypothesized Value 3
Actual Estimate 2.05
df 19
Std Dev 0.68633

Test Statistic 6.1902
Prob > |t| <.0001
Prob > t 1.0000
Prob < t <.0001

10. Use augmented reality

Moments

Mean 2.1
Std Dev 0.7181848
Std Err Mean 0.160591
upper 95% Mean 2.4361209
lower 95% Mean 1.7638791
N 20

Test Mean=value

Hypothesized Value 3
Actual Estimate 2.1
df 19
Std Dev 0.71818

Test Statistic 5.6043
Prob > |t| <.0001
Prob > t 1.0000
Prob < t <.0001
11. Play again in future

Moments

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Test Mean=value

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Composite results (Q1-Q5)

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Test Mean=value

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Composite results (Q6-Q7)

Moments
Mean 0.6897
Std Dev 0.2099171
Std Err Mean 0.0469389
upper 95% Mean 0.7879442
lower 95% Mean 0.5914558
N 20

Test Mean=value
Hypothesized Value 0.875
Actual Estimate 0.6897
df 19
Std Dev 0.20992
Test Statistic -3.9477
t Test 0.0009
Prob > |t| 0.0004
Prob > t 0.9996
Prob < t 0.0004

Composite results (Q8-Q11)

Moments
Mean 0.44335
Std Dev 0.1149358
Std Err Mean 0.0257004
upper 95% Mean 0.4971416
lower 95% Mean 0.3895584
N 20

Test Mean=value
Hypothesized Value 0.8
Actual Estimate 0.44335
df 19
Std Dev 0.11494
Test Statistic -13.877
t Test <.0001
Prob > |t| <.0001
Prob > t 1.0000
Prob < t <.0001
JMP statistical software output for two disability groups: long term (N=9)

1. Level of Difficulty

Moments
Mean: 3.8888889
Std Dev: 1.0540926
Std Err Mean: 0.3513642
upper 95% Mean: 4.6991362
lower 95% Mean: 3.0786416
N: 9

Test Mean = value
Hypothesized Value: 3
Actual Estimate: 3.88889
df: 8
Std Dev: 1.05409

Test Statistic: 2.5298
Prob > |t|: 0.0353
Prob > t: 0.0176
Prob < t: 0.9824

2. Acted in predictable manner

Moments
Mean: 2.8888889
Std Dev: 1.1666667
Std Err Mean: 0.3888889
upper 95% Mean: 3.7856683
lower 95% Mean: 1.9921095
N: 9

Test Mean = value
Hypothesized Value: 3
Actual Estimate: 2.88889
df: 8
Std Dev: 1.16667

Test Statistic: -0.2857
Prob > |t|: 0.7824
Prob > t: 0.6088
Prob < t: 0.3912
3. Satisfying to use virtual harp

Moments
Mean 2.222222
Std Dev 0.833333
Std Err Mean 0.277778
upper 95% Mean 2.8627789
lower 95% Mean 1.5816655
N 9

Test Mean=value
Hypothesized Value 3
Actual Estimate 2.22222
df 8
Std Dev 0.83333

Test Statistic -2.8000
t Test -0.0232
Prob > |t| 0.7287
Prob > t 0.3644
Prob < t 0.6356

4. Comfortable using physically

Moments
Mean 3.111111
Std Dev 0.9279607
Std Err Mean 0.3093202
upper 95% Mean 3.8244049
lower 95% Mean 2.3978174
N 9

Test Mean=value
Hypothesized Value 3
Actual Estimate 3.11111
df 8
Std Dev 0.92796

Test Statistic 0.3592
t Test 0.0232
Prob > |t| 0.7287
Prob > t 0.3644
Prob < t 0.6356
5. Play notes or strings with little or no error

Moments

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<td>lower 95% Mean</td>
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Test Mean=value

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6. Improvement in range of motion

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<td>Std Dev</td>
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<tr>
<td>Std Err Mean</td>
<td>0.2357023</td>
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<tr>
<td>upper 95% Mean</td>
<td>3.876637</td>
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<tr>
<td>lower 95% Mean</td>
<td>2.7898029</td>
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Test Mean=value

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<td>Prob &lt; t</td>
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</table>
7. Improvement in skill level

Moments
- Mean: 1.8888889
- Std Dev: 0.9279607
- Std Err Mean: 0.3093202
- upper 95% Mean: 2.6021826
- lower 95% Mean: 1.1755951
- N: 9

Test Mean = value
- Hypothesized Value: 3
- Actual Estimate: 1.88889
- df: 8
- Std Dev: 0.92796
- Test Statistic: -3.5921
- Prob > |t|: 0.0071
- Prob > t: 0.9965
- Prob < t: 0.0035

8. Motivation over with traditional therapy

Moments
- Mean: 2.4444444
- Std Dev: 0.7264832
- Std Err Mean: 0.2421611
- upper 95% Mean: 3.0028688
- lower 95% Mean: 1.8860201
- N: 9

Test Mean = value
- Hypothesized Value: 3
- Actual Estimate: 2.44444
- df: 8
- Std Dev: 0.72648
- Test Statistic: -2.2942
- Prob > |t|: 0.0509
- Prob > t: 0.9745
- Prob < t: 0.0255
9. Use along with traditional therapy

Moments

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<tr>
<td>Std Err Mean</td>
<td>0.166667</td>
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<tr>
<td>upper 95% Mean</td>
<td>2.384334</td>
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<td>lower 95% Mean</td>
<td>1.615666</td>
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Test Mean = value

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<tr>
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<td>Std Dev</td>
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<td>Prob &lt; t</td>
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10. Use augmented reality

Moments

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<td>upper 95% Mean</td>
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<td>lower 95% Mean</td>
<td>1.581666</td>
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Test Mean = value

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<td>Prob &gt;</td>
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<td>Prob &gt; t</td>
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<td>Prob &lt; t</td>
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</table>
11. Play again in future

Moments

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<td>Std Err Mean</td>
<td>0.1666667</td>
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<td>upper 95% Mean</td>
<td>1.7176674</td>
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<td>lower 95% Mean</td>
<td>0.9489993</td>
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<td>N</td>
<td>9</td>
</tr>
</tbody>
</table>

Test Mean = value

| Hypothesized Value | 3     |
| Actual Estimate    | 1.33333 |
| df                | 8     |
| Std Dev           | 0.5   |

| Test Statistic     | -10.000 |
| Prob > |t|          | <.0001 |
| Prob > t           | 1.0000  |
| Prob < t           | <.0001  |

Composite results (Q1-Q5)

Moments

<p>| | |</p>
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</tr>
</thead>
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<td>Std Dev</td>
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<tr>
<td>Std Err Mean</td>
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<tr>
<td>upper 95% Mean</td>
<td>3.6929321</td>
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<tr>
<td>lower 95% Mean</td>
<td>2.5737345</td>
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<tr>
<td>N</td>
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</tbody>
</table>

Test Mean = value

| Hypothesized Value | 3     |
| Actual Estimate    | 3.13333 |
| df                | 8     |
| Std Dev           | 0.72801 |

| Test Statistic     | 0.5494 |
| Prob > |t|          | 0.5977 |
| Prob > t           | 0.2989 |
| Prob < t           | 0.7011 |
Composite results (Q6-Q7)

Moments
Mean 0.7315556
Std Dev 0.209321
Std Err Mean 0.0697737
upper 95% Mean 0.8924539
lower 95% Mean 0.5706572
N 9

Test Mean=value
Hypothesized Value 0.875
Actual Estimate 0.73156
df 8
Std Dev 0.20932

Test Statistic -2.0559
Prob > |t| 0.0738
Prob > t 0.9631
Prob < t 0.0369

Composite results (Q8-Q11)

Moments
Mean 0.4444444
Std Dev 0.1257866
Std Err Mean 0.0419289
upper 95% Mean 0.5411326
lower 95% Mean 0.3477563
N 9

Test Mean=value
Hypothesized Value 0.8
Actual Estimate 0.44444
df 8
Std Dev 0.12579

Test Statistic -8.4800
Prob > |t| <.0001
Prob > t 1.0000
Prob < t <.0001
JMP statistical software output for two disability groups: short term (N=11)

1. Level of Difficulty

Moments
- Mean: 3.9090909
- Std Dev: 0.9438798
- Std Err Mean: 0.2845905
- Upper 95% Mean: 4.543198
- Lower 95% Mean: 3.2749838
- N: 11

Test Mean=value
- Hypothesized Value: 3
- Actual Estimate: 3.90909
- df: 10
- Std Dev: 0.94388

- Test Statistic: 3.1944
- Prob > |t|: 0.0096
- Prob > t: 0.0048
- Prob < t: 0.9952

2. Acted in predictable manner

Moments
- Mean: 3.0909091
- Std Dev: 0.9438798
- Std Err Mean: 0.2845905
- Upper 95% Mean: 3.7250162
- Lower 95% Mean: 2.456802
- N: 11

Test Mean=value
- Hypothesized Value: 3
- Actual Estimate: 3.09091
- df: 10
- Std Dev: 0.94388

- Test Statistic: 0.3194
- Prob > |t|: 0.7560
- Prob > t: 0.3780
- Prob < t: 0.6220
3. Satisfying to use virtual harp

Moments

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<tbody>
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<td>Mean</td>
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<tr>
<td>Std Dev</td>
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<td>Std Err Mean</td>
<td>0.2335</td>
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<tr>
<td>upper 95% Mean</td>
<td>3.5204</td>
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<tr>
<td>lower 95% Mean</td>
<td>2.4796</td>
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Hypothesized Value: 3
Actual Estimate: 3

Test Mean = value

<table>
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<tbody>
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<tr>
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<td>Prob &gt; t</td>
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4. Comfortable using physically

Moments

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<td>Std Err Mean</td>
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Hypothesized Value: 3
Actual Estimate: 3.2727

Test Mean = value

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<td>Prob &lt; t</td>
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5. Play notes or strings with little or no error

### Moments
- **Mean**: 3.0909091
- **Std Dev**: 1.2210279
- **Std Err Mean**: 0.3681538
- **upper 95% Mean**: 3.9112068
- **lower 95% Mean**: 2.2706114
- **N**: 11

### Test Mean=value
- **Hypothesized Value**: 3
- **Actual Estimate**: 3.09091
- **df**: 10
- **Std Dev**: 1.22103

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6. Improvement in range of motion

### Moments
- **Mean**: 3.1818182
- **Std Dev**: 0.9816498
- **Std Err Mean**: 0.2959786
- **upper 95% Mean**: 3.8412995
- **lower 95% Mean**: 2.5223369
- **N**: 11

### Test Mean=value
- **Hypothesized Value**: 3
- **Actual Estimate**: 3.18182
- **df**: 10
- **Std Dev**: 0.98165

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7. Improvement in skill level

![Boxplot for improvement in skill level](chart1)

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<td>upper 95% Mean</td>
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<tr>
<td>lower 95% Mean</td>
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<tr>
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<tr>
<td>Prob &gt;</td>
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<td>Prob ≤</td>
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8. Motivation over with traditional therapy

![Boxplot for motivation over traditional therapy](chart2)

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<td>upper 95% Mean</td>
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<tr>
<td>lower 95% Mean</td>
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<tr>
<td>t Test</td>
</tr>
<tr>
<td>Prob &gt;</td>
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<tr>
<td>Prob ≤</td>
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9. Use along with traditional therapy

Moments

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Test Mean=value

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| Test Statistic | t Test | Prob > |t| | Prob > t | Prob < t |
|----------------|--------|--------|---|---------|---------|
| -3.6274        | -      | 0.0046 |   | 0.9977  | 0.0023  |

10. Use augmented reality

Moments

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Test Mean=value

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<td>10</td>
<td>0.63246</td>
</tr>
</tbody>
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| Test Statistic | t Test | Prob > |t| | Prob > t | Prob < t |
|----------------|--------|--------|---|---------|---------|
| -5.2440        | -      | 0.0004 |   | 0.9998  | 0.0002  |
11. Play again in future

Moments

<p>| | |</p>
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<tr>
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<tr>
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<tr>
<td>Std Err Mean</td>
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<td>upper 95% Mean</td>
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<tr>
<td>lower 95% Mean</td>
<td>0.9589256</td>
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<tr>
<td>N</td>
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Test Mean=value

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<tbody>
<tr>
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<tr>
<td>Actual Estimate</td>
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<tr>
<td>df</td>
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<tr>
<td>Std Dev</td>
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<tr>
<td>Prob &gt;</td>
<td>t</td>
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<tr>
<td>Prob &gt; t</td>
<td>1.0000</td>
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<tr>
<td>Prob &lt; t</td>
<td>&lt;.0001</td>
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Composite results (Q1-Q5)

Moments

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<td>Std Dev</td>
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<tr>
<td>Std Err Mean</td>
<td>0.2145146</td>
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<tr>
<td>upper 95% Mean</td>
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<td>2.7947589</td>
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Test Mean=value

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<table>
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<tbody>
<tr>
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<tr>
<td>Actual Estimate</td>
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<td>df</td>
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<tr>
<td>Std Dev</td>
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<table>
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<tr>
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<tbody>
<tr>
<td>Prob &gt;</td>
<td>t</td>
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<tr>
<td>Prob &gt; t</td>
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<tr>
<td>Prob &lt; t</td>
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Composite results (Q6-Q7)

Moments
Mean 0.6554545
Std Dev 0.2140207
Std Err Mean 0.0645297
upper 95% Mean 0.7992356
lower 95% Mean 0.5116735
N 11

Test Mean=\text{value}
Hypothesized Value 0.875
Actual Estimate 0.65545
df 10
Std Dev 0.21402

Test Statistic -3.4022
Prob > |t| 0.0067
Prob > t 0.9966
Prob < t 0.0034

Composite results (Q8-Q11)

Moments
Mean 0.4424545
Std Dev 0.1115333
Std Err Mean 0.0336285
upper 95% Mean 0.5173836
lower 95% Mean 0.3675255
N 11

Test Mean=\text{value}
Hypothesized Value 0.8
Actual Estimate 0.44245
df 10
Std Dev 0.11153

Test Statistic -10.632
Prob > |t| <.0001
Prob > t 1.0000
Prob < t <.0001
BIBLIOGRAPHY


ACKNOWLEDGEMENTS

I would like to take this opportunity to express my thanks to those who helped me with various aspects of conducting research and the writing of this thesis. First and foremost, my family for their insights and words of encouragement have often inspired me and renewed my hopes for completing my graduate education. I would like to think Shana Smith for her guidance, patience, and support throughout this research and the writing of this thesis. I would also like to thank my committee members for their efforts and contributions to this work: Kris Bryden for her musical knowledge guidance and Robert McQueeney for his guidance with physical vibrations for strings. I would additionally like to thank H3D forum users and Karlu L. Palmerius for their guidance and assistance with using the programs H3D and ARToolKit. Finally, I would like to thank my friends for their help and support: Michael Oren, Adam Faeth, Kristi Forwein, Robert Taylor, and Jeremiah Still.