UTILIZATION OF AUDITORY CUES TO ENHANCE THERAPY FOR CHILDREN WITH CEREBRAL PALSY

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UTILIZATION OF AUDITORY CUES TO ENHANCE THERAPY FOR CHILDREN WITH CEREBRAL PALSY

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To the giants on whose shoulders we stand.

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LIST OF SYMBOLS AND ABBREVIATIONS

CP	cerebral palsy
VR	virtual reality
RAS	rhythmic auditory stimulus
ROM	range of motion
PAV	peak angular velocity
MT	movement time
STV	spatio-temporal variability
MU	movement unit
P1	protocol 1
P2	protocol 2
PD	Parkinson’s disease
CVA	cerebral vascular accident
SF	shoulder flexion angle
SA	shoulder abduction angle
S3D	3-dimensional shoulder angle
E	elbow angle
bpm	beats per minute
APAE	average percent absolute error
APAD	average percent absolute deviation
STD	standard deviation

SUMMARY

The objective of the research is to examine the impact of auditory stimulus on improving reaching performance in children with cerebral palsy. A form of auditory stimulus, called rhythmic auditory stimulation (RAS), is well-established in neurological fields as well as in music-based rehabilitation and therapy. RAS is a method in which the rhythm functions as a sensory cue to induce temporal stability and enhancement of movement patterns by what is believed to be a temporal constraint of the patient's internal optimized path of motion. In current neurological studies, it is suggested that activity in the premotor cortex may represent the integration of auditory information with temporally organized motor action during rhythmic cuing. Based on this theory, researchers have shown that rhythmic auditory stimulation can produce significant improvement in mean gait velocity, cadence, and stride length in patients with Parkinson's disease. Evidence validating this observation was also seen in a study on hemiparetic stroke wherein patients displayed improvements in spatio-temporal arm control, reduction in variability of timing and reaching trajectories, and kinematic smoothing of the wrist joint during rhythmic entrainment. Lastly, studies have suggested an accompaniment of sound feedback in addition to visual feedback can result in a positive influence and higher confidence in patients who have had a stroke or spinal cord injury. Although an effect of rhythmic cuing on upper extremity therapy has been explored in areas where brain injury has occurred (such as patients who have incurred stroke, spinal injury, traumatic brain injury, etc.), what has not been explored is the effect of rhythmic cuing on upper extremity therapy for individuals with neurological

movement disorders, such as cerebral palsy. Thus, in this research, we set out to explore the effect of RAS in therapeutic interventions for children with cerebral palsy. Through this investigation, we examine its effect on reaching performance as measured through range of motion, peak angular velocity, movement time, path length, spatio-temporal variability, and movement units.

For this assessment, we created a virtual system to test the aforementioned principles. We established clinically based angular measurements that include elbow flexion, shoulder flexion, and shoulder abduction using a 3D depth sensor to evaluate relevant metrics in upper extremity rehabilitation. We validated the output of our measurements through a comparison with a Vicon Motion Capture System. We then confirmed the trends of the metrics between groups of adults, children, and children with cerebral palsy. Through testing our system with adults, children, and children with cerebral palsy, we believe we have constructed a system that may induce engagement, which is critical to physical therapy, and may also have a positive impact on the metrics. Although we see trends indicative of an effect through use of the system on children with cerebral palsy, we believe further testing is needed in order to establish or refute the effect and also to definitively establish or refute the effect of rhythmic auditory stimulation. The system, the angular measurements, and the metrics we employ could provide an excellent foundation for future research in this space.

CHAPTER 1

INTRODUCTION

According to the Center for Disease Control, cerebral palsy is prevalent in 1 in 303 children in the U.S. [1]. Spastic cerebral palsy (CP) represents the majority of cases of CP making up 70 to 80% of all reported cases. The most common form of spastic cerebral palsy is hemiparesis in which only one side of the body is affected and motor deficit is usually greater in the upper extremity [2]. According to Wong’s Nursing Care of Infants and Children, “Developing a treatment program that can be carried out at home is of utmost importance,” [2]. We have devised a low-cost and effective system to promote just such treatment. Nursing interventions for impaired physical mobility related to neuromuscular impairment, as in cases of spastic cerebral palsy, include encouragement of play exercises that involve joint movement and promote fine and gross motor skill acquisition and repetition [2]. The system involves setting up therapeutic exercises under the guise of a virtual reality game. Many studies have investigated the utility and efficacy of virtual reality for use in therapy of children [3–6]. We expand on these results and utilize the metrics from Brooks & Howard (2010), Thaut (2002), as well as those used in Chen et al (2007) to develop our system [4], [7], [8].

A primary aim of the therapy is to increase range of motion, strength, or endurance [2]. In [7]. Brooks & Howard determine a computational method for range of motion, peak angular velocity, and total displacement for the shoulder joint during shoulder abduction. We hope to expand on this approach and develop a metric for the full range of motion of the upper extremity (i.e. shoulder, elbow, and wrist). In [4], Chen proposes four additional parameters that are sensitive enough to effectively detect qualitative changes in movements: movement time, path length, peak velocity, and movement units (describes smoothness of motion). Thaut makes use of a measure of movement variability called spatio-temporal variability (STV) which we will also consider [8]. We record each of these metrics in our system. Since all of these parameters have been validated in past studies, our system should be an effective measure of therapeutic improvements for any upper extremity interventions that involve the kinematics described in [7] and [4].

To develop this low-cost system, we must first assess the tools necessary and validate them with existing methods of assessing motion. We will perform a validation test of the joint data as acquired from the Microsoft Kinect for Windows SDK by performing the comparison against data acquired from a Vicon motion capture system. Once we have validated our hardware, we will begin testing on children to assess engagement of the system. After this assessment, we aspire to perform an intervention-based experiment for evaluation, which involves evaluation of clients (children with spastic cerebral palsy) for the outcome of interest both before (baseline) and after an intervention.

In our test, we will use our system to assess the effectiveness of a well-established therapeutic augmentation called Rhythmic Auditory Stimulus (RAS) for upper extremity therapy for children with spastic cerebral palsy. RAS is a method that goes beyond providing a simple trigger, but actually involves rhythmic auditory-motor entrainment where the rhythm functions as a sensory cue to induce temporal stability and enhancement of movement patterns by what is believed to be a temporal constraint to the patient's internal optimized path of motion [8]. RAS has been effectively used in lower extremity therapy for children with spastic cerebral palsy [9]. RAS, or rhythmic cuing, has also been used effectively in upper extremity therapies for patients with Parkinson's disease and patients who are post-CVA (post Cerebral Vascular Accident, i.e. stroke) [8], [10]. We propose an automated approach to an evidence-based health and wellness decision support system in the space of therapeutic rehabilitation.

CHAPTER 2

BACKGROUND

Virtual Systems for Therapy

Virtual systems have increasingly become the center for new avenues of research. Virtual systems could be used to deploy useful therapy regimes. Many advantages over tradition therapy can be gained through virtual rehabilitation system. One such advantage is that therapists could become much more efficient in terms of the number of patients they could treat simultaneously. Performance assessments could be made not just before or after a therapeutic intervention, but also during. Once a patient leaves clinical therapy, there remains a need for the continuation of rehabilitation in the home [2], [11]. Many have also recognized the need for home-based rehabilitation programs to increase the quality of life in patients with other musculoskeletal conditions [2], [12], [13]. To decrease the load and increase the efficiency of physical or occupational therapists, home-based assessment shows promise.

Virtual systems can be used to provide, not only the therapist with useful data, but also to give the patient much needed feedback on performance. These systems can provide multimodal stimuli for feedback. Patients are able to immediately see feedback in a virtual environment. Feedback is not only important to help to reinforce movement patterns learned [6], but also feel productive during the intervention. Engagement is key to an effective rehabilitation program and virtual systems are becoming more apparent as an effective means to this end [4]. We examine the literature in this up-and-coming field.

General Systems

Reid performed an early (2002) qualitative study on a virtual reality system for improving upper-extremity skills in children with cerebral palsy [6]. Four children were evaluated before and after VR play with the hypothesis that the quality of upper extremity skills would improve after engagement with the program. Overall, this study demonstrated beneficial results in terms of upper extremity skills as measured with Quality of Upper Extremity Test, the Bruininks-Oseretsky Test of Motor Proficiency, and a derived percent accuracy measure. Following eight sessions, children showed varying levels of improvement in their upper extremities. Children also found VR to be a great deal of gun. This study shows that VR provides children with an opportunity to engage in activities that are enjoyable and non-threatening, while increasing play engagement and exercising control over their actions.

Reid's system showed a high degree of motivation, interest, and pleasure in the assessed children. It is observed that virtual systems show great promise in improving motor skills and self-competence. Children with cerebral palsy may try out new skills or movements without the worry of embarrassment or the risk of injury. The benefits go beyond just improved motor skills, but could also give an increase sense of control or self-efficacy. According to motor learning theory, enhanced feelings of self-control will result in heightened motivation and desire to practice which will in turn result in improved movement control [6].Children expressed how the VR games help to increase their confidence [6].

Piron et al's 2005 *Virtual environment training therapy for arm motor rehabilitation* study evaluated fifty subjects with mild to intermediate arm impairments due to stroke [14]. These patients received virtual environment therapy daily for one month. Before and after therapy, motor impairment was assessed using the Fugl-Meyer scale. Velocity, duration, and morphology of reaching movements were also analyzed. The VR therapy yielded significant improvements over baseline values. Their data indicated that motor recovery in post-stroke patients may be promoted by the enhanced feedback provided in a virtual environment.

Wellner et al's 2007 *A study on sound feedback in a virtual environment for gait rehabilitation* observed the importance of sound feedback for gait rehabilitation for stroke and spinal cord injury patients [15]. Their study included 17 healthy subjects and compared no sound feedback, distance feedback, height feedback, and combined feedback. Visual feedback was present in all conditions. Their results indicated that subjects walk fast and hit fewer obstacles when sound feedback was present. Their findings suggest that acoustic feedback, not just visual, manual, or verbal, is important to the rehabilitation and recovery of stroke patients when using VR therapy.

Y. Chen investigates the training effects of VR intervention in the 2007 paper [4]. An upper extremity training program was employed for 4 children with cerebral palsy. After a 4 week training program, the improvements were retained. Virtual systems can provide positive visual and auditory feedback. Chen et al's 2007 study, *Use of virtual reality to improve upper-extremity control in children with cerebral palsy: a single-subject design,* found that children recruited to participate in their study showed a high degree of motivation for, interest in, and opportunity for engaging in play activities during the intervention. They state that "repetition is an important aspect of practice, and repetition of a task has been shown to improve performance in people with or without disabilities." Their results suggest that VR may motivate children with CP to engage in repeated practice of reaching behaviors. Visual feedback on performance are said to be crucial for motor learning in children with CP [4]. Individualized training for motor learning can also result from using virtual or augmented reality systems. Children were found to have a high degree of motivation for engaging in play activities during the intervention. The study is said to show that VR has the potential to improve reaching performance and control in children with CP [4].

Cameirão et al's 2008 *Virtual reality based upper extremity rehabilitation following stroke: A review* systematic review demonstrates how VR therapy has the capabilities of becoming an essential tool in rehabilitation of stroke patients, especially those with upper extremity complications [16]. VR was shown to be beneficial in many different categories, including learning by imitation, reinforced feedback, haptic feedback, augmented practice and repetition, video capture virtual reality, exoskeletons, mental practice, and action execution/observation. There has been large numbers of studies and in general, patients have shown significant improvements in various aspects of performance with an impact on activities of daily living.

In Ahonen-Eerikäinen et al's 2008 study, *Rehabilitation for Children with Cerebral Palsy: Seeing Through the Looking Glass*, The Virtual Music Instrument (VMI) created by Dr. Tom Chau was implemented [3]. This allows children with disabilities to play musical sounds and melodies using gestures. Six participants were recruited and received ½ hour sessions twice a week for a ten-week period. According to research results the VMI creates an environment that is developmentally appropriate and fosters active exploration and engagement, which is key to facilitating social-communicative skills, motor skills and kinesthetic abilities, cognitive development and socio-emotional growth.

Levin et al's 2009 *Virtual Reality Environments to Enhance Upper Limb Functional Recovery in Patients with Hemiparesis* says that more attention should be paid to retraining upper limb coordination or the ability of the arm and hand to interact with the environment rapidly and efficiently [17]. They hypothesize that the environment in which movement is practiced could be crucial to maximize recovery. All of the factors related to environment such as specificity, repetition, intensity and salience of practice could be manipulated using VR. As well offering the individual a practice environment, it also has the potential to enhance their enjoyment and compliance. Other advantages of VR include the ability of VR settings to be adapted to the individual, questions about dexterity and coordination can be more easily addressed, and the possibility to study movement production that may compromise the safety of the individual in a real world setting. Their research suggests that rehabilitation efforts are better when practice is task-oriented and repetitive and outcomes are expected to be better when the learner is motivated and movements are judged to be salient by the learner [17].

In Correa et al's 2009 study, *Computer Assisted Music Therapy: A Case Study of an Augmented Reality Musical System for Children with Cerebral Palsy Rehabilitation*, a system was developed with Augmented Reality techniques which allow music composition [18]. The system simulated sounds of various musical instruments. It was important that the software can be used at home, involving the family, and contributing to the improvement of their life quality. The results of this research, still preliminary, showed that this system could serve therapeutic interventions including learning of cognitive, motor, psychological, social and to stimulate musicality.

Fluet et al's 2009 *Robot-assisted virtual rehabilitation (NJIT-RAVR) system for children with upper extremity hemiplegia* study describes the NJIT-RAVR system, which combines adaptive robotics with VR simulations for the rehabilitation of upper extremity impairments and function in children with CP [5]. The NJIT-RAVR system consists of the Haptic Master, a 6 degrees of freedom, admittance controlled robot and rehabilitation simulations. The system provides adaptive algorithms for the Haptic Master, allowing impaired users to interact with rich virtual environments. All subjects trained with the NJIT-RAVR System for one hour, 3 days a week for three weeks. The subjects played a combination of four or five simulations depending on their therapeutic goals, tolerances and preferences. Subjects differed in the level of activity performed outside of NJIT-RAVR system training. Each group of subjects performed a battery of clinical testing and kinematic measurements of reaching collected by the NJIT-RAVR system. Both groups improved in robotically collected kinematic measures and the Melbourne Assessment of Unilateral Upper Limb Function. They point out that playing computer games is becoming an everyday aspect of children's lives. The game-like VR therapy could add to motivation and participation, especially since some of these children do not have the physical ability to play mass market computer and video games.

Guberek et al evaluated the level of cooperation and satisfaction of children with CP when practicing arm and hand movement during play-like activities in a physical environment compared to a video-capture based VR environment in their 2009 study *Virtual Reality as Adjunctive Therapy for Upper Limb Rehabilitation in Cerebral Palsy*

[19]. A 5-point Likert scale was used for assessment by children. Although the children cooperated during both environments, they preferred the physical environment over the VR environment. This could be because they found VR to be difficult, confusing, or frustrating.

Cameirão et al's 2010 *Neurorehabilitation using the virtual reality based Rehabilitation Gaming System: methodology, design, psychometrics, usability and validation* study used a VR based system they named Rehabilitation Gaming System (RGS) for hemiplegic stroke patients [20]. Their movements were captured by a motion capture system and are then mapped onto the movements of the virtual arms. Difficulty levels could be adjusted. Their results showed a consistent transfer of movement kinematics between physical and virtual tasks. Also, the RGS was highly accepted by the stroke patients as a rehabilitation tool.

Bohil et al (2011) discuss the use of virtual reality in neuroscience research and therapy [21]. In *Virtual reality in neuroscience research and therapy,* also makes the point the VR is high engaging, which is crucial. This provides motivation for rehabilitation that requires consistent, repetitive practice. Virtual reality (VR) systems are best at visual and auditory information conveyance and are increasingly approaching the sensory vividness of the physical world. Their study also shows that VR provides a tool for recording and following minute changes and improvements over time.

Low-cost motion interactive video games in home training for children with cerebral palsy: A kinematic evaluation, a 2011 study by Sandlund et al, had fifteen children diagnosed with CP provided with a Sony PlayStation 2 equipped with EyeToy, Play3 for home training [22]. Play3 includes around 20 different games that typically involve practice of arm-coordination, postural stability and range of motion. Children performed arm movements under two conditions – a virtual condition, while playing EyeToy and reaching for virtual targets; and a real condition, recorded while the children reached for real objects (tassels). Movement registrations were taken before and after the intervention of 20 minutes of play a day for four weeks. The results indicated that the children improved movement precision when playing the virtual games, improved movement smoothness when reaching for real targets, and reduced the involvement of the trunk especially when reaching the non-dominant side.

Jordan et al's 2011 study *ImAble system for upper limb stroke rehabilitation* developed a program called ImAble, which is an integrated upper limb exercise system using computer games and VR [23]. Stroke patients with upper limb hemiparesis were evaluated. The Fugl-Meyer upper limb motor function test was the primary outcome measure. The system can be tailored to different levels of ability and strength, depending on the presentation of the stroke. Their results indicate that the ImAble system has the potential to improve upper limb function and highly motivates the user to exercise.

Molier et al's 2011 *The role of visual feedback in conventional therapy and future research* stressed the importance of visual feedback in rehabilitation as opposed to the usual verbal feedback [24]. It was observed that combined used of visual and sensory (or manual) feedback is used more often in research settings than in current clinical practice. They point out that in clinical practice virtual gaming environments are rarely used. This application of innovative technologies in research and not in clinical practice could contribute to the difference in applied use of feedback between research and clinical practice. The application of practical experiments in the clinic could obtain insight into which modality of feedback other than verbal comments could optimize stroke rehabilitation therapy.

Loon et al's 2011 *Serious gaming to improve bimanual coordination in children with spastic cerebral palsy* study tested the influences of a set of computer games developed to help children with CP loosen the coupling between their hands [25]. The training comprised of three computer games that challenged the participants to move their hands according to six different bimanual coordination patterns. All children improved their performance during the training sessions, as evidenced by their scores on the game.

Doyle et al's 2011 *The effects of visual feedback in therapeutic exergaming on motor task accuracy* study points out that poor exercise technique and lack of adherence prevent a full recovery during rehabilitation [26]. Their study examines the effects of visual feedback during "exergaming" has on a person's accuracy in performing motor tasks. An iPhone was used to send accelerometer reading to a server and an application uses the readings to adjust the game state. Three levels of feedback were given: no feedback (control), limited feedback (instructional video), and visual feedback (exergame). Their results showed that visual feedback result improved accuracy of movements compared to performing exercise from memory or with limited feedback.

Cameirão et al's 2012 *The combined impact of virtual reality neurorehabilitation and its interfaces on upper extremity functional recovery in patients with chronic stroke* sought to know what features of VR rehabilitation are the most beneficial [27]. Three different configuration of the same VR-based system (RGS) were developed using three different interface technologies: vision-based tracking, haptics, and a passive exoskeleton. Forty-four patients with chronic stroke were randomly allocated to one of the configurations and used the system for 35 minutes a day for 5 days a week during 4 weeks. Their results revealed significant within-subject improvements at most of the standard clinical evaluation scales for all groups. It was observed that the beneficial effects of VR-based training are influenced by the visual feedback versus combined visual haptic feedback. Their findings suggest that the beneficial effects of VR-based neurorehabilitation systems such as the RGS for the treatment of chronic stroke depend on the specific interface systems used. These results have strong implications for the design of future VR rehabilitation strategies that aim at maximizing functional outcomes and their retention.

Microsoft Kinect for Therapy

Inexpensive solutions in position determination such as the Microsoft (MS) Kinect ™ could be used by therapists to gain accurate and useful data on patient progress [28–30]. Here we examine papers recently released in this field to examine the current state of the art of the field.

Virtual Reality Based Rehabilitation and Game Technology, Alessandro De Mauro’s 2011 study showed that the benefits of VR are that it is adapted to the patient’s therapy, it is repetitive, motivating, has remote data access, and is a precise tool for the assessment of therapy [31]. It is also low cost.

Taylor et al’s 2011 review, *Activity-promoting gaming systems in exercise and rehabilitation*, says that activity-promoting gaming systems can be used as an effective tool to aid in rehabilitation [32]. They state that one of the main reasons for employing video games in rehabilitation is their ability to increase motivation and alleviate boring and/or painful treatments. They are inexpensive, attractive, enjoyable, and easy. There is also the potential for social interaction. A series of case studies have resulted in encouraging results for the support of gaming in rehabilitation settings. However, a potential limitation of using gaming systems is that although they encourage balance, strength, and fitness, they are not specifically designed for rehabilitation.

Stone and Skubic's 2011 study entitled *Evaluation of an Inexpensive Depth Camera for Passive In-Home Fall Risk Assessment* focused on evaluating the accuracy and feasibility of using the depth data obtained from the Kinect [29]. They found that Kinect addresses an issue in foreground extraction from color imagery and significantly reduces the computational requirements necessary for foreground extraction.

Chang et al's 2012 study, *Towards Pervasive Physical Rehabilitation Using Microsoft Kinect*, found that the Microsoft Kinect was a promising VR neurological rehabilitation tool for use in the clinic and at home [28]. Their study compared the Kinect to the high-cost, multi-camera lab-based system OptiTrack. Their results showed that Kinect can achieve competitive motion tracking performance as OptiTrack, especially in the hand and elbow joints. It also has the benefit of being used in the home, unlike the OptiTrack. While the OptiTrack was 50 milliseconds faster than the Kinect, this difference is negligible for the rehabilitation application. Kinect was shown to be a successful tool for home rehabilitation.

Stone and Skubic's *Capturing Habitual, In-Home Gait Parameter Trends Using an Inexpensive Depth Camera* had a Kinect mounted in five older adults' homes to measure their gait continuously over a four month period [33]. The Kinect proved to be a useful and reliable device for passively and unobtrusively monitoring the gait parameters and capturing trends in those parameters in the home.

Hayes et al, *A Virtual Environment for Post-Stroke Motor Rehabilitation,* developed a 3D virtual environment for post-stroke patients that presented motivating rehabilitation tasks for patients to complete through movement of a virtual arm using their own impaired arm [34]. They designed a virtual environment for hemiparetic upper extremity rehabilitation that provides practice and motivation not found in conventional therapy. Conventional rehabilitation tasks often lack motivation for the patient to complete a high number of repetitions needed for motor learning. They used a Kinect to track the patients during the VR game. The Kinect was found to be motivating, inexpensive, and useful in the implementation of rehabilitation for stroke patients.

Deligiannidis' *Games for Children with Cerebral Palsy* points out that a common problem with children with CP is a reduction in motivation [35]. The goal was to utilize VR technology to provide fun experiences so the used can become motivated to engage in physical activity. This would provide a medium for motor, speech, and memory rehabilitation. This study stresses the importance of equality. It is important that a child without CP can play the game as well. In the game, there must be two players. A child with CP and a child without CP work together to achieve a goal, which not only allows the child with CP to engage in physical activity, but also heighten self-esteem.

In the space of virtual rehabilitation in general, although we see some negative results from studies such as [19], with all of the evidence listed to the contrary we must assume this must have been an issue with implementation. Thus, we will proceed cautiously when devising our game implementation so as not to discourage, confuse, or frustrate children from using virtual systems which seem to be proving to be very beneficial as can be seen in many other studies we have cited [3], [4], [6], [14–17], [22],

[25], [26]. The studies we found on use of the Microsoft Kinect were limited, but of these the overall consensus seems to be that the Kinect proved reliable, successful, and a low-cost method under the large variety of circumstances in which it was used. As noted in [32], we must also consider that the Kinect was developed as a tool for gaming and not specifically for rehabilitation. Thus, we will proceed cautiously when considering its use, however, we believe this advances our cause since one of the main issues with rehabilitation of children is engagement and its crucial role in effectiveness of therapies of all kinds [2].

RAS

Alternative upper extremity therapies for children with cerebral palsy are relatively unexplored especially in the space of rhythmic cuing [36]. Rhythmic cuing, or what some refer to as rhythmic auditory stimulus (RAS), involves therapeutic motion in arms or legs while temporally constrained by an auditory cue [37], [38]. While constraint induced movement therapies drive the amount of motor activity through forced use of the impaired side, rhythmic cued therapy is based on quality of movement in the hemiparetic limb. In the subsequent sections we will explore the neurological foundations for this theory as well as methodical implementations used in prior studies.

Neurological

There is a great deal of foundation for research into rhythmic effects on the brain. The basic premise behind rhythmic cuing is that the technique offers much more than a simple timekeeping cue, rather the cue offers an additional temporal constraint onto the mind when setting a goal in the motor cortex [8–10], [39]. The auditory cortex is said to create an entrainment, or a process in which the body synchronizes its movements rhythmically, between the rhythmic input signal and the motor response [9], [36]. Some believe that this additional temporal constraint allows for the mind to map much smoother and more precise trajectories for the impaired motor system of patients [8], [36]. The following is a non-exhaustive, but thorough review of relevant literature with an emphasis on the physiological influence of auditory cue.

Early studies

In *Audio-spinal influence in man studied by the H-reflex and its possible role on rhythmic movements synchronized to sound* (1976), Rossignol and Jones set the foundations for rhythmic cuing through determining priming and timing of motor responses through the stimulation of audio-motor pathway [40]. The auditory stimulation was made by a sine wave, perceived as a non-startling tonal sequence with distinct pitches as what occurs in music. The subjects were instructed to hop to the beat while their physical response was recorded. It was determined that synchronized movements to repetitive auditory stimuli may promote and be conducive to a timing influence on motor controlled events. Other physiological studies exist that support this idea of a very distinct influence auditory rhythm has on the motor system [41], [42].

In Thaut's 1985 Journal of Music Therapy seminal RAS paper, *The Use of Auditory Rhythm and Rhythmic Speech to Aid Temporal Muscular Control in Children with Gross Motor Dysfunction,* the author examines auditory rhythm as a method in increasing motor rhythm accuracy [43]. Thaut initially taught the children to follow the rhythm through stationary gross motor movement by hand clapping. After the initial training, the subject were instructed to perform a sequence of gross motor motions including steps, hand claps, and knee slaps. The treatment group was aided by an auditory rhythm while the control group was aided by a visual model. The actions were recorded using voltage coded sensors attached to the hands, feet, and back. An average time deviation was calculated for each subject for each trial. The end result is a statistically significant improvement in average time deviation in the treated group over the control group. The study concludes that the findings support the importance of auditory rhythm in developing and maintaining a temporal synchronous gross motor timing [43]. This study emphasizes the idea that motor function and auditory processing are interconnected since an observed improvement in motor function can be induced through training with an auditory stimulus.

Gait Therapy

In the study, *Rhythmic entrainment of gait patterns in children with cerebral palsy*, this idea of auditory-motor interaction is expanded to include people with motor function deficits, such as in children with cerebral palsy [39]. An instrumental music score at 4/4 meter with a metronome beat embedded on the on-beats of the music was used as the rhythmic cue. The intervention consisted of the children being instructed to walk to the beat of the music. In this study, as contrasted with [43], no prior training occurred. The intervention occurred over a three week period with 30 minute training session per day. The beat frequency, or tempo, was increased by 5% each week. Increases in cadence and stride length as well as swing symmetry improvement were observed after the intervention. The end result was improved knee temporal cuing, hip range of motion, and smoothed velocity profiles of knee and hip trajectories. These measures are associated with functional improvement. The positive effects show that further exploration should occur. The children are said to have positively responded to the tempo cues embedded in the musical rhythms. The results are said to indicate that auditory rhythm affects not only temporal organization, but spatial control as well [39].

In *Effect of Rhythmic Auditory Stimulation on Gait Performance in Children with Spastic Cerebral Palsy* (2007), Kwak sets out to determine the effectiveness of RAS in improving gait training for ambulation [9]. The RAS model is defined by Center for Biomedical Research in Music (CBRM) at Colorado St University and is described as use of music as an external time cue to regulate body movements. Kwak notes that, "RAS has been found to be effective in an adjunctive role or as a sole method to increase the effectiveness of traditional physical therapy for ambulation in adult rehabilitation settings." The author then notes the similarities between the adults and with patients with cerebral palsy. "CP patients encounter difficulties with coordination and muscle control similar to those experienced by rehabilitation patients, which suggests that RAS may be beneficial if used to enhance traditional physical therapy treatments." RAS's key element is auditory entrainment, or the ability for the body to synchronize its movements rhythmically. Kwak cites previous studies, such as [40] and [44], to state that internal, subconscious perceptual shaping occurs at a sub-cortical level during auditory entrainment. This is given as the reason behind an arousal and rise of excitability of spinal motor neurons. At the time of this publication, the author notes that RAS has been used to help regulate motor control system by stimulating lower-level brain functions of the basal ganglia, cerebellum, brain stem, and spinal cord for patients with Parkinson's, stroke, Huntington's disease, and traumatic brain injury, however, no conclusive evidence had yet been published using RAS in a clinical setting for children with CP [9].

The study in this paper compares the effectiveness of RAS enhanced ambulation with traditional ambulation training in children with CP. The author notes a previous study of CP patients in a home setting [39]. Results are said to indicate improved velocity, cadence, stride length, and symmetry, as well as kinematic improvements of knee and hip ranges of motion and trajectories [39]. In Kwak's study, results for cadence, using paired-sample t-test, no statistical difference between pre and posttest resulted between the control group and the tested groups. Stride length was shown to improve (lengthen) by 15.8% overall in the therapist-guided group, while the control and self-guided groups showed no significant difference. Velocity improved from 20.73% primarily in the therapist guided group which was much greater than the improvement made in the other groups. Symmetry, as defined as the shorter swing time of one leg from toe-off to heel strike divided by the longer swing time of the other leg, improved 16.97% in the therapist group which is again a great improvement over the other groups. Using a one-way analysis of variance (ANOVA), no significant difference between the groups regarding gait parameter improvement was identified. The author notes that, "There were no significance difference on measures in other tests used for analysis; however, differences in velocity, cadence, and stride length were observable and indicated a positive outcome with the methods of this study"[9].

Kwak concludes that although RAS does show an influence on gait performance of people with CP, further research should cautiously explore methods of application since sometimes current cadence results from irregular foot contact and should not be increased in such cases. The author does state that RAS may still prove to be beneficial to patients with CP, but it must be applied carefully and considering the results presented[9].

Arias and Cudeiro's *Effects of rhythmic sensory stimulation (auditory, visual) on gait in Parkinson's disease patients*, provides further insight into some of the neurological effects RAS has on therapeutic regimes[45]. The study sets out to explore (among other things) to identify the effect of external sensory cues (auditory, visual, and both) on performance of patients with significant alterations in walking patterns (at frequency equaling preferred walking cadence) as well as to test the effect of applying sensory stimuli at different frequencies to determine which frequency yields the best results. In more severe patients compared to the control group, there was a reduction in step amplitude and velocity while there was an observed higher coefficient of variance of stride time and coefficient of variance (CV) of step amplitude. Cadence was reduced in all cases. Auditory stimulus induced faster walking than visual, however, both stimuli affected both groups the same way. The CV stride time was reduced for auditory and auditory combined with visual stimuli. In less severe patients, there was no difference to the control group. This indicates the differences in step length, velocity and CV stride time can be attributed to the alterations in the more severe group. Step amplitude and velocity were reduced in PD patients compared to control. Sensory stimulation of any kind reduced step cadence in control group and the severe PD patients. Auditory stimulation alone worked best for velocity, velocity reflecting the interaction between cadence and step amplitude. The author notes that there is a more powerful interaction between motor and auditory systems than motor and visual systems and this seems enhanced in PD patients. It is also noted that auditory stimulation has been demonstrated to have an effect on the excitability of motor neurons which the author believes may be the reason for a difference of patient reaction in the presence of auditory cues[45].

Upper Extremity Therapy

In the 1991 paper, *Analysis of EMG activity in biceps and triceps muscle in an upper extremity gross motor task under the influence of auditory rhythm*, Thaut et al describe the effects of auditory rhythm as a stimulus for movement. The authors investigate the muscle activation by measuring changes in the electromyographic (EMG) patterns of the biceps and triceps. The subjects were assigned to one of three groups: repeat task as in pretest (control group); perform task with auditory rhythm matched to internal tempo; and perform task with auditory rhythm slower than internal tempo. The results of this study show that using musical stimuli can help stimulate movement, which therefore improves endurance, strength, and range of motion. This study lays the foundation for further upper extremity therapy application of the theory. The author specifically indicates that the findings suggest that using auditory rhythm in therapeutic motor activity could modify muscle activity in a productive manner substantiative to the aim of the therapy.

Thaut's 2002, *Kinematic optimization of spatiotemporal patterns in paretic arm training with stroke patients*, illustrates more relevant auditory-motor connections in an assessment of paretic arm training for victims of stroke [8]. In this paper, Thaut et al compare the reactions of the subjects to an optimization model to help give insight into the inner physiological processes. The study analyzes arm acceleration profiles in a mathematical optimization model in an attempt to demonstrate that the added temporal information provided by the rhythm give the subject's brain the ability to construct more temporally smooth positional changes in the paretic arm. In other words, does the information provided by the rhythmic cue allow the brain to map a smoother trajectory in arm movement? Improvements in spatiotemporal arm control, reduction in variability of timing and reaching trajectories, reduction in variability of arm kinematics, increases in angle ranges of elbow motion, and kinematic smoothing of wrist joint during rhythmic entrainment were observed. The study also explored the connection between rhythmic sensory timing and spatiotemporal motor control by forming an optimization model that minimizes peak acceleration. The author of the study states that, due to acceleration and velocity being time derivatives of position, "the model data suggest[s] that [the] enhanced timing precision via temporal phase and period coupling of the motor pattern to the rhythmic time timekeeper enhances the brain's computational ability to optimally scale movement parameters across time" [8]. It is also noted that arm motor function is more common and more resilient to rehabilitation efforts than leg in ischemic hemispheric stroke victims.

In the rhythmic model of rehabilitative motor training, "rhythm functions as a sensory cue to induce temporal stability and enhance the temporal organization of motor control in the nervous system by translating the temporal structure of movement patterns into temporally isomorphic auditory rhythmic patterns to entrain the movement in question" [8]. Functional arm movements are said to be discrete, biologically non-rhythmic, and volitional in contrast to gait patterns which are rhythmic in nature. Although this is true, the programming and execution of motor skills in high performance environments such as music or sports training have been successfully rhythmically stimulated. The author states that the, "comprehensive dynamic changes in spatiotemporal and force parameters during rhythmic gait training strongly suggest that a simple trigger of pacing function can only insufficiently explain the effect of rhythm on motor control" [8]. The brain is cited as planning movement patterns around optimization principles, such as minimizing certain physiological or kinematic cost functions, in the central nervous system. Physiological research points to auditory input raising "spinal motor neuron excitability to increase moor readiness before supraspinal input occurs" as well as "auditory rhythm rapidly [creating] stable perceptual traces as anticipatory time schema which attract and rapidly entrain the periodicity of motor patterns" [8]. The idea of periodicity entrainment in rhythmic cuing is said to be as a result of a direct coupling of a motor function in response to a sensory input. This concept is said to be similar to entrainment of coupled oscillators.

Thaut et al describe in their results that movement trajectories became more stable with rhythm than with no rhythm. Improvements in temporal and spatial variability during rhythm occurred. Rhythm condition yielded a mean deviation of much less than no rhythm when compared to the optimal path that minimizes peak absolute acceleration. This indicates a better model fit for the data cued by rhythm. It should also be noted that non-rhythmic reaching motions to a target using auditory cues as stop and go signals did not improve motor learning. The data from this study of changes in timing and trajectory control "strongly suggest that the structured timing information in auditory rhythm added significant kinematic stability to the patient's paretic arm motions" [8].

In *Rhythmic auditory-motor entrainment improves hemiparetic arm kinematics during reaching movements: a pilot study*, Malcolm et al explores the changes in kinematic parameters of arm motions in the presence of a rhythmic cue [10]. RAS is said to emphasize quality of movement which distinguishes RAS from the more conventional constraint-induced movement therapies. It also has strong research base in neuroscience. Paltsev and Elner, and Rossignol and Melvill-Jones “were among the first to show evidence for auditory-motor pathways that could influence threshold excitability of spinal motor neurons, creating a readiness or priming effect on the segmented motor system via auditory input.“ Participant trained for a total of 2 weeks on Mon., Wed., and Friday for 1 hr/day of onsite (participant trainer and supervised by occupational therapist) training and 2hr of home-based training. Tuesday and Thursdays were 3 hr home-based training days (research assist called them to answer questions and provided guidance if needed for the training).

The protocol was designed to incorporate: movement timing, range of motion, and feed-forward processing. First the researchers determined the baseline rhythmic auditory frequency. Then the auditory cues were generated using a digital metronome. Participants were instructed to move in-sync with the rhythmic auditory stimuli during subsequent trials. 5 to 10 30-second trials were completed with 15 to 20 seconds of rest between trials and 1 to 2 minutes of rest between each 5 to 10 block of trials. Auditory cue frequency was increased or decreased between blocks of trials.

Outcome measures were selected in two domains: motor control and functional use. Motor control assessments were carried out using kinematic motion analysis of a reaching task. Secondary kinematic measures included movement time (to complete 4 reach cycles) and reach velocity. Functional use measures assessed motor function (Wolf Motor Function Test -WMFT), capacity (Fugl-Meyer Upper Extremity Assessment), and quality of use. These were administered immediately prior to and following the 2-week intervention period. The WMFT was an array of tasks that were timed. Fugl-Meyer included presence/absence of deep tendon reflexes, movement within and outside of synergy patterns, and gross grasp. A 6-pt scale interview was given to assess perceived quality of movement on 30 daily, real-world activities outside of the lab. Trunk movement was prevalent prior to RAS training, but decreased significantly post RAS training. Shoulder flexion significantly increased as well. Movement time significantly decreased. Mean reaching velocity also increased significantly. WMFT performance time significantly decreased, Fugl-Meyer (motor capacity) significantly improved following RAS. Perceived quality of movement also significantly improved. Note: Kinematics provide a precise method for characterizing changes in motor control performance; however, they do not fully capture the impact of rehabilitative strategies on actual movement abilities for at least basic movement skills important for daily living. In [8], Thaut et al demonstrate that rhythmic-cued movements are significantly more stable and smooth compared to uncued. This study speaks only to utility of RAS for mild to moderate motor deficiency. RAS training decreased compensatory reaching strategies. This pilot study is said to demonstrate beginning efficacy for incorporating rhythmic cuing as a rehabilitative effort aimed at improving hemiparetic arm movements.

Other Studies

In *Interactions between auditory and dorsal premotor cortex during synchronization to musical rhythms*, Chen et al [46] use the more recent technology of fMRIs to further study the interaction between the auditory and motor areas of the brain. Specifically, they set out to determine how the metric structure of a rhythm can facilitate motor action and also to illuminate the neural processes behind the auditory–motor interactions that result from an observed rhythm. The researchers constructed 5 variations of a rhythmic pattern each with an increasing emphasis on a rhythmic period through an increased amplitude in the wave (i.e. an increase in volume). Subjects were instructed to tap in synchrony as accurately as possible to the rhythms. They were also told that some tones would be louder/softer than others. The observation was made from the fMRI scan that the tones induced a blood-oxygenation level dependent (BOLD) response in the auditory and also the dorsal premotor cortices. In fact, as the saliency of the rhythm was increased, the taps became longer in duration – an effect that was not observed during the baseline which contained no metric structure. The authors call this a functional connectivity between the bilateral posterior superior temporal gyrus (STG) and the bilateral dorsal premotor cortex (dPMC) due to the observed modulation, seen as longer tap duration, by stimulus amplitude manipulation. It is observed that "Auditory–motor interactions may take place at these regions with the dorsal premotor cortex interfacing sensory cues with temporally organized movement" [46]. The results are said to indicate that metric organization (as in the intensity accentuated rhythm) modulates motor behavior and neural responses in auditory and dorsal premotor cortex. Thus, "the metric structure of a rhythm is an effective cue in driving motor behavior" [46].

A comprehensive review of literature is presented in, *Rhythmic auditory stimulation in rehabilitation of movement disorders: a review of current research* [36]. The article links the early physiological studies connecting the auditory and motor areas of the brain to more recent studies on music and auditory rhythm influencing motor output in PD patients on to the most recent RAS studies initiated by EMG imaging evidence for auditory-motor pathways. The broad nature of RAS and its application is explored. Of particular interest is the broad scope of types of studies that have been performed. In Parkinson's, traumatic brain injury, post cerebral vascular accident, and cerebral palsy, RAS has proven effective as a treatment method. The paper concludes with the assumption that RAS uses multiple auditory-motor pathways to entrain and access central motor processors that respond and couple to rhythmic time info to stabilize motor control independent of specific neuropathologies. The assumption is drawn from the fact that RAS has shown improvements across a variety of patient groups with a variety of gait deficits and kinematic features resulting from differing neuropathologies.

Conclusions

We see there is a well-established foundation of research on the neurological connection in auditory and motor processing and the effect of rhythmic entrainment. From the preliminary findings of Paltsev and Elner [44] to the more recent fMRI studies of Chen, Zatorre, and Penhune [46], one can see the rich connection between auditory processing and motor action. These internal connections led to the early studies of M. Thaut to try and exploit this connection to aid in rehabilitation of gait. The theory of rhythmic auditory stimulus (RAS) grew to encompass areas of Parkinson's disease[38], [45], [47], post-stroke [48], [49], and even cerebral palsy [39]. Although gait tends to be more rhythmic in nature, more recently it was realized that the theory could be applied to the seemingly more erratic motion of the upper-extremities as well [8], [10], [37], [50]. The comprehensive changes present with RAS in entrainment lead to the conclusion that RAS provides much more than a pacemaker role in therapies. By augmenting with timing as the primary coordinative control structure in the generation of the complex movement sequences, improvements are yielded in positional and muscular control. Since RAS has shown improvements across a wide variety of groups of patients with a wide variety of motor control deficits, we are supported in our premise. Clearly there is a foundation for this therapeutic method and there has even been recognized a lack or at least a deficit of exploration in the area of cerebral palsy when it comes to RAS therapy [36].

Methodical

Not only is a neurological foundation set, but there is also a methodical foundation in current research as well, although it is primarily for gait training and primarily focused on patients with Parkinson's disease and stroke victims [8], [37], [45], [49], [51]. Typically, the methods used to implement rhythmic cuing are to initially determine a baseline, or "natural" frequency of motion [8], [9], [45]. The system is then calibrated to implement the rhythmic cue at this frequency for the training. Sometimes a metronome is used or a song with an emphasized note at the rhythmic cue [9], [15], [37], [39], [45]. Some studies scale the cue if the natural frequency is too slow to have the music be played at an appropriate listening tempo [15]. The tempo can be kept constant throughout the intervention while some studies have utilized an adaptive approach where the frequency is either incremented or decremented as determined by the therapist based on the patient's individual needs [9], [36], [39], [45], [47].

Gait Therapy

A majority of the literature and research in RAS is devoted to gait therapy. We present it here to examine methods RAS testing implementation to assist in the design of a testing protocol based around the established principles used in implementing RAS.

In the 1996 paper, *Rhythmic Auditory Stimulation in Gait Training for Parkinson's Disease Patients*, Thaut et al perform one of the earlier studies using an RAS protocol [51]. The test was performed over a 3 week period as a home-based gait training program for patients with Parkinson's disease. The training was performed 30 minutes each day. An electromyogram (EMG) was used to evaluate gait patterns before and after the intervention. The data was compared to 2 control groups: one did not participate in any gait training and the other group participated in an internally self-paced training program.

Subjects walked at 3 different tempos, each at one-third the total day's training timing (10min) and were given 4 choices of which instrumental piece they would like to hear (in the style of folk, classical, jazz, or country). The music was in 2/4 or 4/4 meter and 32 measures in length. Audiotapes were used that had rhythmically accentuated music with metronome on/off ticks embedded in them. An embedded musical structure was chosen based on the authors reported findings that their use reduced response variability and synchronization offset more effectively than single-pulse pattern for frequencies between 1 and 2 Hz (60 to 120 steps/min) [51]. "Patients who trained with RAS significantly ($p < 0.05$) improved their gait velocity by 25%, stride length by 12%, and step cadence by 10% more than self-paced subjects who improved their velocity by 7% and no-training subjects whose velocity decreased by 7%. In the RAS-group, timing of EMG patterns changed significantly ($p < 0.05$) in the anterior [leg] muscles" [51].

An excellent 1997 journal article by McIntosh et al [47] describes another implementation of RAS and significant findings to support its use. The paper was entitled, *Rhythmic auditory-motor facilitation of gait patterns in patients with*

Parkinson's disease, and gives the results of a 31 patient study assessing the effect of RAS on gait velocity, cadence, stride length, and symmetry for gait. The patients walked under four conditions: their own maximal pace (baseline), in time with RAS matching their baseline cadence, in time with RAS 10% faster than their baseline cadence, and with no external rhythm to check if the effect carries over. The rhythm was a 50 ms square wave pulse embedded in a Renaissance-style 2/4 meter score [47].

The results indicated a significant improvement ($P < 0.05$) in mean gait velocity, cadence, and stride length for the 10% faster RAS in all groups tested. These results are said to be consistent with prior reports of rhythmic auditory facilitation in Parkinson's disease gait when there is mild to moderate impairment [47].

In the 1998 study, *Rhythmic entrainment of gait patterns in children with cerebral palsy*, an instrumental music score at 4/4 meter with a metronome beat embedded on the on-beats of the music was used as the rhythmic cue to examine the effects of RAS on gait performance of children with cerebral palsy [39]. Our knowledge of the study is limited, however, to just the abstract. The study was a within-subject repeated measures design with 4 conditions counter-balanced across subjects: (1) uncued normal walk, (2) normal walk with RAS 5% higher than baseline cadence, (3) uncued fast walk, (4) fast walk with RAS 5% higher than fast cadence. A pre-test and posttest were given around the 3-week intervention. No training was given and subjects were asked to walk to the beat of the music for 3 weeks daily for 30 minutes at home with their primary caregiver, using prerecorded RAS tapes, a tape player, and headphones wherein the beat frequency was increased by 5% each week. The results indicated that “during entrainment of normal walking speed, gait velocity improved from 28.3 +/- 4.6 m/min to 36.4 +/- 7.6 m/min with RAS. During fast walking, gait velocity improved from 40.7 +/- 7.4 m/min to 43.9 +/- 7.8 m/min with RAS," with all changes being statistically significant. To summarize, "In two preliminary experiments, children with spastic diplegia were able to access rhythmic stimuli to entrain their gait patterns and improve gait measures associated with functional improvement," [39].

In the 2007 Journal of Music Therapy, E. Kwak makes an assessment, *Effect of Rhythmic Auditory Stimulation on Gait Performance in Children with Spastic Cerebral Palsy* [9]. Motor function was analyzed by a stride analyzing software that reads 4 pressure sensors on the foot. Cadence, stride length, velocity, gait cycle, gait symmetry, and foot contact pattern are analyzed by the software.

A pretest was used to get the baseline data and for producing the prescribed music for each participant. The participants walked at their most comfortable tempo. The prescribed music was determined based on pretest, observation, and conference with the physical therapist. Some had tempo of music increased by 5%, some decreased by 5%, and some remained the same the first week of therapy depending on the client's needs. The value of 5% from current cadence was decided by a Weber fraction, which is a percentage of the different thresholds obtained for different sensory stimulus (Ex. In order to perceive the difference between electric shocks, a person needs to have 1.3% difference between them). For auditory time perception, the Weber fraction is 5% from 0.4 sec to 2.0 sec. The cadence of the participants was between 37 (1.62 sec between steps) and 145 (0.41 sec between steps). The imperceptible changes in tempo of the music were essential to make the training as comfortable as possible. Tempo changes were made every week, depending on their progress. Sessions were 30 min for 5 days a week for 3 weeks. The author notes that the duration should be changed to 10-20 minutes and up to twice a day due to the excessively laborious nature of the task. RAS helps to develop new motor pathways in children with CP since a child with CP never learns to walk “normally” or “correctly” and must rely on their damaged motor pathways. Using a drum or clapping with the prescribed music to emphasize the actual cadence was found to be very effective. The author also makes the claim that “The use of music combined with physical therapy for infants, toddlers, and adults with CP need to be examined,” [9].

Cakewalk Pro Audio 8.0 MIDI program was used to provide variable tempo changes of recorded music used to accommodate the various cadences of each participant’s gait. Three different songs used: Dixie Land, When the Saints Go Marching In, and a blues-style selection. All of the songs were recorded at 4/4 meter with quarter notes equal to 100 bpm. Normal walking is said to be 105 to 120 steps per minute. The music was recorded at a slower pace because children with CP walk slower than typically developed children. Tempo varied from 80 bpm to 120 bpm in the study. A metronome was used to confirm accuracy of the tempo and assisted in synchronizing participants during the warm-up activity. If the cadence fell below 65 steps per minute, then the cadence was scaled by 2 for tempo for the RAS music to avoid excessively slow music, but an accompanying clap or drum beat maintained an equal bpm to cadence [9].

Results for cadence, using paired-sample t-test, no statistical difference between pre and posttest resulted between the control group and the tested groups. Stride length was shown to improve (lengthen) by 15.8% overall in the therapist-guided group, while the control and self-guided groups showed no significant difference. Velocity improved from 20.73% primarily in the therapist guided group which was much greater than the improvement made in the other groups. Symmetry, as defined as the shorter swing time of one leg from toe-off to heel strike divided by the longer swing time of the other leg, improved 16.97% in the therapist group which is again a great improvement over the other groups. Using a one-way analysis of variance (ANOVA), no significant difference between the groups regarding gait parameter improvement was identified. The author notes that, "There were no significance difference on measures in other tests used for analysis; however, differences in velocity, cadence, and stride length were observable and indicated a positive outcome with the methods of this study," [9].

In Wellner's 2007, *A Study on Sound Feedback in a Virtual Environment for Gait Rehabilitation* we can find many useful strategies for designing our protocol [15]. The researchers use the FMOD audio library to implement the sound feedback used in a virtual rehabilitation program for gait therapy. A time-varying interval ping sound was utilized to convey obstacle distances. A change in tonal pitch was used to indicate absolute foot height. Three different levels of height were mapped to 3 different pitches: C4, E4, and G4. The sound was played over a Dolby 5.1 channel audio surround system continuously when the obstacle is close by. 17 subjects with median age of 28.15 years were tested in this study. ANOVA (analysis of variance) was used to analyze the data. Sound feedback from height and distance had a significant impact on gait speed where gait speed was calculated relative to each subject's gait speed under normal conditions. Wellner et al believe that since the results for self-chosen gait speed in the presence of continuous acoustic feedback makes the subject choose significantly higher gait speeds that higher speed is indicative of higher confidence. They could not, however, conclude anything on the influence of acoustic feedback on task performance. The methods used in this study such as using the FMOD library or an equivalent and using a Dolby 5.1 channel audio system can be incorporated into our protocol as well.

In Thaut et al's 2008 paper, *Rhythmic auditory stimulation improves gait more than NDT/Bobath training in near-ambulatory patients early poststroke: a single-blind, randomized trial*, a comparison was made on the effectiveness of rhythmic auditory stimulation (RAS) and neurodevelopmental therapy (NDT) in gait training of hemiparetic stroke patients [49]. Two separate groups used each type of training over a 3 week period for 30 minutes each weekday. To ensure testing consistency, four gait therapists conducted the training for each group. The therapists were not blinded to the treatment conditions of the study.

The authors note that they use the "established protocols" for RAS training. The protocol consisted of a metronome and specifically prepared digital music in the MIDI format. This was to ensure temporal precision and tempo stability in addition to full capacity for frequency modulation based on patient's needs. First, an initial cadence assessment is performed to determine "cuing frequencies" for the first quarter of the session. Cue frequencies were increases in 5% increments thereafter by not compromising postural stability [49].

A t test comparison for posttest differences between groups yielded velocity, stride length, cadence, and symmetry gains significantly improved in the RAS group over the NDT group. The results suggest that RAS is an effective therapeutic method to enhance gait training in hemiparetic stroke rehabilitation [49].

Another 2008 paper examines rhythmic stimulation called *Effects of rhythmic sensory stimulation (auditory, visual) on gait in Parkinson's disease patients* [45].

Frequencies of the auditory stimulation that either matched or exceeded preferred walking cadence interacted most effectively with abnormal kinetic parameters in the most severe Parkinson's disease (PD) patients. Performance is said to have improved at frequencies above the preferred walking cadence. Frequency of a tone was ranged from 70% to 110% in increments of 10% around the frequency: 4.625 kHz. Note: Amplitude was adjusted so that it was not annoying, but still clearly perceived. Auditory stimulation at a frequency matching the preferred walking cadence was found to be effective in facilitating walking in severe PD patients. To facilitate gait (increased step length and reduced CV stride time), the authors prescribe frequencies equaling or above preferred walking cadence. 110% auditory stimulation (i.e. 1.1 x 4.625kHz tone) increased step length and velocity in severe patients and control group, but did not alter CV stride time [45].

Upper Extremity Therapy

In the 2002 *Neuropsychologia* paper, K*inematic optimization of spatiotemporal patterns in paretic arm training with stroke patients*, Thaut et al present their first major upper extremity work in RAS [8]. For their protocol, the frequency of the rhythmic cue was matched to the patient's self-paced movement frequency (which was assessed prior to start of the first trial). Auditory rhythm was a metronome-like 1 kHz square wave tone with a 50ms plateau time. The sound was produced by MIDI-sequencing sound software, Logic 2.5. Patients were asked to move their arm in time with the rhythm by touching the sensors on the beat. Patients started movements in the trial after they heard the metronome beat two to three times. Movement durations recorded from voltage coded sensor touch signal and arm kinematics from 3D camera [8].

For analysis, mathematical loop sums are employed as a dynamic indicator of movement stability since the loop sum decreases or increases continually adjusts to changes in variability in the movement sequence [8]. A decreasing mathematical loop sum over consecutive movement trajectories is said to be indicative of an increasing temporal movement stability or a decrease in movement variability. The patient's movement trajectories are said to have become more stable with rhythm than with no rhythm and also improvements in temporal and spatial variability during rhythm occurred. Thaut et al use an optimal path algorithm that sought to minimize peak absolute acceleration. During the rhythmic cuing, the mean deviation from the optimal path was much less than with the no rhythm condition. The authors also note that the rhythm lacking condition that used audio cues as stop and go signals did not improve motor learning [8]. The data from this study of changes in timing and trajectory control "strongly suggest that the structured timing information in auditory rhythm added significant kinematic stability to the patient's paretic arm motions" [8]. Thaut et al also note that a reduction in elbow range of motion due to upper limb muscle spasticity is a serious detriment to functional use of the afflicted arm. From this, we must observe that patients can benefit through an increase in range of motion.

Other Studies

In Thaut's 1985 Journal of Music Therapy seminal RAS paper, *The Use of Auditory Rhythm and Rhythmic Speech to Aid Temporal Muscular Control in Children with Gross Motor Dysfunction,* Thaut explores the idea of using auditory rhythm to enhance temporal muscular control in children with gross motor dysfunction [43]. The author examines auditory rhythm as a method in increasing motor rhythm accuracy. The experiment used patterns of gross motor motion sequenced to an auditory rhythm to show that an increase in temporal accuracy can be improved through training over time. That used voltage coded sensors on the subjects hand, feet, and back to measure the motion. A four-beat percussive pattern was repeated rhythmically at a metronome speed of 58 per quarter note. The subjects were initially taught to move to the beat before they were to perform the motion sequence in the trial. Twenty-four male subjects were tested and each had to have scored 40 or below on the Bruinicks-Oseretsky Test of Motor Proficiency.

Conclusion

Much of the current research on rhythmic stimulus has been focused on patients with Parkinson's disease, patients who have incurred stroke, or spinal injury. Very little is offered in the space of patients with cerebral palsy, although some researchers have explicitly pointed to the need for such research [36]. There is concern whether or not the effect will be as prominent since all of the former cases involve reassertion or reconnection of neural pathways that have been damaged through the condition. Cerebral palsy is unique in that the appropriate pathways have never been formed [9]. Fortunately, rhythmic cue therapy is not unprecedented for use with children with cerebral palsy [9], [39], although the effect has not to our knowledge been tested for the upper extremities.

There are no negative side effects associated with implementing rhythmic cuing in a training regime [9]. The implementation is relatively inexpensive as well as it is not prohibitively complex [9], [51]. This allows for creation of a system that patients are able to use at home. The system can be used in conjunction with other treatments or as an independent treatment since it is a noninvasive procedure [9], [36], [47]. From our assessment of the methodical implementations, we aspire to construct as system capable of generating a rhythmic beat or cue overlaying a song or melody as is suggested in [51] due to its effect on reducing variability and increasing synchronization. The rhythmic cue must always be synchronous with the melody and it must also be of greater intensity. The tempo or frequency of the rhythmic cue shall be determined by an initial trial that is meant to assess the natural tempo [9], [47], [49], [51], or comfortable motor action speed of the subject. The natural tempo will be used in the trials as the tempo for the rhythmic cue. The melody or song is used to add further engagement or appeal and thus, as in [9], the melody will be scaled if the natural tempo falls below a threshold tempo. Also, it may be prudent to further examine and utilize the Weber fraction for human hearing to find an acceptable change in tempo for the intervention [9].

Evaluation Metrics

In von Hofsten's 1991 *Structuring of Early Reaching Movements: A Longitudinal Study*, divided movements into units, each consisting of acceleration and a deceleration phase [52]. Five infants' reaching movements were studied quantitatively. They were recorded at 19 weeks of age, until 31 weeks of age. Reaching trajectories were found to be relatively straight within these units and to change direction between them. The structuring of reaching movements changed in four important ways during the period studied. First, the structuring became more systematic with age, with the dominating transport unit beginning the movement. Second, the duration of the transport unit became longer and covered a larger proportion of the approach. Third, the number of action units decreased with age, approaching the two-phase structure of adult reaching. Finally, reaching trajectories became straighter with age.

Fetters and Todd's 1987 *Quantitative Assessment of Infant Reaching Movements* identified a property of motor behavior termed movement units (MU) [53]. It is defined as a tight coupling of the curvature-speed relationship, and it occurs regardless of the distance of duration of the reach. A unit of action has been identified in all reaches at each age and condition. The unit is defined by inflection points in the reach when a speed valley (slowing) occurs at a curvature peak. The peak must occur within 20 ms of the speed valley. A movement unit is defined as that portion of the reach occurring from one curvature peak to the next.

Thaut et al's 2002 *Kinematic optimization of spatiotemporal patterns in paretic arm training with stroke patients* reaching movements was studied with and without rhythmic metronome cueing on spatiotemporal control of sequential reaching movements [8]. Results showed statistically significant improvements of spatiotemporal arm control during rhythmic entrainment. Rhythm also produced significant increases in angle ranges of elbow motion and significant kinematic smoothing. Their studies show that rhythm functions as a sensory cue to induce temporal stability and enhance the temporal organization of motor control in the nervous system.

Chen et al's 2007 study, *Use of virtual reality to improve upper-extremity control in children with cerebral palsy: a single-subject design,* found that children recruited to participate in their study showed a high degree of motivation for, interest in, and opportunity for engaging in play activities during the intervention. They state that "repetition is an important aspect of practice, and repetition of a task has been shown to improve performance in people with or without disabilities." Their results suggest that VR may motivate children with CP to engage in repeated practice of reaching behaviors.

The outcome measures used included four kinematic parameters, which were movement time (MT), path length (PATH), peak velocity (PV), and movement units (MU). The MT was defined as the time between the beginning and the end frame of a reach. Hand PATH was a measure of the distance traveled by the hand from the beginning to the end frame of a reach. With a fixed starting position, PATH reflected the straightness of the reaching trajectory. The amplitude of the resultant PV of the hand was an indirect measure of the amount of force in a reach. The PV was the maximum resultant velocity of the wrist from the beginning to the end frame of a reach. The number of MUs was a measure of movement smoothness: the fewer the MUs, the smoother the movement. The MU was defined from the acceleration-deceleration profile of the wrist marker by use of a method described in the literature on reaching.

In Ronnqvist and Rosblad’s 2007 *Kinematic analysis of unimanual reaching and grasping movements in children with hemiplegic cerebral palsy* eleven children with mild to moderate CP were observed while reaching and grasping [54]. This was done with both the non-preferred and preferred sides and several kinematic parameters were investigated. In comparison to the control and the mild hemiplegic children, the moderate children exhibited more segmented reaches and longer reach and grasp durations. Their reaching path with the non-preferred hand was also more segmented. The mild hemiplegic children performed reaches with similar duration and trajectory as controls. The velocity at hand–object-contact and the quality of their grasping was however affected in comparison to the controls.

In Brooks and Howard’s 2011 *Quantifying Upper-Arm Rehabilitation Metrics for Children through Interaction with a Humanoid Robot*, range of motion (ROM) and peak angular velocity (PAV) were used in the analysis results [55]. These parameters were used because their work focused on non-contact, upper-arm rehabilitation. ROM is a typical metric used by physical therapists, while PAV provides more accurate quantitative analysis. These give two physical therapeutic metrics for the purpose of analyzing a patient's current status and overall progress. Also, they can be calculated via computer vision techniques and therefore be utilized in a robotic system.

Garcia-Vergara et al's 2013 *Super Pop VR: an Adaptable Virtual Reality Game for Upper Body Rehabilitation* describes the Super Pop VR game and its advantages [56]. It is developed to work on any general-purpose computer system running a Windows 64-bit operating system. A 3D depth camera, the Microsoft Kinect, is used to capture and store depth images from the user's movements. When playing Super Pop, the user is sees virtual bubbles surrounding them on a screen. The goal of the game is to pop as many bubbles as possible in a certain amount of time by moving the hand over the center of the bubble. The user is instructed to pop the yellow bubbles and avoid the red bubbles. Game sessions can be customized to the capabilities of the user by changing the difficulty level. When the user passes a level, the game increases its difficulty. The goal of this VR system is to autonomously evaluate the user's performance during game-play using the Fugl-Meyer assessment methodology, which is a numerical scoring system for motor recovery, balance, sensation, and joint ROM. Because research is focused on non-touch upper-arm rehabilitation, measuring ROM is the focus of these experiments.

Compared to previously developed VR systems, the one presented in this work allows for individuals to use it in the comfort of their homes without the need for additional equipment. This enables therapy interventions to be accessible to a larger demographic of patients with disorders that affect their motor skills. Most importantly, the system allows the therapist to select the parameters of any game such that they match with the user's needs. Another observation throughout the experimental sessions is that all the users were concentrated and focused during game-play.

Conclusion

We have determined from the literature that the best approach for our problem is to use the following metrics: range of motion (ROM) for the shoulder and elbow joints, path length (PATH), peak angular velocity (PAV), movement time (MT), spatio-temporal variability (STV), and movement units (MUs). ROM is defined as the difference between the maximum and minimum angles during a trajectory and its increase is linked to an increase in functional use of an afflicted arm [4], [7], [8]. PATH is defined as the 3-dimensional length of the path travelled by the hand and is said to reflect straightness of a reaching trajectory [4]. PAV is the maximum angular velocity that occurs during a trajectory. This is used as an indirect measure of force, of which an increase would be indicative more confident motion [4]. MT is the time required to move in one trajectory. STV is a term to define the variability of motion as it relates to time of which is comprised of temporal variability and spatial variability when correlated [8]. MUs are defined as the quantity defined in [4], [52], [53], [57] which basically amounts to the number of peaks in the trajectory curvature. These metrics will allow us to characterize reaching movement to determine whether a treatment is effective or not. A more detailed and exhaustive explanation can be found in *Assessment Metrics*.

CHAPTER 3

APPROACH

Objectives

From our review of the literature, we have determined the most appropriate method to employ as we proceed in our discovery. We will explore the theory of Rhythmic Auditory Stimulus using a virtual system employing inexpensive depth sensing technologies for upper extremity therapy of children with cerebral palsy. An apposite subsequent step is to define what research questions we aim to address.

Research Question #1

Rhythmic entrainment is a well-established method or augmentation of therapy and has been used successfully to enhance upper-extremity therapy [8], [10], [50]. It has also been used successfully as an augmentation of gait therapy for children with cerebral palsy [9]. We seek to explore the effect of rhythmic entrainment on upper extremity therapy for children with cerebral palsy using the metrics outlined in [3], [9], [28],& [29]. Specifically, we aim to explore how rhythmic cue impacts range of motion (ROM), peak angular velocity (PAV), movement time (MT), spatio-temporal variability (STV), path length (PATH), and movement units (MUs) of the upper-extremities. In particular, we aspire to focus on the scapula (shoulder), lateral epicondyle of the humerus (elbow), and ulnar styloid process (wrist).

Definitions

Kinematic Metrics – We use this term to collectively indicate range of motion (ROM), peak angular velocity (PAV), movement time (MT), path length (PATH), spatio-temporal variability (STV), and movement units (MUs) of the upper-extremities as defined in *Assessment Metrics*.

Rhythmic Cue – We use this term to differentiate the underlying tonal beat played during a score or song from simply the song itself. The cue is distinguished through an increase in amplitude and occurs at equal time steps throughout the entire score.

Hypothesis

Through utilization of a **rhythmic cue**, the patient shows improvement in the **kinematic metrics**.

Research Question #2

Oftentimes therapy consists of repetitive motion that we believe can lead to a lack of engagement. The use of a virtual environment offers the advantage of providing for alternative methods of engagement, such as the presentation of the therapy as being a game [17]. In keeping with the spirit of a game, we hope to show that equal gains can be achieved in upper extremity therapy through a random assortment of therapeutic exercises and through a more repetitive execution of motion as in typical rehabilitation.

Definitions

Random - Bubbles are equidistant from the previous bubble position, but still placed randomly.

Repetitive - Bubbles are equidistant from the previous bubble position, but only alternate between 2 different positions.

Hypothesis

In the presence of a **rhythmic cue**, changes in **kinematic metrics** for **random** will be equivalent to changes in **kinematic metrics** for **repetitive**.

CHAPTER 4

METHODOLOGY

With the goal of exploring the questions presented and the current status of each respective field in mind, we aim to design such a virtual system that will be able to adequately engage the patients to reach the fundamental goal of physical therapy that is to achieve and facilitate muscle learning. Considering the home-based approach, we must also validate our sensing method to ensure an accurate assessment can be made by the clinician. After we have developed our system and validated our sensor we may then use the system to assess the research questions we have posed.

Assessment Metrics

As we have stated in *Evaluation Metrics*, our metrics are based on current metrics defined in the literature (ROM, PAV, PATH, MT, STV, MUs). Here we describe how each is implemented numerically.

Range of Motion

In the general sense, range of motion (ROM) can be defined as the distance a movable object may travel when attached to another. In the anatomical sense, ROM of some joints refers to the maximum angular distance from the fully flexed position in a joint rotation to the fully extended position [58]. Children with cerebral palsy are characterized by having a limited range of motion. The goal of treatment is to help the patient attain adequate mobility to perform activities of daily living to maximal performance [2]. Thus, the goal of therapy is to increase mobility and ROM is a good measure of long-term progress for people with restricted motion.

We use the clinical definitions of arm motion to describe different types of arm ranges of motion we will measure in our study. Range of motion (ROM) is clinically defined based on the type of joint being measured. Both the shoulder and the elbow are under the classification of a synovial joint, which are joints in which the articulating bone ends are separated by a joint cavity containing synovial fluid [58]. Synovial joints are further sub-classified into other types based on the types of movements that are allowed by the joint. For instance, the elbow is a hinge joint wherein movement is only allowed uniaxially (in one plane). **Flexion** is a movement, typically in the sagittal plane (See Figure 4.1), that decreases the angle of a joint and reduces the distance between the two bones of the joint. In contrast to this, **extension** is a movement that increases the angle of a joint and the distance between the bones [58]. Elbow ROM can be defined as the point at which there is maximum flexion to the point where there is maximum extension of the arm at the elbow joint. Typical values can range from 155 degrees to 165 degrees with some variations found depending on the source literature. The shoulder, however, is a little more complex and a little less easily defined. The shoulder is a ball-and-socket joint which is a multiaxial joint wherein movement is allowed in all directions and pivotal rotation [58]. **Abduction** is a movement of a limb away from the midline or median plane (a sagittal plane through the midline of the body), generally on the frontal, or coronal plane (See Figure 4.1). In contrast, what is sometimes referred to as the opposite of abduction, **adduction** is movement toward the midline of the body [58]. The shoulder abduction/adduction ROM (which we will summarily refer to as just shoulder abduction) is defined as the point at which there is maximum abduction to the point at which there is maximum abduction (See Figure 4.2b). This can be thought of the arm motion used to make a snow angel. Shoulder flexion/extension ROM (again, summarily referred to as simply shoulder flexion) is defined as the point at which there is maximum flexion to the point where there is maximum extension of the arm at the shoulder joint (See Figure 4.2a). This can be thought of as the motion of the arm from rest in a standing position to straight up in the air as if to give a high five.

Since these clinical definitions of motion are restricted to motion on a fixed plane, we must derive our own classification for the unique motion that occurs in normal random reaching. We define our shoulder flexion angle is defined as the angle of the shoulder made by projecting the upper arm onto a sagittal plane (perpendicular to the line made by the shoulder joint to the center shoulder joint) versus the coronal plane (See Figure 4.1). Similarly, the shoulder abduction/adduction angle is defined as the angle formed by the upper arm projected onto a coronal plane versus the same sagittal plane used for flexion. Numerically, we determine each of these in *Angle Calculation*.

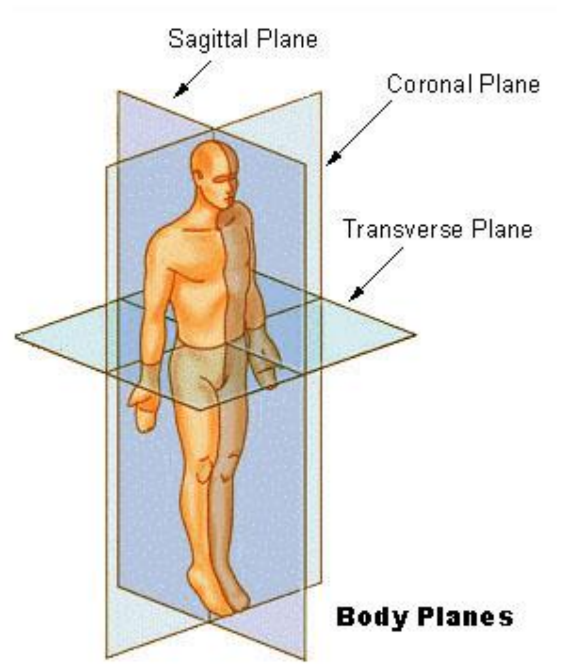

Figure 4.1: The planes used to describe parts and actions of the body [77].

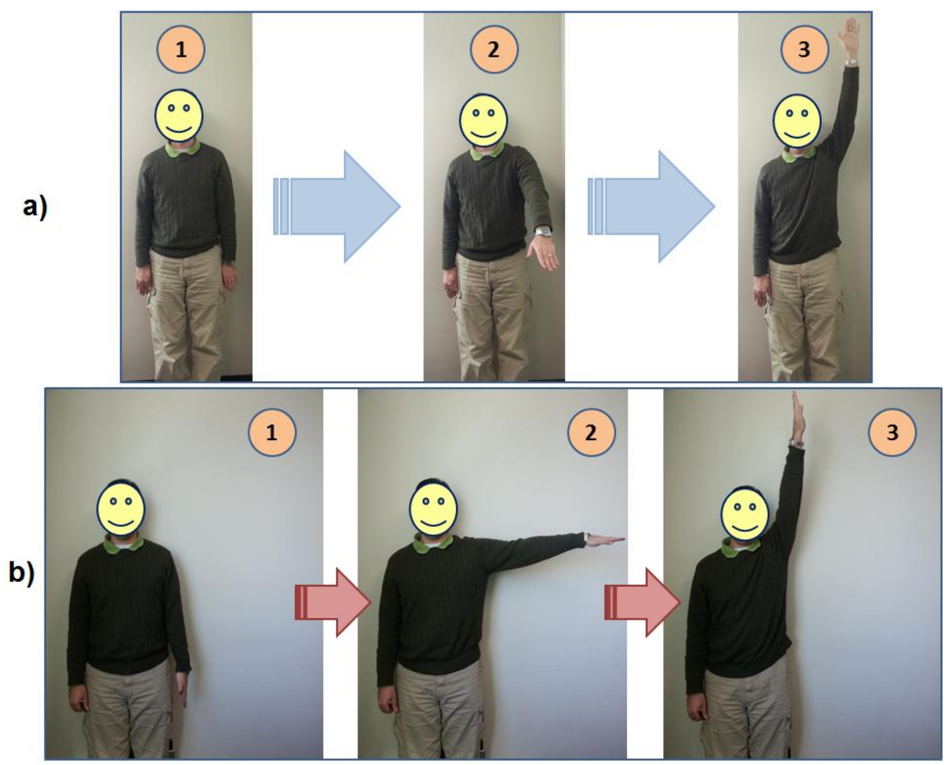

Figure 4.2: A demonstration of the range of motion of shoulder flexion/extension (a) and shoulder abduction/adduction (b).

Range of motion, for people with limited mobility, is expected to increase with practice and thus it would be utilized in determination of effectiveness in an intervention which may span multiple days, weeks, etc.

Peak Angular Velocity

Peak velocity is sometimes used as an indirect measure of the amount of force in a reach which is a metric used for assessing progress in therapy [4]. How forceful one moves may be indicative of confidence in motion. Peak velocity is expected to increase with age and practice. A related term, peak angular velocity (PAV), can also be used for the same purposes since it is more specific to the individual components of motion in reach. The definition for PAV is a little easier to obtain after describing ROM. In a single trajectory, with the angular velocity being the difference in position divided by the difference in time, peak angular velocity is simply the maximum value of angular velocity, where angular velocity is the rate of change of velocity over time, for a given trajectory (See Eq. 4.1).

$$PAV = \max\left(\frac{d\theta}{dt}\right), \qquad \textbf{4.1}$$

where $d\theta$ is the change in angle, dt is the change in time, and $d\theta/dt$ is the collection of values of angular velocity for each discrete data point in time.

Path Length

Path length (PATH), or the sum of the distances between each discrete data point, reflects the straightness of the reaching trajectory when using a fixed starting position [4]. PATH is determined by finding the 3-dimensional Euclidean distance between each discrete data point and taking the sum of the distances for each trajectory.

$$PATH = \sum_{i=1:end} \sqrt{(x_{i1} - x_{i2})^2 + \ (y_{i1} - y_{i2})^2 + (z_{i1} - z_{i2})^2}\ , \qquad \textbf{4.2}$$

where *i=1:end* is the set of all data points, and each of the two points is P(x_{i1}, y_{i1}, z_{i1}) and Q(x_{i2}, y_{i2}, z_{i2}). The PATH should decrease for each fixed length trajectory with age and practice [4].

Movement Time

Movement time (MT) is defined as the difference in the times at which each bubble is popped (i.e. the temporal boundaries for each trajectory). Movement time should decrease with age and practice [4].

Spatio-Temporal Variability

To find the temporal variability, we perform a temporal loop sum as in [8]. A loop sum is, by definition, indicative of movement stability. A loop sum increases or decreases as an adjustment in variability in a reaching movement [8]. The temporal loop sum we use is a cumulative difference between each successive movement interval and all other movement intervals (See Eq.4.3).

$$TLS_N = \sum_{i=1}^{M} |t_N - t_i|, \qquad \textbf{4.3}$$

where TLS_N is the temporal loop sum for trajectory N, M is the number of movement trajectories, and t_i is the travel time for movement trajectory i.

Spatial variability is a similar term to temporal variability that is used as a measure of movement variability in a spatial context. It can be found using Eq.4.4.

$$SLS_N = \sum_{i=1}^{M} d(N,i), \tag{4.4}$$

where SLS_N is the spatial loop sum for trajectory N, M is the number of movement trajectories, and d(N,i) is the distance from point N to point i.

Using the TLS and the SLS, we can find the spatio-temporal variability. Spatio-temporal variability (STV) is a quantitative measure found by taking the cross-correlation (See Eq. 4.5 & Eq. 4.6) of the spatial and temporal variability functions at zero lag (i.e. at no time shift). The normalized cross-correlation (Eq. 4.6) yields a value between -1 and 1. A highly correlated STV where a value closer to 1 is indicative of coherent and time-synchronized arm movement and can be used to determine improvement in the stability of arm movement across trials with rhythmic cuing [8].

$$r_{xy}[l] = \sum_{n=-\infty}^{\infty} x[n]y[n-l], \tag{4.5}$$

where r_{xy} is the cross-correlation of two discrete time sequences x[n] and y[n], n is the index of the value in the set, and *l* is the integer value of lag (i.e. the time shift between x and y) [59].

$$\rho_{xy}[l] = \frac{r_{xy}[l]}{\sqrt{r_{xx}[0]r_{yy}[0]}}, \tag{4.6}$$

where $\rho_{xy}[l]$ is the normalized cross-correlation of the sequences x and y, $|\rho_{xy}[l]| \leq 1$, $r_{xx}[0]$ and $r_{yy}[0]$ are the zero lag autocorrelation sequences of x and y, respectively [60].

Movement Units

Movement units (MUs) are defined as a measure of movement smoothness of reach wherein the fewer the movement units, the smoother the movement [52], [57]. We utilize the definition of movement units outlined in von Hofsten and Rönnqvist's 1993 article [57]. Each unit is derived from the velocity profile of a trajectory and consists of an acceleration phase and a deceleration phase. Each new acceleration phase marks a new MU. Further, we adhere to the conditions wherein the acceleration or deceleration is required to exceed 5 mm/sec^2 and the change in velocity must be greater than 20 mm/sec. MUs are expected to decrease with age and practice.

Data Validation

Low cost depth sensors such as the Microsoft Kinect™ could potentially allow for home-based care and rehabilitation using virtual systems. Prior to our study, no publicly available and peer-reviewed assessment has been made on the accuracy of the joint position data determined by the Kinect for Windows SDK to the best of our knowledge. We make just such an assessment of the Microsoft Kinect™ and the Kinect for Windows SDK skeleton position algorithm by comparing the shoulder joint flexion angle, shoulder joint abduction/adduction angle, and elbow joint angle of 19 subjects at distances of 1.5m, 2.0m, and 2.5m using an eight camera Vicon Motion Capture system.

Introduction

Rehabilitation after injury is crucial to recovery and to maintaining an adequate quality of life. Once a patient leaves clinical therapy, there remains a need for continuation of rehabilitation in the home [2], [11]. Many have also recognized the need for home-based rehabilitation programs to increase the quality of life in patients with other musculoskeletal conditions [2], [12], [13]. Engagement is key to an effective rehabilitation program and virtual systems are becoming more apparent as an effective means to this end [4], [17]. To decrease the load and increase the efficiency of physical or occupational therapists, home-based assessment shows promise. Inexpensive solutions in position determination such as the Microsoft (MS) Kinect TM could be used by therapists to gain accurate and useful data on patient progress [28–30]. Virtual systems can be used to provide, not only the therapist with useful data, but also to give the patient much needed feedback on performance and encourage activity [17], [23], [31], [32]. Patients are able to immediately see feedback in a virtual environment. Virtual systems are also proving to be an effective means of functional recovery in upper limb rehabilitation [4], [17], [61]. Feedback on performance is crucial to motor learning and it is also an effective means of allowing for the patient to feel productive during the intervention [4].

Currently, very expensive motion capture systems have been used in rehabilitation and other motion capture studies [28], [62], [63]. One such system is the Vicon camera system. The user must wear a non-infrared reflective suit with passive infrared (IR) reflective balls, or nodes, attached to it. The Vicon system uses multiple cameras to gain an accurate determination of the position of the nodes in 3-space.

For home-based care, it would be extremely cost-prohibitive to utilize the Vicon. The Kinect has the advantage of being relatively inexpensive and also that it requires no special clothing or equipment to use. If proven to be accurate enough for use in therapeutic assessment, the Kinect could allow for a dramatic increase in the efficiency of therapists and the number of patients they can treat simultaneously, engagement of patients during home-based care, and quality of life for patients through its use in virtual rehabilitation.

Related Previous Work

In [30], a very promising study was performed to demonstrate the accuracy of the Kinect sensor versus the Vicon, however, this study was limited to stationary blocks. Previous work [29] determined human motion by comparing Kinect with Vicon was limited to only determining stride length. Although an assessment of the Kinect hardware versus another motion capture technology [28] has been performed (using the OptiTrack Optical Motion Capture System), it was recognized that a larger sample size and a larger variety of motion was still needed. In addition to those shortcomings, there is currently no public assessment on the accuracy of the data provided by this algorithm for skeleton positions.

Equipment

Figure 4.3: Microsoft Kinect

The Kinect (or the underlying PrimeSense™ sensor) consists of an infrared (IR) emitter (or projector), an IR depth sensor (camera), and an RGB sensor (camera) in addition to other unrelated hardware. The emitter projects a speckle pattern of IR waves that are reflected off of objects which are then received by the IR depth sensor. These reflected waves create a new speckle pattern from which distances to objects may be determined by assessing the deformity of the new speckle pattern compared to the original. The technical specifications and details of the operation of the Kinect sensor can be found in observing the patents filed by PrimeSense [64–66]. The distances are used to form a depth image [67]. The Kinect for Windows SDK 5.1.0.3.191 determines skeleton position information from the provided depth image. The result is Cartesian coordinates of joint positions related in meters with the Kinect depth sensor center as the origin. These skeletons can be acquired at a rate of about 20 to 26 samples per second which has been deemed more than adequate in determination of postures in industrial settings [68].

Figure 4.4: Wall-mounted Vicon MX Camera

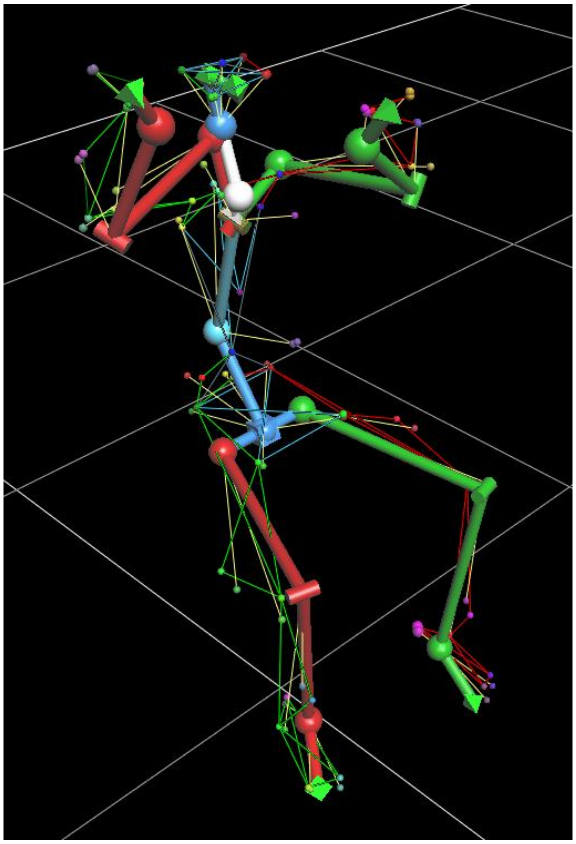

Figure 4.5: ViconiQ 2.5 Screenshot

The Vicon system used for this experiment consists of eight Vicon MX cameras whose data are analyzed using the software ViconiQ 2.5 Build 275. Each camera has an array of IR lights that emit IR waves. These waves are reflected by the passive reflectors the subject is wearing at specific points on the body. The camera data is compiled in the Vicon 612 5.R511 data station and then sent to a separate workstation with the ViconiQ software. The data from all 8 cameras is utilized to determine 3-dimensional positions of the reflectors. Once a capture session has been run, each passive IR reflector node must be labeled throughout the entire session. From this, the ViconiQ software generates a skeleton to fit within the nodes. After filtering the acquired data with a weighted average filter and a low pass Butterworth filter with an 8Hz cutoff and fitting the skeleton to each trial data, the result is position data of each joint in meters. The Vicon-generated-skeleton's joints do not all correspond exactly to the joints determined by the Kinect. For example, the Head joint on Vicon corresponds to the top of the head, while on the Kinect it is meant to represent the center of the head. Fortunately, in our study, we are only concerned with the elbow, 3-dimensional shoulder, shoulder flexion, and shoulder abduction/adduction angles. For this we only require the positions of the shoulder, elbow, and wrist joints.

Procedure

For the evaluation, 19 participants (13 male and 6 female) between the ages of 18 and 33 were instructed to play the Super Pop VR™ game [56] wherein virtual bubbles are projected onto a screen in randomly dispersed locations (See Figure 4.6). On the same screen, the participant sees a video stream of themselves in real time. The subjects are instructed to pop as many bubbles as they can in a 40 second time span. This procedure is repeated where the back of a stool on which the subject sits is placed at distances of: 1.5m, 2.0m, and 2.5m from the Kinect.

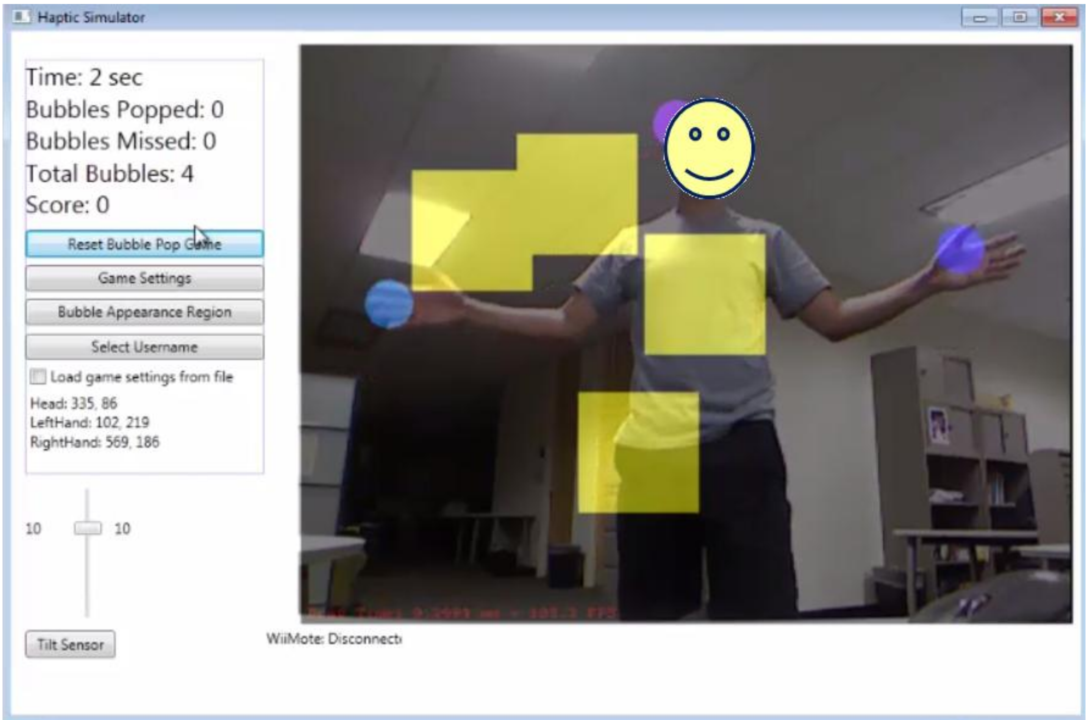

Figure 4.6: Screen capture of Super Pop VR^{TM} game play with yellow square bubbles.

Data

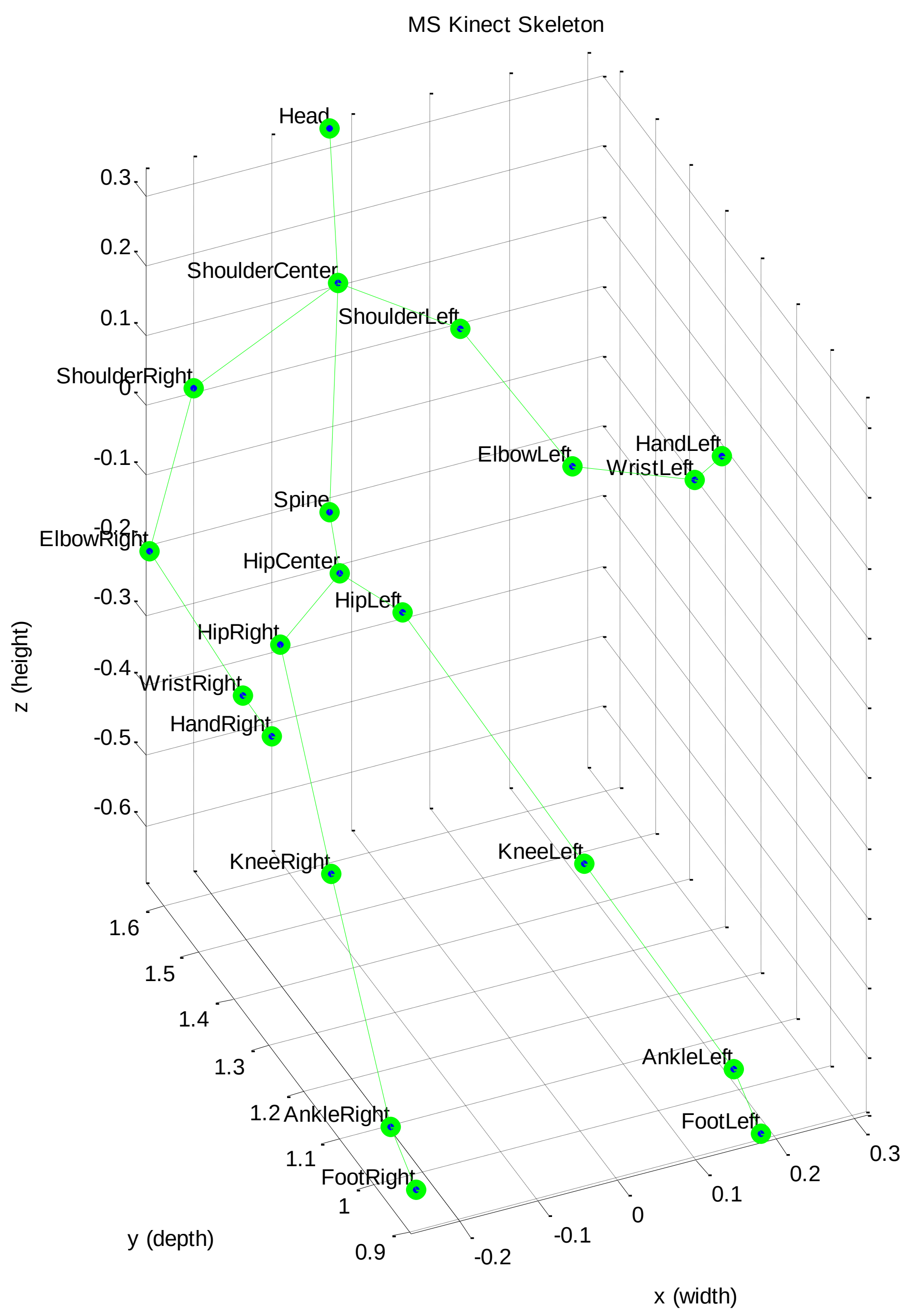

Figure 4.7: Microsoft Kinect Skeleton With Labeled Joints

Noise Classification

The joint position determination algorithm was able to provide between 20 and 26 positions for each joint per second for a total of around 1,100 sample frames for each approximately 45 second distance trial. The Vicon yields exactly 100 joint positions per second for a total of usually 4,500 sample frames for each distance.

For occluded or untracked joint positions, the Kinect algorithm must make an inference. Oftentimes the inference leads to what is characterized as spike noise in the data set [69]. This spike noise, quantization noise, and other white noise associated with the sensor electronics must be filtered out before post-processing the data and determining joint angles since all subsequent calculations will amplify any noise that is present on the signal.

Butterworth Filtering Method

We first utilize what is typically used in the field for joint tracking data: a Butterworth filter [4], [70]. Particularly, a 6th order with a cutoff frequency of 3Hz. We choose 3Hz through observation of the frequency content of our motion signal (Figure 4.8). From the figure, some of the noise looks to be above 6Hz, however, we achieve optimal results with the cutoff at 3 Hz (i.e. we achieve -3dB, or half, of the passband power at 3Hz). The Butterworth filter is an infinite impulse response (IIR) lowpass filter (LPF) [71]. Due to its recursive nature, this filter's impulse response extends for an infinite period of time. Butterworth filters are characterized as maximally flat, or with no ripple, in the passband [71]. As a 6th order Butterworth, our filter has a response with roll off of -36 dB per octave (-120 dB/decade) attenuation in the stopband.

We achieve this design using the MATLAB™ Digital Signal Processing Toolbox function butter() by specifying the filter order and the normalized cutoff frequency. The result is a discrete (Z-transform) transfer function (See Eq. 4.7) that can be applied using the filter() function. Our resulting Butterworth coefficients can be found in Table 4.1.

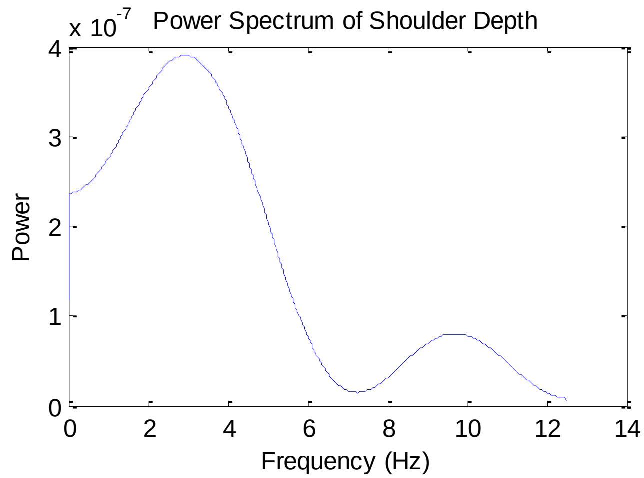

Figure 4.8: Power Spectrum of Shoulder Depth

$$H(z) = \frac{b(1) + b(2)z^{-1} + \cdots + b(n+1)z^{-n}}{1 + a(1) + a(2)z^{-1} + \cdots + a(n+1)z^{-n}} \qquad \textbf{4.7}$$

Table 4.1: Butterworth coefficients for a 6th order with 3 Hz cutoff frequency (ordered 1 to n+1).

Numerator (b-terms)	Denominator (a-terms)
$8.575\text{x}10^{-4}$	1.000
0.0051	-3.099
0.0129	4.416
0.0172	-3.557
0.0129	1.685
0.0051	-0.4411
$8.575\text{x}10^{-4}$	0.0496

Essentially, the process for the design algorithm of an IIR filter is implemented by taking the poles and zeros of a classical lowpass prototype filter in the continuous (Laplace) domain to obtain a digital filter through frequency transformation and filter discretization via the bilinear transform method (to the Z domain). The design algorithm used by the butter() function is described in the MATLAB™ documentation as follows:

1. It finds the lowpass analog prototype poles, zeros, and gain using the buttap() function.
2. It converts the poles, zeros, and gain into state-space form.
3. It transforms the lowpass filter into a bandpass, highpass, or bandstop filter with desired cutoff frequencies, using a state-space transformation.
4. For digital filter design, butter uses bilinear to convert the analog filter into a digital filter through a bilinear transformation with frequency pre-warping. Careful frequency adjustment guarantees that the analog filters and the digital filters will have the same frequency response magnitude at Wn or w1 and w2.
5. It converts the state-space filter back to transfer function or zero-pole-gain form, as required.

The results of the Butterworth filter can be seen in Filtering *Results*.

An Alternative Filtering Method

Through a characterization of the noise types using [69], we determined that we could also make an attempt to utilize a cascade of two filters: 9th order 101 point Savitzky-Golay filter in series with a 35 point Median filter. The Savitzky-Golay (SG) filter is typically used to eliminate noise where the frequency span of input data without noise is large (as with joint positions from the Kinect). The SG smoothing filter is a low pass filter, sometimes called an Auto Regressive Moving Average (ARMA), that essentially performs a local polynomial regression (of order k – See Eq. 4.8) on a series of values (of at least k+1 points which are treated as being equally spaced in the series) to determine the smoothed value for each point [69], [72].

$$f_K(x) = \sum_{i=0}^{K} c_i x^i, \tag{4.8}$$

where K is the polynomial order, i is the number of terms in the polynomial, c is a constant coefficient, and x is the dependent variable [69]. The SG filter implementation aims to minimize the mean-squared approximation error for a group of samples. Using N previous and M future samples, the SG filter finds the c_i coefficients of a polynomial that minimize the term inside of min() in Eq. 4.9 [69], [73].

$$H = \min\left(\sum_{i=-M}^{N} \left(X_{n-i} - f_K(n-i)\right)^2\right) \tag{4.9}$$

The characteristic output of an ARMA filter is a weighted average of current and N previous inputs, and M previous filter outputs. The main advantage of this approach is that it tends to preserve features of the distribution such as relative maxima, minima and width, which are usually 'flattened' by other adjacent averaging techniques (such as in the case of moving averages) [72].

The Median filter is characterized as a nonlinear filter used to eliminate spikes in data sets. Typically it finds use in image processing applications and can be used to eliminate speckle noise and salt-and-pepper noise [69]. An example of our implementation of the median filter is as follows:

```
% N-pt median filter

oneSide = (N-1)/2;
len = length(rawJoint.X);
for a1=oneSide+1:(len-oneSide)
    smoothedJoint.X(a1) = median(rawJoint.X(a1-oneSide:a1+oneSide),1);
    smoothedJoint.Y(a1) = median(rawJoint.Y(a1-oneSide:a1+oneSide),1);
    smoothedJoint.Z(a1) = median(rawJoint.Z(a1-oneSide:a1+oneSide),1);
end
```

In this implementation, we only use odd values for N. The results of the cascade filter using the Savitzky-Golay and Median filters can be seen in *Filtering Results*.

Filtering Results

As seen in Figure 4.9, our 6th order, 3Hz cutoff Butterworth filter implementation is shown to have eliminated the high frequency noise components. The filtered Kinect data is much more correlated to the Vicon sensor data. Elbow data is used instead for this demonstration since the filter effects are more prevalent in the elbow.

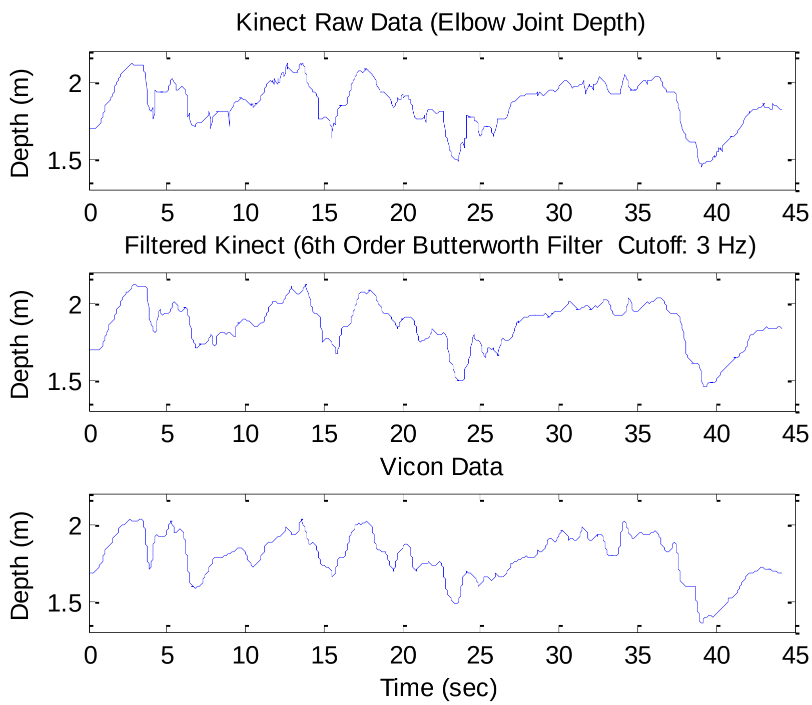

Figure 4.9: A Comparison of Raw Kinect (Top), 3Hz cutoff, 6th Order Butterworth Filtered Kinect (Middle), and Vicon data (Bottom).

We should note that Butterworth filters, or more broadly IIR filters may have a nonlinear phase response and induce phase distortions usually in the form of lags. We also note that noise spikes (which are expected in Kinect data as noted in [69]) may alter a localized period of the signal when using a Butterworth filter.

Figure 4.10 shows the same comparison as Figure 4.9, but using instead the cascaded SG/Median filter implementation. The performance difference is clear when comparing with the Butterworth. We see a much smoother filter output, which ultimately results in overall less error as can be seen in Figure 4.11. We should also note that the Vicon data output also has noise, even after the Vicon software has filtered the data. We restrict our use of the Vicon data to what is typically used in current studies so as to best compare our implementation.

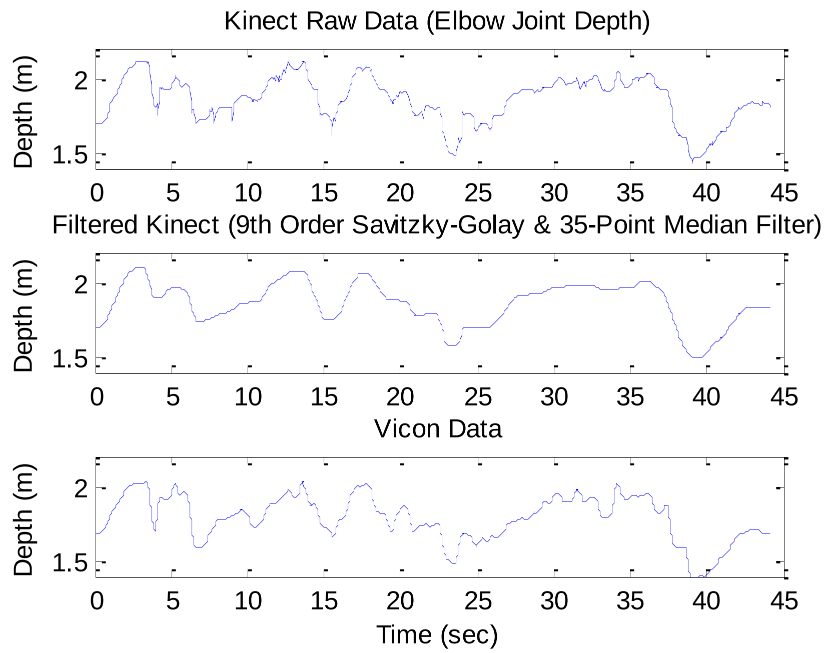

Figure 4.10: A Comparison of Raw Kinect (Top), Median/SG Filtered Kinect (Middle), and Vicon data (Bottom).

In Figure 4.11, we examine the difference between selected types of filters. We examined many other filters in our assessment, but we chose to display these as they had the most variance and represent the most prominent difference in visual results. Overall, as can be seen in the figure, the cascaded filter using a 9th order SG and 35-point Median filter had the least amount of average percent absolute error and the least absolute average deviation. A more in-depth description of the error and deviation terms as well as a tabular version of the best performing filter can be found in *Error Calculation*.

Angle Calculation

As noted in *Assessment Metrics*, we use the clinical definitions of arm motion to describe different types of arm ranges of motion we will measure in our study. Since these clinical definitions of motion are restricted to motion on a fixed plane, we must derive our own classification for the unique motion that occurs in normal random reaching. We define our shoulder flexion angle is defined as the angle of the shoulder made by projecting the upper arm onto a sagittal plane (perpendicular to the line made by the shoulder joint to the center shoulder joint) versus the coronal plane. Similarly, the shoulder abduction/adduction angle is defined as the angle formed by the upper arm projected onto a coronal plane versus the same sagittal plane used for flexion.

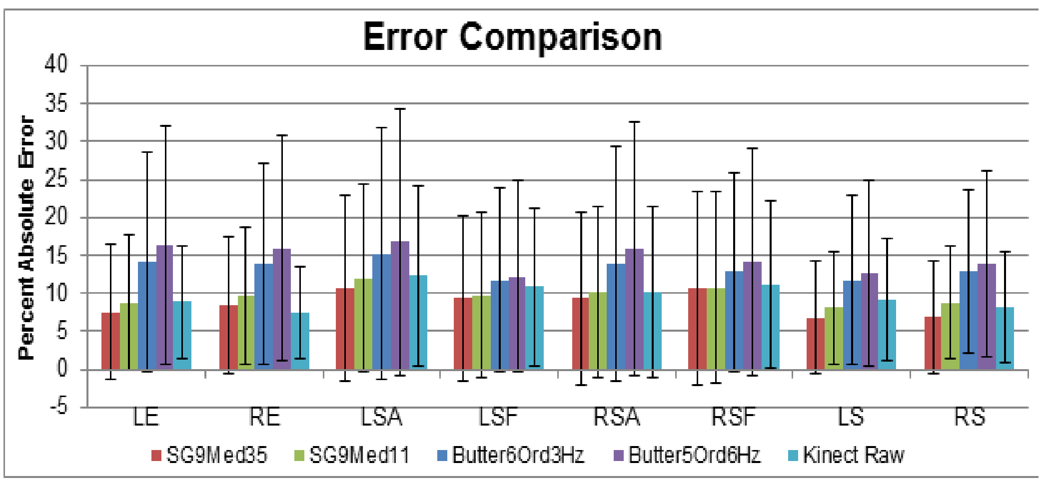

Figure 4.11: Comparison of filtering techniques at 1.5m. The bars are absolute average error and the lines through the bars represent the +/- average absolute deviation. The raw Kinect data is on the rightmost bar in light blue, the leftmost, red bar is the 9th order SG filter cascaded with a 35-point median filter. The Green bar is a 9th order SG filter with an 11-point median filter. The dark blue is a 6th order Butterworth filter with 3Hz cutoff frequency and the purple is a 5th order 6Hz cutoff Butterworth filter.

The 3-dimensional left and right shoulder angles are a trivial matter of calculation. We simply determine the angle between the vector created by the elbow joint and the shoulder joint and the vector created by the shoulder joint and the center shoulder joint (See Figure 4.7) to determine the 3D shoulder angle. We perform a similar operation for the elbow angle by determining the angle between the vector created by the elbow joint and the shoulder joint and the vector created by the elbow joint and wrist joint.

$$\theta_{3D} = \cos^{-1}\left(\frac{\boldsymbol{s} \cdot \boldsymbol{u}}{|\boldsymbol{s}||\boldsymbol{u}|}\right) \quad \textbf{4.10}$$

Since we have the 3 Cartesian coordinates of the joints in 3-space, we can create the vectors s and u and we can then easily find the 3D angle, θ_{3D}, between the two vectors as seen in Eq. 4.10 [74].

Forming the clinical angles requires a little more work. The shoulder abduction angle is created by projecting the upper arm onto a plane, D (which has a normal **m**), created by the cross product of shoulder vector **u** and upper spine vector **g** (See Figure 4.12, Figure 4.7, and Eq. 4.11). The projection will be called vector **5.** The plane can be thought of a pseudo-coronal plane. After making the projection, we shift the upper spine to connect with the shoulder joint and call the shifted spine, vector **p**. The abduction angle can then be found by determining the angle between **v** and **p** using Eq. 4.10. Programmatically, we are solving the problem of intersecting a circle, C (whose radius is the upper arm with length d and has normal **n**: See Eq. 4.12), and the plane D. If the point of intersection is P, then we are essentially solving for P as in Eq. 4.13. Since this will have 2 solutions, we choose the one closest to the elbow joint.

$$\boldsymbol{m} = \boldsymbol{u} \times \boldsymbol{g} \quad \textbf{4.11}$$

$$C = d\cos(t)\cdot \boldsymbol{c} + d\sin(t)\,(\boldsymbol{n}\times\boldsymbol{c}) + S, \tag{4.12}$$

where S is the circle's centroid and **c** is an arbitrarily defined vector from S to the edge of circle C.

$$(C - P)\cdot \boldsymbol{m} = 0 \tag{4.13}$$

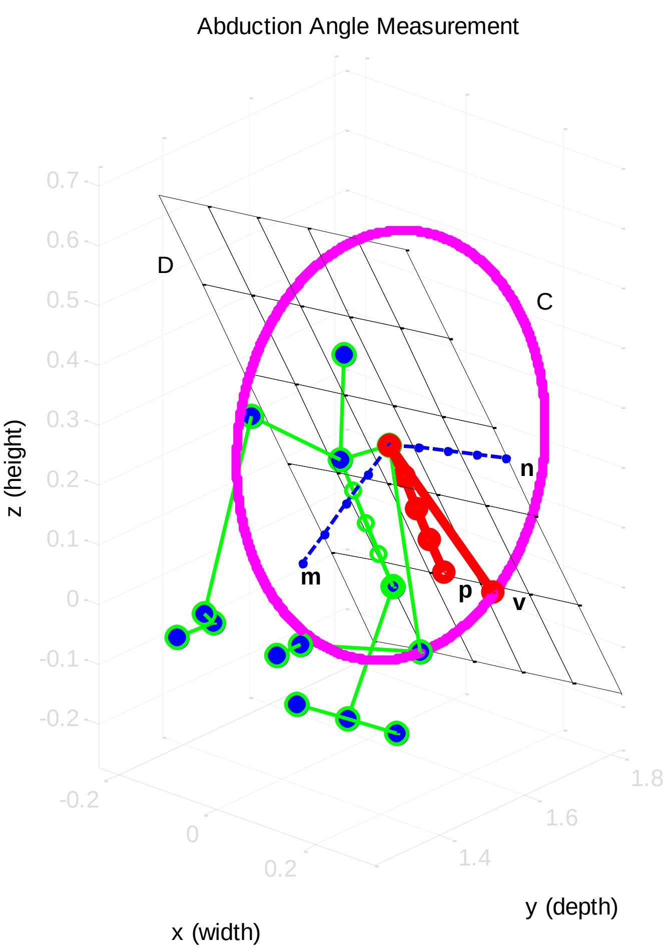

Figure 4.12: The Abduction Angle Calculation Visualization.

In a similar fashion as the abduction angle, we are able to determine the flexion angle. Here we are measuring the projection, vector **w**, against the same vector of the shifted spine, **p**. Vector **w** is formed by the point of the intersection of the circle with radius formed by the upper arm and with a normal perpendicular to **n** and the plane that is perpendicular to D and passes through the shoulder joint.

Results

Temporal Synchronization

Since the two data sets are not sampled at precisely the same time, to make a comparison we must determine some method of correlating the data. After up-sampling the Kinect data rate to match the Vicon's, a mathematical correlation proved unsuccessful, presumably due to the stochasticity of motion and the noise in the data sets. Each subject was instructed to remain still until a countdown had completed. We use this time with a very low frequency of motion to line up the two data sets so that we may form a comparison. Since our sample times also do not match up, we use the following metric for determining the error between each arm trajectory where a trajectory is defined as motion during the time between bubble pops in the virtual reality game.

Error Calculation

We determine the average absolute error and the average absolute deviation for the shoulder angle range of motion (ROM) which is the difference of the maximum and minimum observed angles in a trajectory. We define absolute error (AE) as the ratio of the observed angles and the theoretical maximum of the angles, which is 180 degrees for shoulder angles and 166 degrees for elbow angles (Eq. 4.14). We chose these angles as our maximum because they correspond to our observed maximums and they also conform to the ranges referred to in clinical literature [58]. AE is averaged for each subject's trial and all subjects are then averaged. That is what we report by the solid bars in Figure 4.13. The average absolute deviation is a measure of dispersion from the mean. It is found by finding the square root of the average of the variances.

$$AE = \frac{|ROM_V - ROM_K|}{180} * 100 \qquad \textbf{4.14}$$

We compared the data from three distances: 1.5m, 2.0m, and 2.5m. We measured this distance from the sensor to the back of the stool each participant sat in, or the position where the participant stood. On average, the data for all subjects at 2.0m yielded the lowest average percent absolute error of all three distance we tested at for the cascaded Median/SG filter. LE had 6.32% versus the raw Kinect with 8.87%. RE had 6.29% versus the raw Kinect with 7.45%. LSA had 9.20% versus the raw Kinect with 12.38%. LSF had 10.08% versus the raw Kinect with 10.82%. RSA had 8.68% versus the raw Kinect with 10.15%. RSF had 11.66% versus the raw Kinect with 11.19%. LS had 6.55% versus the raw Kinect with 9.21%. RS had 5.98% versus the raw Kinect with 8.26%. The comparison also yielded that the 2.0m condition had the lowest average absolute deviation. LE had an average absolute deviation of +/-6.03 versus the raw Kinect with +/-7.38. RE had +/-5.97 versus the raw Kinect with +/-6.16. LSA had +/-10.25 versus the raw Kinect with +/-11.85. LSF had +/-11.44 versus the raw Kinect with +/-10.42. RSA had +/-8.98 versus the raw Kinect with +/-11.20. RSF had +/-13.27 versus the raw Kinect with +/-11.00. LS had +/-6.66 versus the raw Kinect with +/-8.09. RS had +/-5.70 versus the raw Kinect with +/-7.36. All of these values are summed up in Figure 4.13.

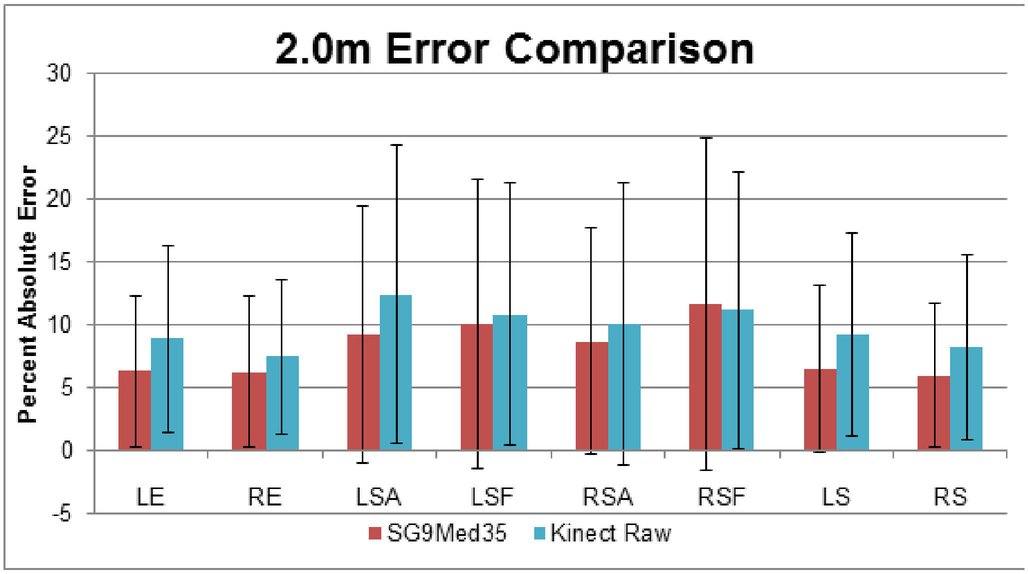

Figure 4.13: The plot shows the average percent absolute error comparison at 2.0m of a 9th order 101 point Savitzky-Golay filter in cascade with a 35 point Median filter (leftmost bars) and the raw Kinect data (rightmost bars) each versus the Vicon data for all 19 subjects. The vertical bars represent +/- the average absolute deviation. LE: Left Elbow Angle, LSA: Left Shoulder Abduction Angle, LSF: Left Shoulder Flexion Angle, LS: Left Shoulder 3D Angle, and the same angles for the Right side.

For completeness, in Table 4.2, Table 4.3, and Table 4.4, we present all of the values of average percent absolute error for each of the 19 subjects for each angle at the distances of 1.5m, 2.0m, and 2.5m, respectively.

Table 4.2: Average Percent Absolute Error of all trajectories at 1.5m.

Summary of Average Absolute Error of All Trajectories at 1.5m								
	LE (%)	**RE (%)**	**LSA (%)**	**LSF (%)**	**RSA (%)**	**RSF (%)**	**LS (%)**	**RS (%)**
Subject1	6.15	4.33	4.41	8.21	2.58	5.89	2.66	3.92
Subject2	7.57	6.95	3.97	7.52	5.16	4.77	5.54	2.84
Subject3	3.85	5.64	1.45	2.07	3.46	2.58	1.04	2.14
Subject4	4.33	4.34	3.28	3.69	4.03	4.92	2.48	2.92
Subject5	6.08	5.86	12.58	8.90	6.53	6.46	10.11	5.50
Subject6	4.32	6.07	6.38	4.65	5.98	8.70	6.53	8.22
Subject7	3.75	4.40	4.08	9.56	3.51	5.38	4.50	2.34
Subject8	4.45	7.62	6.37	15.46	7.77	18.29	6.87	6.86
Subject9	10.58	9.73	7.28	7.50	11.12	9.90	4.83	6.84
Subject10	25.71	28.35	21.29	14.73	16.61	16.65	17.28	24.77
Subject11	6.17	9.03	4.42	3.31	9.29	14.43	5.62	5.65
Subject12	4.47	2.74	5.43	7.21	3.82	3.47	4.89	3.73
Subject13	5.87	8.97	6.53	8.36	14.24	7.29	4.32	5.80
Subject14	6.63	12.49	26.93	10.97	14.24	17.03	8.61	7.65
Subject15	9.95	8.89	18.45	13.12	15.47	15.75	10.47	8.24
Subject16	6.32	8.72	16.91	12.21	16.57	12.38	9.74	10.98
Subject17	9.81	10.66	26.03	9.83	19.59	28.30	9.70	9.24
Subject18	7.74	6.50	14.62	17.25	8.49	7.96	5.02	6.47
Subject19	8.72	8.85	11.87	13.68	9.11	13.77	8.87	6.97

Table 4.3: Average Percent Absolute Error of all trajectories at 2.0m.

Summary of Average Absolute Error of All Trajectories at 2.0m								
	LE (%)	**RE (%)**	**LSA (%)**	**LSF (%)**	**RSA (%)**	**RSF (%)**	**LS (%)**	**RS (%)**
Subject1	7.93	8.00	6.20	6.64	5.78	14.15	4.36	7.52
Subject2	4.87	3.43	3.14	4.61	8.35	9.79	5.41	8.60
Subject3	9.17	12.85	16.20	5.66	10.03	7.61	6.09	4.61
Subject4	3.81	6.05	2.34	3.17	5.06	5.24	2.16	2.92
Subject5	3.74	6.67	5.50	5.54	9.36	8.25	4.43	6.22
Subject6	5.38	4.69	5.27	8.50	4.35	7.09	7.11	4.32
Subject7	4.38	6.19	5.63	6.77	5.12	10.61	4.70	3.64
Subject8	9.90	8.38	9.37	15.21	6.70	16.57	11.87	9.70
Subject9	4.33	6.23	8.67	20.79	12.85	16.91	6.66	6.12
Subject10	11.52	3.55	13.01	11.82	7.25	4.41	11.78	6.27
Subject11	4.80	3.90	6.26	4.95	4.17	6.57	4.60	3.84
Subject12	3.39	3.56	15.19	14.23	6.83	5.63	7.34	3.86
Subject13	3.93	7.94	8.16	6.95	6.35	8.41	5.93	4.52
Subject14	5.23	5.08	6.30	8.90	10.74	9.46	5.14	4.13
Subject15	13.21	11.48	13.25	16.15	16.82	19.55	6.72	9.61
Subject16	4.60	4.89	8.76	6.76	9.30	10.01	7.61	5.23
Subject17	3.58	4.57	18.01	7.53	9.85	7.24	4.87	4.28
Subject18	4.49	3.85	11.26	17.75	12.13	25.57	6.45	8.96
Subject19	11.82	8.17	12.27	19.53	13.97	28.37	11.29	9.37

Table 4.4: Average Percent Absolute Error of all trajectories at 2.5m.

Summary of Average Absolute Error of All Trajectories at 2.5m								
	LE (%)	**RE (%)**	**LSA (%)**	**LSF (%)**	**RSA (%)**	**RSF (%)**	**LS (%)**	**RS (%)**
Subject1	10.08	6.22	7.10	5.32	3.31	5.48	8.80	3.87
Subject2	5.29	8.82	8.01	12.51	7.80	10.76	5.89	8.67
Subject3	7.89	8.21	6.07	7.92	5.47	13.49	4.80	4.91
Subject4	6.76	5.96	4.25	7.25	5.41	5.99	2.60	4.01
Subject5	7.17	7.67	8.56	11.91	8.74	11.44	5.10	5.48
Subject6	7.26	4.60	4.64	7.82	2.18	4.99	7.56	4.96
Subject7	3.94	7.14	8.30	9.95	7.84	15.02	4.57	7.29
Subject8	11.24	11.11	12.86	20.48	10.02	19.77	10.77	16.20
Subject9	7.98	4.71	6.82	20.73	5.27	12.76	7.82	5.86
Subject10	10.62	10.78	15.64	16.10	8.07	13.45	11.60	12.39
Subject11	4.85	6.09	8.00	15.14	8.71	11.74	8.17	7.23
Subject12	6.30	3.60	7.20	16.85	4.76	5.70	6.68	2.94
Subject13	9.30	7.95	9.25	21.34	12.31	10.09	6.03	6.03
Subject14	3.34	4.84	8.95	25.96	6.15	8.41	3.60	7.66
Subject15	15.10	12.65	20.48	28.01	12.64	22.36	12.45	9.97
Subject16	9.11	6.63	8.04	6.24	11.82	11.73	4.01	12.52
Subject17	7.64	4.16	9.29	13.26	9.25	8.35	6.65	5.91
Subject18	10.90	9.20	15.24	31.85	11.67	14.00	9.84	7.62
Subject19	13.12	16.34	12.05	24.55	10.57	28.81	11.64	8.17

Our highest deviations were observed in trajectories where we note occlusions of joint positions in the Vicon data. Particularly occluded data was observed for all trials of Subject 10. We believe this to mainly be a result of Subject 10 being much smaller a size than the Vicon suit which resulted in occlusions formed by the suit folding over and covering the markers on almost every reaching motion. The error was higher for the angles which were determined from the original positions using many calculations such as LSA, LSF, RSA, and RSF. This fits our intuition since we propagate the error in the position measurements when performing further calculations.

Discussion

We have termed and validated clinical angle measurements that can be used to classify motion of the arm. Using these angle definitions, everyday arm motion may more easily be quantitatively defined and assessed for therapeutic or other purposes.

The results indicate that an acceptable margin of error exists for angle determinations from the Kinect for use in a rehabilitative context. This result then allows for the use of the Kinect in a virtual rehabilitation system. As a direct result, home-based therapy can then be used to provide quantitative feedback to patients and therapists in an inexpensive way. By using such systems, therapists could treat many more patients and increase their overall efficiency. Through more meaningful feedback patients can not only gain functional recovery much more expeditiously, but also increase their aptitude for motor learning and perhaps an increase in engagement. All this ultimately leads to a better patient quality of life.

Conclusions

From this assessment, we have formed a quantitative measure of the accuracy of the MS Kinect for the elbow flexion angle, shoulder flexion angle, shoulder abduction/adduction angle, and the 3-dimensional shoulder and elbow angles observed in random reaching activities. We have also created a method for translating reach into measurable clinically-based shoulder angles.

Game Design and Operation

We employ the Super Pop VR^{TM} developed by García-Vergara & Howard in [56] as a foundation for our implementation. The basic game is a virtual or augmented reality design in which the player sees in the game window a live video stream of themselves (See Figure 4.6). When the game starts, bubbles begin to appear in randomly dispersed locations and the player can use their hands to move to where the bubbles are on the screen to “pop” the bubbles. A timer and game statistics are also shown on the game window.

Although the game offers an excellent design foundation for our therapeutic regime, we require certain modifications to allow it to be used to meet the end of implementing RAS in a home-based therapy. We made several additions to the original program including: an RAS tempo calculation assessment, an RAS catered game, a song add/edit menu, skeleton joint position acquisition and storage, game settings persistence after program termination, and general GUI improvements derived from Human-Computer Interaction literature. We discuss those modifications further in the following sections.

Design Considerations

Since the game operation and infrastructure had already been implemented and shown to be engaging using typical children (See [56]), we set out to use its function as a foundation for our implementation. Several considerations were made on our design. The primary addition would be the auditory stimulus. Since the game had been written in the C# .NET 4.0 style, we sought out a library already written in that language. We also required a library that would allow manipulation of the tempo of the auditory cue. The library must also allow for the dynamic creation of songs at a specified tempo and also the ability to play the song in a background process so that the game itself would not distort the timing of the rhythm. Through a review of resources freely available online with these parameters in mind, we found a Midi player library written by the author of the book, *Programming in the Key of C#*, Charles Petzold [75]. The library met all requirements with some modifications.

Program Flow

The game has been designed such that we may implement an RAS intervention or augmentation of therapy. The primary functions necessary are as follows:

1. We seek to determine the natural tempo or natural frequency of reaching motion.
2. We must be able to make targets for the reaching motion at variable distances.
3. We must also be able to change the size of the targets.
4. We must be able to change the duration of a session.
5. We must be able to acquire and store joint position data and trajectory time data to make an assessment using the metrics.

Figure 4.14 demonstrates the flow of the program.

Figure 4.14: Program Flow Diagram

Game Parameters

The game offers many parameters that can be set to customize how the game can be played. There are multiple settings menus such as: Game Settings, Kinect Settings, RAS Game Settings, and Bubble Settings. The Game Settings menu allow for changes of parameters such as: game duration, number of bad bubbles, bubble size, and the scores for the bad and good bubbles (See Figure 4.15). These can be set to pre-determined values by checking the difficulty level or by selecting *Custom*, you can choose your own values. There are also options for changing the shape of the bubbles. They can be turned into squares, triangles, and also into circles. One can also select sound feedback under *Sound Options*. These include a simple popping sound, or the successive notes in the songs *Twinkle, Twinkle Little Star* or *Fur Elise.* The last feature on the menu is to access the RAS Game Menu.

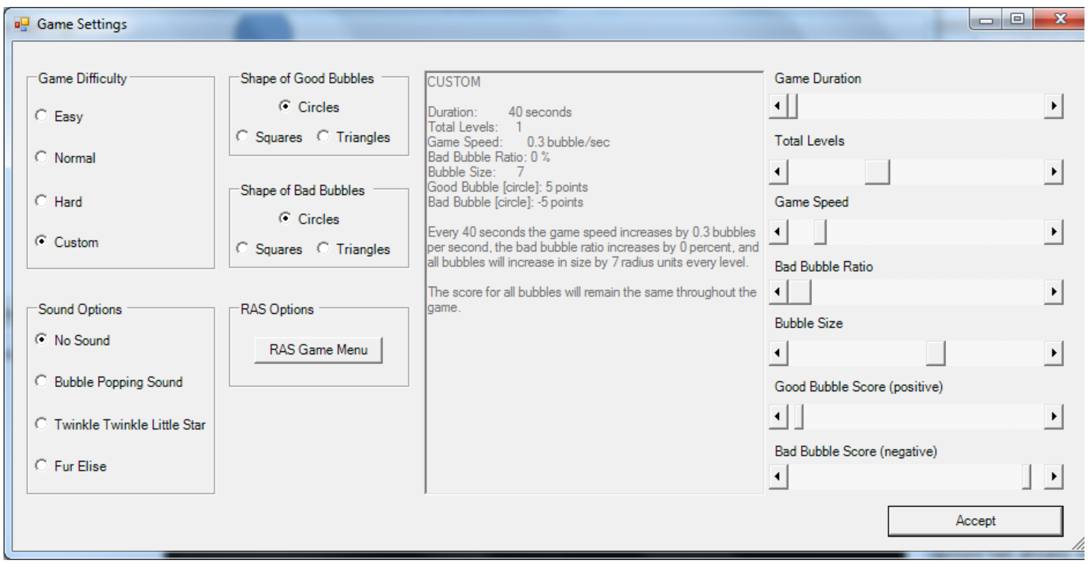

Figure 4.15: Game Setting Menu

The RAS Game menu offers game features specific to the Rhythmic Auditory Stimulus game (See Figure 4.16). One can select the song to play as the stimulus, the separation distance (in pixels) between each bubble, whether the game is the Random condition or the Repetitive condition (See *Research Question #2*), and also whether or not to use the natural tempo determined during the Initial Assessment game or to use the tempo (in bpm) set in the RAS Game Settings menu.

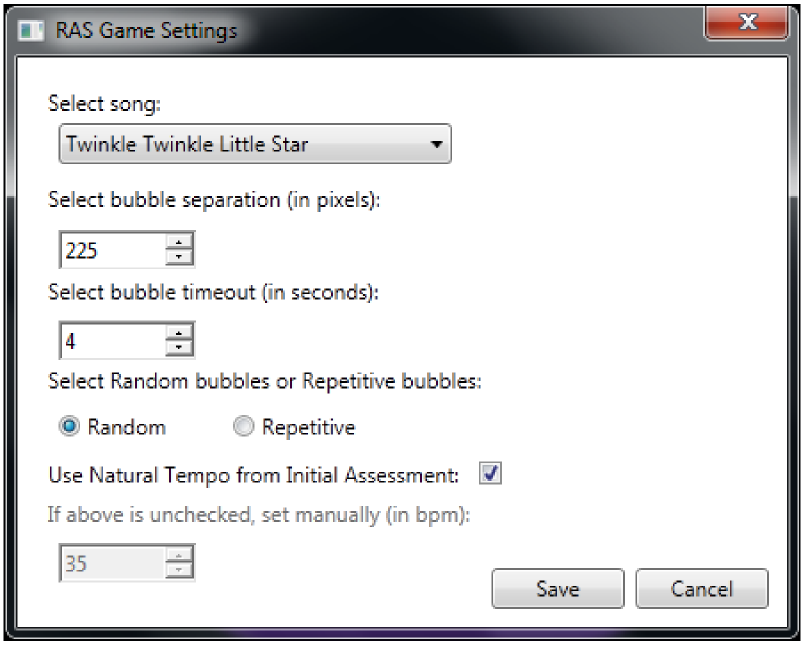

Figure 4.16: RAS Game Settings

Song Creation

Each subject has a natural pace in which they can move comfortably. To find this natural pace, or natural frequency of motion, we constructed an initial assessment form of the game that records the time at which each bubble is popped. Participants are asked to move at a comfortable pace so that the tempo will not be excessively fast or slow. We then take an average of the amount of time taken per bubble and convert this into bubbles popped per minute. We calculate the number of bubbles popped per minute and use the conversion factor of a single beat per bubble pop (one beat per trajectory) to find beats per minute (frequency of beats, i.e. tempo). This beats per minute is the Natural Frequency of the subject. We use this to as the frequency of the rhythmic cue throughout all of our testing. The resulting equation, Eq. 4.15, is used in the program to determine the Natural Frequency, or natural tempo, of the subject after the subject performs the initial assessment.

$$Natural\ Frequency\ \left(\frac{beats}{minute}\right) = \left(\frac{bubbles\ popped}{second}\right) \cdot \left(\frac{60\ seconds}{minute}\right) \cdot \left(\frac{1\ beat}{1\ bubble}\right) \qquad \textbf{4.15}$$

Using the game duration (length of time for a single game), the determined Natural Frequency, and the number of notes in the song we are able to construct the song file to be played for each individual subject. We determine the song length (SL) in Eq. 4.16 below. We multiply the Natural Frequency (i.e. tempo) which is defined in terms of beats per minute and the duration of the game converted to minutes. Now we must find notes from beats. For our assessments, we will restrict our songs to a 4/4 meter (known as common time), which is a time signature that means there will be 4 quarter notes per measure. A time signature specifies how many beats are in each measure and which note value constitutes one beat. So since tempo is defined as beats per minute, or rather in 4/4 meter it is the number of quarter note beats per minute. Thus, we define song length (SL) as follows:

$$SL\ (notes) = tempo\left(\frac{beats}{min}\right) \cdot duration(sec) \cdot \left(\frac{1\ min}{60\ sec}\right) \cdot \left(\frac{1\ note}{{}^{1}\!/_{4}\ beat}\right) \qquad \textbf{4.16}$$

Ex. Tempo = 60 bpm, 40 second game duration

- (60)(40)(1/60)(4) = 160 notes per game

Each song is comprised of the base notes of the song (the melody) and the rhythmic cue (a metronome-like beat played with the song).We scale the song tempo above the natural tempo if the natural falls below a threshold of 25 bpm since the song becomes difficult to listen to below this tempo. Other studies [9] have used 65bpm for the threshold, but considering the 4/4 meter of our songs we believe 25 bpm is acceptable.

The rhythmic cue is distinguished by an increased amplitude, or volume. Specifically, we use 120/127 for the amplitude of the rhythmic cue as compared to the song's 100/127.

Ex. Natural tempo = 20 bpm.

- Scale by multiple of 2.
- Song tempo = 2*(Natural) = 40 bpm.

Testing Protocols

Protocol 1 (P1) Definition

Our original design set out to answer both research questions defined in the Chapter, *APPROACH*. The first question results in our primary hypothesis that music, or in particular rhythmic cuing, can positively impact our defined metrics in *Assessment Metrics*. The second question comes from the need for engagement in therapy, especially for therapy involving children. The hypothesis that is defined is that a Repetitive condition is equivalent to a Random condition in terms of improvements in the metrics. We seek to test both hypotheses on a single participant group. We utilize the program defined in *Game Design and Operation* to test these hypotheses by allowing the subjects to play the Super Pop VR™ game altered to meet each testing condition. The test subjects are not given any information about the nature of the study except that it will be used in rehabilitation of children and that it involves music.

Typical Adults (P1)

Before we test our primary target group, we have determined that our efforts would best be suited to assessing the function and utility of our program and testing design on typical adults. We employ a crossover study for the testing of our hypotheses (defined in Sections *Research Question #1* and *Research Question #2*) on the typical adults. With 19 adults (13 male and 6 female) whose ages ranged from 18 to 32+ years were instructed to play the Super Pop VR^{TM} game [56] wherein virtual bubbles are projected onto a screen in randomly dispersed locations (See Figure 4.6). On the same screen, the participant sees a video stream of themselves in real time. The subjects are instructed to first pop the bubbles at a comfortable pace. Each subject was then asked to flip a coin twice. The first flip determined whether they would be in the rhythmic present group or the rhythmic absent group. The second flip determined whether they would be in the Repetitive first / Random last group or vice versa group. A single hand was used in the Repetitive condition, but both hands were allowed in the Random condition since presumably we could selectively assess only trajectories from a single arm. After 6 weeks a follow-up test was given and those who had the rhythm present condition were given the rhythm absent and those who had the rhythm absent condition were given the rhythm present. The 6 week interval was chosen to try and eliminate any learning effect. For these tests the rhythm was fixed at 22 beats per minute, which was slower than any participant tested.

Typical Children (P1)

Since testing time is extremely sparse amongst children with CP, we perform our next set of tests on 8 typical children (7 female and 1 male). The 8 children ranged between 5 years 6 months to 10 years 4 months. We employ a repeated measures design, as in [39], specifically, a crossover design since our sample group size is relatively small to test our hypotheses (defined in Sections *Research Question #1* and *Research Question #2*). After the adult test, it became apparent that several changes needed to be made for the children test. From the literature, it became clear that a tempo based on the natural frequency of motion was desired to achieve results typical in RAS studies. It also became clear that all conditions needed the requirement that the subjects use a single arm. It was also determined that a time-split follow-up would not be possible, thus we employ the repeated measures design wherein each child performs all four conditions: Random, Repetitive – each with Rhythm and No Rhythm. The children were given multiple attempts to learn how to play the game if needed before proceeding to the following condition.

Protocol 2 (P2) Definition

After our initial trials with typical adults and typical children, we determined that a revised protocol was needed to better represent the RAS theory. We also believe that the current presentation may lead to confusion due to a conflict in auditory and visual feedback. This is from what we observe as hesitation in both children and adults when they have popped the current bubble, but are waiting to pop the subsequent bubble after the next metronome tick. We devise the revised protocol by attempting to better represent how RAS had been presented in the past studies (See *Methodical*) and also to alleviate the issues observed in P1.

The conflict of feedback was the first amendment made on the protocol. This, we believed could be hedged by having bubbles only disappear at the instant of the metronome ticks and by showing no more than a single bubble at a time. We also needed to give feedback when a bubble was popped, so we also had the bubbles disappear when the hand came within an acceptable proximity to the bubble. Since the bubbles appeared at metronome ticks and disappeared on them as well, this effectively helped to emphasize the underlying desired rhythm. We also believe this would help reinforce the rhythm by accompanying it with visual feedback. Bubbles were not awarded as points if the subject did not reach the proximity to the bubble before it disappeared.

From the literature, we also noted that the best improvements were given from an increase in tempo from the natural frequency of motion. In particular, a 5% rhythm was used as this correlates to the Weber fraction for perceivable difference in audible tempo (See *RAS*). Thus, we decided to employ an increased tempo for subsequent tests after the natural tempo was determined.

Since we use a digital medium, we are not confined by the spatial boundaries found in a real-world setting. Typically in RAS tests the targets for reaching trajectories are in fixed locations. Clearly this would allow for easier path planning between each target since both are always observable. We make note of this in P1 through the Repetitive condition; however, this had the risk of becoming less engaging due to its tedium and consequently, we devised the Random condition. After noting the findings from the children's assessment, it has become clear that we may combine these conditions and also keep the advantages of both. We accomplish this by having a *current* bubble appear at the given time, but also be accompanied by a *subsequent* bubble. The current bubble appears in yellow and the subsequent in red. The test subjects are instructed that the yellow bubbles are worth 5 points on their score and the red are worth -5 points. When the current bubble is popped, the red bubble then becomes yellow and a new red subsequent bubble is created. This effectively coerces the subject to pop the bubbles in sequence.

These changes result in effectively eliminating our second hypothesis and allow for a simplified testing protocol. From feedback from our clinician, Dr. Yu-ping Chen, the simplified protocol would be better suited for implementing with children with cerebral palsy.

Typical Adults (P2)

On this test, we employ a crossover study for testing of our first hypothesis (defined in *Research Question #1*) with typical adults. The test was given to 7 typical adults (3 female and 4 male) whose ages ranged from 18 to 48 years with no known arm function impairments. Each adult was asked to choose a single arm to use to play the game and was instructed to use the same for each 40 second game. We first assess the natural frequency of motion during an initial assessment. Using this natural frequency or tempo we then utilize a pseudo-random number generator to determine whether the participant has the rhythm present or rhythm absent condition first (to account for learning effects). We hope to observe greater positive effects on the metrics during the rhythm present condition, regardless of whether it comes first or second, than the rhythm absent condition.

Typical Children (P2)

We employ a crossover design since our sample group size is relatively small to test our hypothesis (defined in *Research Question #1*). The test was given to 3 typical children (1 male and 2 female) whose ages were 8 years 2 months, 5 years 11 months, and 4 years 3 months. The children were first asked to choose which arm they would like to use to play the game and that arm was used throughout the entire protocol. We first assess the natural frequency of motion during an initial 40 second assessment. Using this natural frequency or tempo we then utilize a pseudo-random number generator to determine whether the participant has the rhythm present or rhythm absent condition first (to account for learning effects). Just as the typical adult assessment, we hope to observe greater positive effects on the metrics during the rhythm present condition, regardless of whether it comes first or second, than the rhythm absent condition.

Children with Cerebral Palsy (P2)

Again, a crossover study is used to assess our hypothesis (defined in *Research Question #1*) since we again have a very small sample size. In this study, there were two male children with spastic cerebral palsy. The first child tested was 8 years, 11 months. He has a mixed type of CP (Spastic Quadriplegia combined with Athetoid). The second was 10 years, 10 months. He has a mild form of spastic quadriplegia. It became clear that employing the single arm test would not be possible without additional support from the clinician or a parent which was not available at the time of testing so we elected to assess the metrics for both arms. The test was given the same as the typical children test wherein first a natural frequency is assessed in a 40 second game. A pseudo-random number generator determined whether the next game would be the rhythm present or rhythm absent condition. The second child then performed the opposite of the first.

CHAPTER 5

RESULTS

Quantitative

Protocol 1

As is typical in the behavioral sciences, we employ a repeated measures design, or in particular, a crossover dependent (within-group) design [76]. An in depth description of this protocol can be found in *Protocol 1 (P1) Definition*. We are testing both hypotheses described in Section CHAPTER 3. Subjects are chosen to serve in more than one condition and we attempt to compensate for order effects through randomized assignment of the order each condition is tested. We randomize order by having each subject flip a coin twice to determine which group they are in first. We also attempt to compensate for learning effects by alternating the Rhythm condition first or the No Rhythm condition first (also randomized via the second coin flip).

Statistical Approach

In a dependent protocol such as this, one statistical method for hypothesis testing is the t Test. We have two primary dueling treatments we are testing, specifically: Random Vs. Repetitive and Rhythm Vs. No Rhythm. For our analysis of this protocol, we employ the correlated groups t test since our control group is also our treatment group. Also we can consider each treatment independent of the other. For instance, we can test the Rhythm Vs. No Rhythm conditions for the Random condition and then do the same for the Repetitive condition separately. That is exactly how we proceed in our analysis.

To form our assessment of each protocol we enlist the metrics outlined in *Assessment Metrics*, or to reiterate: MT, PATH, MUs, STV, PAV, and ROM. Each subject performs from 5 to 35 reaching trajectories per trial. Since we amass so much data for each of the metrics we must consolidate by taking averages of MT, PATH, MUs, PAVs, and ROM. Since STV is a correlation derived from each trial it can reported and compared for each subject directly.

We work the analysis as described in Ha's 2011 *Integrative Statistics for the Social and Behavioral Sciences* [76]. We look at our consolidated metrics for each subject and for each metric we first find a difference. So for example, we begin by looking at the Repetitive condition and observe the differences between average movement times (MT) for the Rhythm condition versus the No Rhythm condition. These difference scores are averaged to find the mean difference score ($\overline{D}$) which will be compared to the mean difference score, μ_D, of the null hypothesis population. The mean difference score of the null hypothesis population assumes a null effect on the testing populace, i.e. $\mu_D=0$. We estimate the population difference scores based on our sample and assume that we know the populations mean. Thus we use the t distribution to evaluate our t obtained value [76]. The value for t Obtained is found using the following equation.

$$t_{obtained} = \frac{\overline{D} - \mu_D}{\sqrt{\frac{ss_D}{n(n-1)}}}, \qquad \textbf{5.1}$$

where n is the number of difference scores and ss_D is the sample standard deviation of the difference scores [76].

For each metric, the literature states that MT, PATH, and MUs ([4], [52], [53], [57]) will decrease while STV, PAV, and ROM will increase "with age and practice" [4], [8]. Since we hypothesized these one-directional changes in each of our metrics, we employ a one-tailed t Test. We use a critical level of α=0.05 and we know that the number of degrees of freedom is equal to n-1. If our obtained P-vale is $\leq \alpha$, then we say the difference in the samples is statistically significant, HOWEVER, we note that in our testing since we do not have greater than or equal to 30 participants, the t distribution is not typically considered to approximate a normal distribution. Thus, since our statistical power is diminished, the results should be interpreted keeping this fact in mind. From this information we can look up out t critical value from a table, such as the one found in [76]. We then reject the null hypothesis (i.e. that the treatment bares no effect or an opposite effect on the metrics) if the following condition is satisfied:

$$|t_{obtained}| \geq |t_{critical}|. \qquad \textbf{5.2}$$

And if this condition is not met, then we fail to reject the null hypothesis and a revision is necessary in our protocol.

Typical Adults P1

Our first assessment was performed on typical adults as described in *Typical Adults (P1)*. Of the 19 adults, we were able to compare data between all conditions for 14 since 5 did not complete the follow-up assessment. We present the summary of the findings here in the following table.

Table 5.1: Rhythm versus No Rhythm metrics comparison for the typical adults test using protocol 1. A green number in the P-value column indicates with the compliance of being less than our critical level of 0.05, while red means it does not comply. Green text in the Effect column indicates conformity with our hypothesized change.

Repetitive			Random		
Metric	P-value (< 0.05)	Effect	Metric	P-value	Effect
MT	0.009723522	Increasing	MT	0.008501355	Increasing
PATH	0.056008702	None	PATH	0.092798588	None
MU	0.001855987	Increasing	MU	0.041170596	Increasing
STV	0.007234091	Increasing	STV	0.18646215	None
ELBOW PAV	0.02238263	Increasing	ELBOW PAV	0.198408433	None
SA PAV	0.435321901	None	SA PAV	0.13567276	None
SF PAV	0.013870798	Increasing	SF PAV	0.2485983	None
S3D PAV	0.152758516	None	S3D PAV	0.376540235	None
ELBOW ROM	0.008920036	Increasing	ELBOW ROM	0.072197134	None
SA ROM	0.102583863	None	SA ROM	0.368060899	None
SF ROM	0.0059834	Increasing	SF ROM	0.416823389	None
S3D ROM	0.010442261	Increasing	S3D ROM	0.101435401	None

Table 5.1 is a summary of our findings related to the metrics in the typical adult test. The values in the P-value column were found using the TTEST() function in Microsoft Excel. We performed the t Test using a one-sided type 1 (paired) analysis. This function "determines whether two samples are likely to have come from the same two underlying populations that have the same mean," as stated in the Excel documentation. We then use the Data Analysis add-on function in Excel to determine the specifics of the assessment, such as the direction of the effect and also the t obtained and t critical levels for the one-tailed and two-tailed t tests. If the t obtained value is negative, then we report the effect as "Increasing" in the Effect column in Table 5.1.

From the table, we see that in both the Random and Repetitive conditions we have a statistically significant (i.e. the probability that it is due to chance is less than 5%)

increasing effect on movement time and movement units. That is, the reaching trajectories seem to take longer and are less smooth during the Rhythm condition than during the No Rhythm condition. We believe this is a direct result from our use of a tempo of 22 beats per minute (bpm) for the rhythmic cue. Of all of our 14 subjects, the lowest natural tempo was measured to be 33 bpm. Thus, we are requesting the subjects "move to the beat" which naturally would increase travel time (i.e. MT). The MUs increase also implies that this forced slowing of motion also induces a contradictory effect to smoothness.

Table 5.1 also shows a significant increasing effect in the Repetitive condition for STV, SF PAV, Elbow ROM, SF ROM, and the S3D ROM. The increasing effect of STV conveys that, in the presence of the rhythmic cue, we see a stronger mathematical correlation between temporal movement variability and spatial movement variability. This means the motion is more spatially correlated to the temporal domain which is just as we hypothesize. The PAV increases are indicative of an increase of force since PAV is considered an indirect measure of force in upper extremity rehabilitation. More forceful motion might imply a greater confidence in reach path planning – an effect we predict in our hypothesis. The increases in ROM were not expected for such a short duration of a test (as each trial was only around 40 seconds long, but this also matches our predictions prior to the assessments.

The contradictory effects found in MT and MUs leads us to the revision wherein we apply a matched tempo for the rhythmic cue as opposed to one less than the subject's natural rhythm. We also suspect that the Repetitive condition may be superior to the Random condition, but we will first test on children before making any changes.

Typical Children P1

Our second assessment was performed on typical children as described in *Typical Children (P1)*. Of the 8 children, we were able to compare data between all conditions for 6 since 2 had too few data points recorded. We were unable to acquire sufficient data on those 2 subjects due to difficulties arising from the following: the children were not sitting with their legs hanging down from the chair resulting in an inability to properly acquire their Kinect skeletons in the software, the odd shape of the chair resulting in false positives in Kinect skeleton acquisition, and possibly also due to inadequate lighting. We present the summary of the findings here in the following table.

Table 5.2: Rhythm versus No Rhythm metrics comparison for the typical children test using protocol 1. A green number in the P-value column indicates with the compliance of being less than our critical level of 0.05, while red means it does not comply. Green text in the Effect column indicates conformity with our hypothesized change.

Repetitive			Random		
Metric	P-value (< 0.05)	Effect	Metric	P-value	Effect
MT	0.476541554	None	MT	0.101873744	None
PATH	0.320761936	None	PATH	0.016126341	Decreasing
MU	0.421065889	None	MU	0.130150154	None
STV	0.071829882	None	STV	0.057773068	None
ELBOW PAV	0.35494028	None	ELBOW PAV	0.4325442	None
SA PAV	0.107021326	None	SA PAV	0.319871444	None
SF PAV	0.173465187	None	SF PAV	0.01402872	Decreasing
S3D PAV	0.009478482	Decreasing	S3D PAV	0.158590263	None
ELBOW ROM	0.487738685	None	ELBOW ROM	0.094779701	None
SA ROM	0.399834623	None	SA ROM	0.041515399	Decreasing
SF ROM	0.373601325	None	SF ROM	0.056477581	None
S3D ROM	0.288770945	None	S3D ROM	0.34892329	None

Table 5.2 is derived in the same way as described for Table 5.1. We see a significant decreasing effect for PATH in the Random condition. This implies the length

of the path from one bubble to the next was shortened through the use of the rhythm which is an effect we hypothesize prior to the experiment. However, the table also shows a significant decreasing effect for S3D PAV in the Repetitive condition and also for the SF PAV and SA ROM in the Random condition, which is counter to our hypothesis. Since PAV is an indirect measure of force, it would seem then that the S3D angular motions in Repetitive and the SF angular motions in the Random trials are less forcefully applied when rhythm is present. This may seem to counter our theory, but when coupled with a lack of effect in other angular changes, this may simply be an effect of fatigue. For instance, the child's shoulder has become fatigued through game play and then compensates through changes in elbow motion or possibly in the direction of shoulder motion. Lastly, we see a decreasing trend for SA ROM in the Random condition. We do not place as much significance on this result since when compared using a two-tailed t Test, this effect is no longer significant and thus could be a result of pure chance that our sample has trended as such.

From these results, we cannot clearly declare either the Random or Repetitive conditions superior, nor can we say anything about the rhythm present or rhythm absent conditions. We should also note that since our sample size is much smaller than in the adult trials, we could be seeing the effect of a less powerful experimental design. However, we cannot write off what our results seem to imply, which is that there is little to no effect of rhythm in our current design. In the interest of forming a more relevant assessment, we will attempt to redesign our test to better represent the RAS theory in the literature. Since many of the RAS tests we have cited use an increasing tempo for the rhythmic cue over the subject's natural rhythm, we will try the same. We also noted hesitation in the children during the rhythm-present trials. We believe these hesitations to be due to a lack of correlation between auditory and visual stimulus (i.e. the rhythmic cue occurs independent of the bubble appearances since the bubbles appear and disappear only when the subject pops them). We attempt to address these issues in our revised protocol.

Protocol 2

For our revised protocol we use a dependent (within-group) design [76]. An in depth description of this protocol can be found in *Protocol 2 (P2) Definition*. We are testing our first hypothesis defined in Research Question #1. Just as in P1, subjects are chosen to serve in more than one condition and we attempt to compensate for order effects through randomized assignment of the order each condition is tested. We randomize order by having each subject flip a coin to determine which group they are in first. We also attempt to compensate for learning effects by alternating the Rhythm condition first or the No Rhythm condition first.

Statistical Approach

For our second protocol, we use the same two-sample within-group t Test as in protocol one. Now we need only to compare between the Rhythm and No Rhythm conditions.

Typical Adults P2

Our first assessment for the second protocol was performed on typical adults as described in *Typical Adults (P2)*. In this assessment, we had 7 adults (3 male and 4 female) participate. Of the 7 adults, all 7 completed the full protocol. We present the summary of the findings here in the following table.

Table 5.3: Rhythm versus No Rhythm metrics comparison for the typical adults test using protocol 2. A green number in the P-value column indicates with the compliance of being less than our critical level of 0.05, while red means it does not comply. Green text in the Effect column indicates conformity with our hypothesized change.

Metric	P-value	Significant Effect
MT	0.267593729	None
PATH	0.203858138	None
MU	0.349347701	None
STV	0.057549227	None
ELBOW PAV	0.272533865	None
SA PAV	0.179116738	None
SF PAV	0.239250421	None
S3D PAV	0.422438864	None
ELBOW ROM	0.473636276	None
SA ROM	0.156227706	None
SF ROM	0.179418414	None
S3D ROM	0.246962075	None

From Table 5.3, we saw no significant difference in performance in comparing the Rhythm condition to the No Rhythm condition and for all metrics we fail to reject the null hypothesis. This result pushed us to make another modification to our assessments. We would now acquire data not just in the presence and absence of rhythm, but also before the test to perform our comparison.

Typical Children P2

Our second assessment for the second protocol was performed on typical children as described in *Typical Children (P2)*. In this assessment, we had 3 children (2 female and 1 male) participate. Of the 3 children, all 3 completed the full protocol. A distinction is made between this test and the adult testing for protocol two. In this test we have each subject perform three trials, one initially with no rhythmic cue or sound, and then two more with a randomly assigned Rhythm or No Rhythm condition. We present the summary of the findings here in the following table. We should note that since our testing sample size is so low, and thus our experimental power is very low, there is a chance that these findings would not translate to the general population being tested.

Table 5.4: Metrics comparison for the typical children test using protocol 2 comparing the first and last trials. A green number in the P-value column indicates with the compliance of being less than our critical level of 0.05, while red means it does not comply. Green text in the Effect column indicates conformity with our hypothesized change.

Metrics	P-value	Significant Effect
MT	0.029556702	Decreasing Effect
PATH	0.023889091	Increasing Effect
MU	0.211736499	None
STV	0.483339959	None
ELBOW PAV	0.337905551	None
SA PAV	0.15158568	None
SF PAV	0.31501314	None
S3D PAV	0.477062392	None
ELBOW ROM	0.090425852	None
SA ROM	0.025551541	Decreasing Effect
SF ROM	0.029839694	Decreasing Effect
S3D ROM	0.110226646	None

When assessing the typical children test, as summarized in Table 5.4, we see that there is a significant decreasing effect in movement time average from the first game trial to the last game trial. This would imply the children are able to acquire bubbles quicker over time. There also seems to be an increasing effect in PATH which means the distance the hand travels becomes longer from the first to last conditions. This effect is significant even when considering the two-tailed t Test, but by a very close margin. Nonetheless, we believe that this effect, since only present in a 3-child assessment and the margin is about 0.1% from not being significant for a two-tailed hypothesis test, is not indicative of a real effect. There is also a decreasing effect present in the SA ROM and SF ROM, however, when assessed as a two-tailed hypothesis, neither of these effects are significant (i.e. $|t_{obtained}| < |t_{critical}|$).

Table 5.5: Metrics comparison for the typical children test using protocol 2 comparing the first trial and the No Rhythm trial. A green number in the P-value column indicates with the compliance of being less than our critical level of 0.05, while red means it does not comply. Green text in the Effect column indicates conformity with our hypothesized change.

Metrics	P-value	Significant Effect
MT	0.092220441	None
PATH	0.106279505	None
MU	0.199281952	None
STV	0.408351926	None
ELBOW PAV	0.472639067	None
SA PAV	0.156884699	None
SF PAV	0.373007443	None
S3D PAV	0.121439719	None
ELBOW ROM	0.084578612	None
SA ROM	0.014712925	Decreasing Effect
SF ROM	0.060390199	None
S3D ROM	0.091681657	None

Table 5.5 shows the comparison between the first game trial and the rhythm absent condition. We see a decreasing effect in SA ROM. Since this effect only occurs in one angular dimension, we believe this may a small effect of fatigue, wherein the subject compensates for shoulder fatigue by displacing motion in other shoulder dimensions or perhaps in the elbow dimension.

Table 5.6: Metrics comparison for the typical children test using protocol 2 comparing the first trial and the Rhythm trial. A green number in the P-value column indicates with the compliance of being less than our critical level of 0.05, while red means it does not comply. Green text in the Effect column indicates conformity with our hypothesized change.

Metrics	P-value	Significant Effect
MT	0.438375142	None
PATH	0.093040974	None
MU	0.170620315	None
STV	0.366640337	None
ELBOW PAV	0.497587882	None
SA PAV	0.489456105	None
SF PAV	0.421607225	None
S3D PAV	0.23144078	None
ELBOW ROM	0.261971293	None
SA ROM	0.462140448	None
SF ROM	0.279430328	None
S3D ROM	0.443762477	None

Table 5.6 shows the difference between the initial game trial and the music condition. We see there is no significant effect on any of the assessment metrics and thus we fail to reject the null hypothesis. This result seems to imply that the positive results shown in Table 5.4, comparing the first and last game trials, are indicative of the learning effect. We believe that this result could be due to one of several factors including, but not limited to the limited number of participants in the assessment or the perhaps the short duration of the treatment.

Children with CP

Our second assessment for the second protocol was performed on typical children as described in *Children with Cerebral Palsy (P2)*. In this assessment, we had 2 children (2 male) participate. Of the 2 children, both completed the full protocol. We present the summary of the findings here in the following table. We should note that since our testing sample size is so low, and thus our experimental power is very low, there is a chance that these findings would not translate to the general population being tested.

Table 5.7: Metrics comparison for the children with CP test using protocol 2. A green number in the P-value column indicates with the compliance of being less than our critical level of 0.05, while red means it does not comply. Green text in the Effect column indicates conformity with our hypothesized change.

Metrics	P-value	Significant Effect	α =0.10
MT	0.095370651	None	Decreasing Effect
PATH	0.159738424	None	
MU	0.01039171	Decreasing Effect	Decreasing Effect
STV	0.154472382	None	
ELBOW PAV	0.003126801	Decreasing Effect	Decreasing Effect
SA PAV	0.126833852	None	
SF PAV	0.177395708	None	
S3D PAV	0.154611518	None	
ELBOW ROM	0.415946704	None	
SA ROM	0.194809999	None	
SF ROM	0.050656255	None	Decreasing Effect
S3D ROM	0.409764158	None	

In Table 5.7 we see a comparison of the first and last trials for the children with CP. Here we note a significant decreasing effect of MUs which implies a smoother trajectory between the first and last trials. We also see a decreasing effect in Elbow PAV which is counter to our hypothesis. This may be a result due to fatigue since the child may be compensating for elbow fatigue by distributing motion to the shoulder. We extend our critical value to α=0.10 in the fourth column to look at the trends of the other metrics. It would seem that movement time decreases, i.e. movements become quicker. Also, SF ROM decreases, which may be the same sort of fatigue effect seen in Elbow PAV.

Table 5.8: Metrics comparison for the children with CP test using protocol 2 comparing the first trial and the No Rhythm trial. A green number in the P-value column indicates with the compliance of being less than our critical level of 0.05, while red means it does not comply. Green text in the Effect column indicates conformity with our hypothesized change.

Metrics	P-value	Significant Effect	α =0.10
MT	0.093768422	None	Decreasing Effect
PATH	0.280943106	None	
MU	0.056735701	None	Decreasing Effect
STV	0.294412906	None	
ELBOW PAV	0.289716389	None	
SA PAV	0.290275585	None	
SF PAV	0.26398298	None	
S3D PAV	0.201984144	None	
ELBOW ROM	0.001192547	Increasing Effect	Increasing Effect
SA ROM	0.278337489	None	
SF ROM	0.475388228	None	
S3D ROM	0.101592028	None	

Table 5.8 shows the comparison made between the first game trial and the No Rhythm condition trial. We see an increasing effect for average Elbow ROM. Since this effect is only present in a single angular dimension, we believe that this may be a result of a compensation made to cope with shoulder fatigue. When extended to α =0.10, the trend seems to be decreasing MT and MUs as well which would imply quicker and more smooth motion between the first trial and the rhythm present trial.

Table 5.9: Metrics comparison for the children with CP test using protocol 2 comparing the first trial and the Rhythm trial. A green number in the P-value column indicates with the compliance of being less than our critical level of 0.05, while red means it does not comply. Green text in the Effect column indicates conformity with our hypothesized change.

Metrics	P-value	Significant Effect	α =0.10
MT	0.175109425	None	
PATH	0.183796971	None	
MU	0.18630521	None	
STV	0.225143769	None	
ELBOW PAV	0.12153191	None	
SA PAV	0.162354065	None	
SF PAV	0.16123295	None	
S3D PAV	0.176187484	None	
ELBOW ROM	0.185648458	None	
SA ROM	0.036413875	Decreasing Effect	Decreasing Effect
SF ROM	0.122269871	None	
S3D ROM	0.078521826	None	Decreasing Effect

Table 5.9 shows a decreasing trend for SA ROM, however, when applying a two-tailed t Test, the effect is not significant. We also see for α =0.10 S3D ROM decreases as well, but it is not significant.

Overall Metrics Assessment

Here we look at the differences between the tested groups to assess our metrics measurements. We describe the method of hypothesis testing and then apply the method to a comparison between typical children and typical adults then between children with CP and typical children.

Statistical Approach

For this comparison, since we are comparing completely different groups, we have an independent (between-groups) design. Since we are testing for a potential statistical significance of a true difference between sample means, we again use a sampling distribution of the difference between our sample means. However, we now have the situation wherein we do not know the null hypothesis population mean as before. Thus, we must employ a different hypothesis testing tool: the independent t test.

Just as done previously in *Protocol 1* & *Protocol 2*, to form our assessment of each protocol we enlist the metrics outlined in *Assessment Metrics*, or to reiterate: MT, PATH, MUs, STV, PAV, and ROM. Each subject performs from 5 to 35 reaching trajectories per trial. Since we amass so much data for each of the metrics we must consolidate by taking averages of MT, PATH, MUs, PAVs, and ROM. Since STV is a correlation derived from each trial it can reported and compared for each subject directly.

We again work the analysis as described in Ha's 2011 *Integrative Statistics for the Social and Behavioral Sciences* [76]. In this assessment we must make the assumption that the sample variances are estimating the underlying population's variance, i.e. the null hypothesis population variance. In Eq. 5.3 we find this variance, s_w^2 by using a weighted function depending on each group's number of degrees of freedom.

$$s_w^2 = \frac{df_1 s_1^2 + df_2 s_2^2}{df_1 + df_2}, \tag{5.3}$$

where df is the number of degrees of freedom and s^2 is the variance for groups 1 or 2.

Using the equation for variance, we are able to derive an expression for the independent t test (Shown in Eq. 5.4).

$$t_{obtained} = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{s_w^2(1/n_1 + 1/n_2)}}, \tag{5.4}$$

where $\bar{X}$ is the mean for the sample group and n is the number of difference scores in both groups 1 and 2, respectively [76].

For each metric, the literature states that MT, PATH, and MUs ([4], [52], [53], [57]) will decrease while STV, PAV, and ROM will increase "with age and practice" [4], [8]. We then hypothesize that the difference in effect from child assessment to adult assessment will be in those respective directions. We anticipate the same in the comparison between typical children and children with CP. Since we hypothesize these one-directional changes in each of our metrics, we employ a one-tailed t Test. We use a critical level of α=0.05 and we know that the number of degrees of freedom for each group is equal to n-1. We again note that in our testing since we do not have greater than or equal to 30 participants, the t distribution is not typically considered to approximate a normal distribution. Thus, since our statistical power is diminished, the results should be interpreted keeping this fact in mind. From this information we can look up out t critical value from a table, such as the one found in [76]. We then reject the null hypothesis (i.e. that the treatment bares no effect or an opposite effect on the metrics) if the following condition is satisfied.

$$|t_{obtained}| \geq |t_{critical}| \qquad \textbf{5.5}$$

And if this condition is not met, then we fail to reject the null hypothesis and a revision is necessary in our protocol.

Typical Children Vs. Typical Adults

In this assessment, we compare the typical children metrics to the typical adult metrics obtained in the rhythm absent conditions for both.

Table 5.10: A comparison between the typical children and the adults. The data was taken from trials wherein no rhythm was played and the adult data was taken from the Random condition test. A green number in the P-value column indicates with the compliance of being less than our critical level of 0.05, while red means it does not comply. Green text in the Effect column indicates conformity with our hypothesized change.

Metrics	P-value	Effect
MT	0.042785753	Decreasing Effect
PATH	7.26142E-05	Decreasing Effect
MU	0.023696255	Decreasing Effect
STV	0.00259841	Decreasing Effect
ELBOW PAV	0.009643947	Decreasing Effect
SA PAV	0.006327673	Decreasing Effect
SF PAV	0.016449673	Decreasing Effect
S3D PAV	0.000987202	Decreasing Effect
ELBOW ROM	0.007052415	Decreasing Effect
SA ROM	0.000690199	Increasing Effect
SF ROM	0.004518936	Increasing Effect
S3D ROM	0.000147672	Increasing Effect

Table 5.10 is a summary of our findings related to the metrics in the typical adult test. The values in the P-value column were found using the TTEST() function in Microsoft Excel. We performed the t Test using a one-sided type 2 (two-sample assuming unequal variances also referred to as heteroscedastic) analysis. This function result "corresponds to the probability of a higher absolute value of the [t obtained value] under the 'same population means' assumption," as stated in the Excel documentation. We then use the Data Analysis add-on function in Excel to determine the specifics of the assessment, such as the direction of the effect and also the t obtained and t critical levels for the one-tailed and two-tailed t tests. If the t obtained value is negative, then we report the effect as "Increasing" in the Effect column in Table 5.10.

We see from the table that there is a significant effect on all of our metrics. Average MT, PATH, MU, SA ROM, SF ROM, and S3D ROM all conform to our expected trends that we anticipate from the literature. However, we also see a decreasing effect for STV, all PAVs, and the Elbow ROM. The decrease in STV means that when comparing the typical children to adults, we see a drop in temporal correlation with spatial movement. We believe that this is a result spawning from the fact that the adults were allowed to use both hands and thus, some trajectories use either hand which skews this metric. PAVs are used in the literature as an indirect measure of force. We propose that, in these circumstances, the children have higher PAVs because they are much more engaged by the activity and thus, move more forcefully. This, accompanied with longer movement times also could explain the more jagged motion represented by a greater number of MUs. Since ROM is a measure of average ROM for a joint, a decrease in the adults arises perhaps because the adults are using a greater variety of joints in reach. This theory is supported in that for SA, SF, and S3D, the average ROM increases between kids and adults.

Children with CP Vs. Typical Children

In this assessment, we compare the children with CP to the typical children metrics obtained in the rhythm absent conditions.

Table 5.11: A comparison between the children with CP and typical children. The data was taken from trials wherein no rhythm was played. A green number in the P-value column indicates with the compliance of being less than our critical level of 0.05, while red means it does not comply. Green text in the Effect column indicates conformity with our hypothesized change.

Metrics	P-value	Effect
MT	0.42910173	None
PATH	0.047801153	Increasing Effect
MU	0.43797597	None
STV	0.300320001	None
ELBOW PAV	0.097339695	None
SA PAV	0.015253825	Increasing Effect
SF PAV	0.209087848	None
S3D PAV	0.35071442	None
ELBOW ROM	0.152044424	None
SA ROM	0.000402923	Increasing Effect
SF ROM	0.010179683	Increasing Effect
S3D ROM	0.051830411	None

Table 5.11 is created in the same way as Table 5.10. First we observe an effect counter to our predictions in PATH. We believe this is a direct result from the use of shorter between bubble spacing in the children with CP's assessment. To be specific, the spacing for typical children was around 200 to 225 pixels depending on the child's arm length while the children with CP this was approximately 75 to 100 pixels. These distances were dependent upon the bubble appearance region determined at the beginning of each child's assessment. The maximum bubble spacing was determined by the smallest dimension of the rectangular region of bubble appearance. Therefore, it is not surprising that we see the PATHs of the children with CP are on average shorter than that of the typical children.

We also observe an increasing effect for the SA PAV, which as stated previously indicates a higher force applied in the typical children group. This effect is one which we hypothesize. We also note an increasing effect in SA ROM and SF ROM. This coupled with the low P-value of S3D ROM leads us to believe that this may be the result of a real effect. In fact, when we look at the trend of the data for S3D we see that it also is increasing. This result seems indicative that our metrics show an appropriate relation between children and children with CP. We are confident that such an effect would continue with an increase in sample size.

Qualitative

Typical Adults P1

Here in Figure 5.1 we see the summary of the results from the survey given to each of the 19 adult participants in the P1 assessment. The survey presented a broad range of questions inquiring about the Super Pop VR^{TM} game and the user's experience. Each of the 36 questions was asked where the subject could choose between: Strongly Agree, Agree, Neutral, Disagree, and Strongly Disagree (or N/A). We quantize the data into a 5-point Likert scale where "Strongly Agree" corresponds to a 5 and "Strongly Disagree" corresponds to 1. The questions were sectioned into 5 primary sections: User Background and Game Presentation, Motivation, Difficulty, Playing with Music, and Physical Effort.

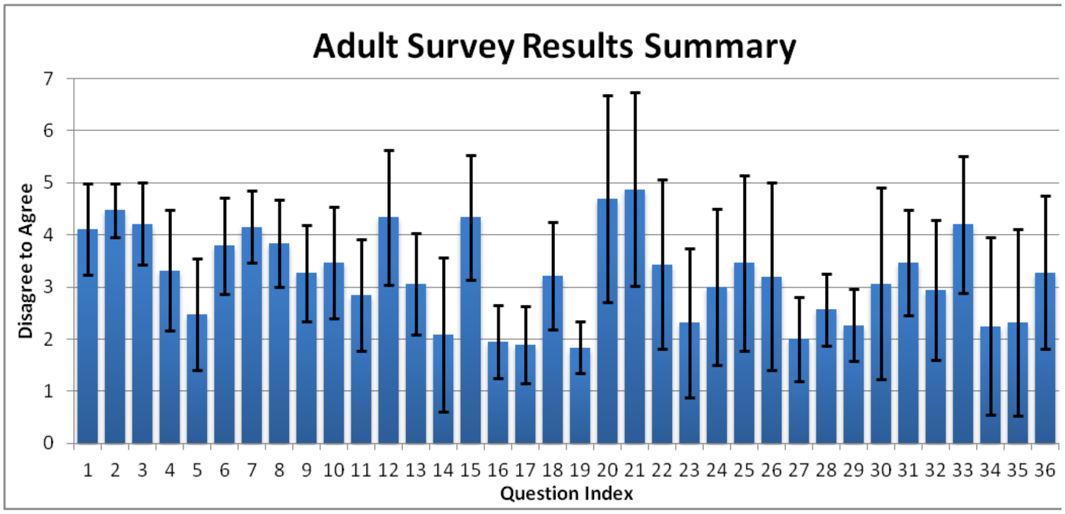

Figure 5.1: Results of the survey given for the adult test of P1. The blue bars are the average answer which range from "Strongly Agree" (5) to "Strongly Disagree" (1) – a typical 5-pt. Likert scale. The black lines represent the +/- standard deviation over the mean.

User Background and Game Presentation

In Table 5.12 we see the questions related to the user's gaming experience and the Super Pop VR™ game's presentation. We show the averages and the standard deviations (STD) for the responses for each question. We will refer to each question as Q# to indicate question number #. In Q1, we see with small (<1 Likert point) deviation, most users are familiar with video games or computer games. With high consistency, most participants considered the game easy to understand and its rules were apparent without any further instruction (Q2, Q3). Most users were just told they would use their arms to pop bubbles on a screen and this was adequate. Q4 shows that most participants were neutral on whether the game objects were interesting with high deviation. Q5 shows that most users thought there was a delay in the game's responses to their actions with a high deviation from the average. Q6 yields the result that most people found their own appearance on the screen to be nice.

Table 5.12: A table conveying the averages and standard deviations of the responses in the surveys for each question in the section on game presentation and user background.

Question	Average	STD
1 I have a lot of experience playing video or computer games.	4.10526316	0.87526103
2 The game interface is easy to understand.	4.47368421	0.51298918
3 The rules of the game are clear from the current presentation.	4.21052632	0.78732651
4 I found the moving things / objects in the game very interesting.	3.31578947	1.15723001
5 There was no delay in what I did and what I saw in the game.	2.47368421	1.07333442
6 I found it nice to see myself in the game.	3.78947368	0.91766294

Based on the data with least variation, we can glean from this information that the participants, on average, were experienced in game play. They also thought the game to be intuitive and lacking in ambiguity. They seemed to believe there were delays in the game's response times. Most people also were pleased to have themselves appear in the game.

Motivation

In Table 5.12 we see the summary of the data acquired on questions related to the user's motivation. Q7 shows that with very little deviation most users agreed that the game was enjoyable. In Q8 they for the most part believed that they did well on the game, but lean a little toward neutral. The majority look as though they are neutral on the prospect of playing the game very often or every day (Q9, Q10). Q11 most users are neutral, leaning toward disagreeing with the prospect of playing the game twice a week for at least 30 minutes each time. With a high deviation, in Q12 most participants considered the idea of playing the game with others to be nice. In Q13, most were neutral when asked about the extent of engagement of the game. Q14 reveals that with a high deviation, the majority disagreed that the game was less fun than typical physiotherapy. On average, but with a high deviation, most believed their speed and accuracy would improve if they played the game repeatedly (Q15).

Table 5.13: A table conveying the averages and standard deviations of the responses in the surveys for each question in the section on motivation.

Question	Average	STD
7 I enjoyed playing the game overall.	4.15789474	0.6882472
8 I think I performed well in the game.	3.84210526	0.83421007
9 I would like to play this game more often.	3.26315789	0.93345864
10 I would be willing to play the game every day for a few minutes.	3.47368421	1.07333442
11 I would be willing to play the game twice a week for at least 30 minutes.	2.84210526	1.06787213
12 It would be nice if I could play the game with other children at the same time.	4.33333333	1.28645667
13 The game was so engaging that I lost track of the time.	3.05263158	0.97031978
14 Training with the 'Super Pop' game is less fun than with regular physiotherapy.	2.09090909	1.47493681
15 If repeatedly played, I believe the speed and accuracy of my movements when playing the game would improve.	4.33333333	1.19697474

Based on the data with least variation, we can glean from this information that the participants, on average, enjoyed playing the game and thought they did well. They were neutral in whether they would like to play the game more often and in that the game was so engaging that they lost track of time.

Difficulty

In Table 5.14, the data for the survey questions relating to the game's difficulty are summarized. With low deviation, most users thought the game was not too fast, nor did they want a slower version of the game (Q16). Also with very low deviation, in Q17 most disagreed the game was too difficult and did not wish to play an easier version of the game. In Q18 on average most were roughly neutral when asked if they could predict what would happen in the game after they made an action. Q19, all subjects overwhelmingly disagreed with very low deviation that the game was hard to play through the use of their arms.

Table 5.14: A table conveying the averages and standard deviations of the responses in the surveys for each question in the section on difficulty.

Question	Average	STD
16 The game was too fast. I would have liked to play a slower version of the game.	1.94736842	0.70503619
17 The game was too difficult. I would have liked to play an easier version of the game.	1.89473684	0.73746841
18 I could predict what was going to happen after I had made a movement.	3.21052632	1.03166249
19 I found it hard to play the game by moving my arms.	1.84210526	0.50145986

Based on the data with least variation, we can glean from this information that the participants, on average, that the user's mostly disagree that the game was too fast or too difficult and also that it was difficult to play by moving their arms around.

Playing with Music

In Table 5.15 we show the summary of the responses to questions regarding the sound in the game. Note: Q25, 27-29 were omitted since during P1 these questions were irrelevant and the only appropriate response would have been "N/A". With very high deviation, the users mostly strongly agreed that they were familiar with the song played during the game and could hear it very well (Q20, Q21). Q22 with high deviation most users were neutral when asked if they believed the song sounds to be attractive. Most disagreed when asked if they believed the music to be distracting (Q23). On average, with high deviation, most were neutral when asked if they were more focused with no sound (Q24). Q26 shows that most agreed with high deviation that they were more focused when playing the game with the song "Twinkle Twinkle Little Star" playing. Q30 shows that most were neutral with high deviation when asked if they were more focused when playing with music than without music. Most overwhelmingly disagreed that the songs were too fast for them to keep up (Q31) and were neutral when asked if the songs played were too slow (Q32). Most disagreed that they popped the bubbles faster when the music was playing (Q33) and were neutral with high deviation when asked if they popped the bubbles slower when the music was playing (Q34). Most agreed the metronome tone helped them to keep focus (Q35). Q36 shows that most were neutral with high deviation when asked if they thought their accuracy increased in the presence of the music. Q37 shows that most agreed with high deviation that having more songs to choose from would make the game more interesting.

Table 5.15: A table conveying the averages and standard deviations of the responses in the surveys for each question in the section on the game music.

Question	Average	STD
20 I have heard the songs before and I am very familiar with them.	4.6875	1.98532629
21 I could hear all the songs very well.	4.875	1.8527678
22 The sounds I heard out of the game were very attractive.	3.4375	1.6294081
23 The music was distracting.	2.3125	1.4327008
24 I was more focused when playing with no sound.	3	1.50437957
26 I was more focused when playing with the “Twinkle Twinkle Little Star” song.	3.46153846	1.67890245
30 I was more focused when playing with music overall than I was without music.	3.2	1.80155878
31 The songs played were too fast for me to keep up.	2	0.80568158
32 The songs played were too slow.	2.5625	0.6882472
33 I popped the bubbles faster when the music was playing.	2.26666667	0.6882472
34 I popped the bubbles slower when the music was playing.	3.06666667	1.83691834
35 The metronome tone allowed me to keep my focus.	3.46666667	1.00291971
36 I think that my accuracy was better when the music was playing during the game.	2.9375	1.34425353
37 Having more songs to choose from would have made the game more interesting.	4.2	1.31567251

Based on the data with least variation, we can glean from this information that the participants, on average, most disagreed the songs were too fast, were neutral on whether the songs were too slow. Most also disagreed that they could pop bubbles faster with the music playing.

Physical Effort

Table 5.16 shows the summary of responses for questions on physical effort. Q38 shows that most disagreed with a deviation that they became more tired from the game over regular physiotherapy and that they had learned new movements with this game. Most were neutral with high deviation that they could learn new movements from the game.

Table 5.16: A table conveying the averages and standard deviations of the responses in the surveys for each question in the section on physical effort.

Question	Average	STD
38 I become more tired from playing this game than from regular physiotherapy.	2.25	1.70996392
39 I have learned new movements by playing this game.	2.3125	1.79016155
40 I think I could learn new movements by playing the game more often.	3.27777778	1.46698561

Typical Children P1

In Figure 5.2 we present the summary of the data taken from the surveys presented to the typical children in the P1 test assessment. Each question was asked on a 5-point Likert scale where 1 corresponds to “Completely Disagree,” 2 “Slightly Disagree,” 3 to “Neutral,” 4 to “Slightly Agree,” and 5 to “Completely Agree.” These surveys were given orally by the clinician wherein the clinician deemed the most appropriate selection for the child’s response to each question.

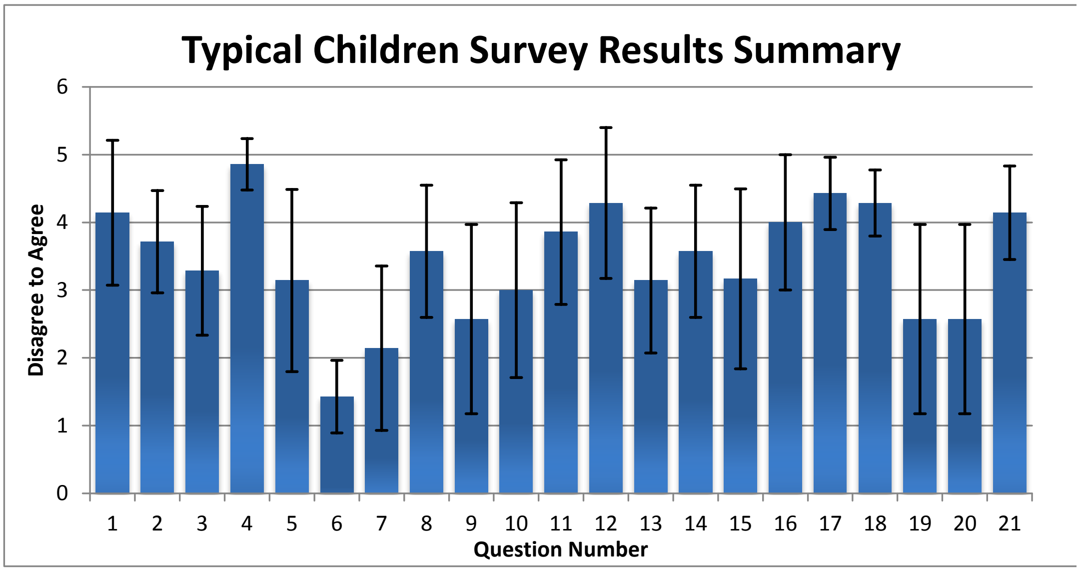

Figure 5.2: Typical children test of P1 survey data summary. . The blue bars are the average answer which range from 5 (Agree) to 1 (disagree) – a typical 5-pt. Likert scale. The black lines represent the +/- standard deviation over the mean.

Table 5.17 shows the full list of questions from the survey presented to the children during the P1 assessment. We also include the average response and standard deviation (STD).

Table 5.17: A table conveying the averages and standard deviations of the responses in the surveys for each question.

#	Questions	Average	STD
1	I could see all my movements from the screen very well	4.142857	1.069045
2	I found the objects in the game very interesting	3.714286	0.755929
3	The objects I saw in the game were very attractive	3.285714	0.95119
4	I could hear all music in the game very well	4.857143	0.377964
5	The music I heard out of the game was very attractive	3.142857	1.345185
6	I could not hear where all of the sounds out of the game came from	1.428571	0.534522
7	The movements to play the game were too hard	2.142857	1.214986
8	The movements used to touch objects in the game were so fast, they were not too easy; but also were not too hard	3.571429	0.9759
9	I must still learn a lot before I can play the game well	2.571429	1.397276
10	I could predict what was going to happen after I had made a movement	3	1.290994
11	I had the feeling I could accomplish the game	3.857143	1.069045
12	I would find it nice if I could play the game together with more friends at the same time	4.285714	1.112697
13	The game was so attractive that I lost all count of time	3.142857	1.069045
14	I would like to play the game more often	3.571429	0.9759
15	The game training is less fun than regular computer/video games	3.166667	1.32916
16	The request from the game was easy to understand	4	1
17	The request from the game was easy to follow	4.428571	0.534522
18	It was very logical playing the game by popping the objects	4.285714	0.48795
19	I found it hard to follow the game by moving my hands	2.571429	1.397276
20	I become more tired from playing with the game than from the regular computer/video games	2.571429	1.397276
21	I like playing the game	4.142857	0.690066

Here we present the data from the questionnaire with the most significance (deviations less than or equal to 1). In Q2, most children found the objects in the game to be interesting. They also found the objects in the game to be attractive (Q3). In Q4, the children mostly agree that they could hear all of the sound from the game very well. Most disagreed that they could not hear where the game sound was coming from (Q6). Most agreed the movements used in the game were not too fast or slow (Q8). Most also agreed that they liked playing the game.

CHAPTER 6

DISCUSSION

Quantitative Evaluation of Error

The results from our study in *Results* indicate that an acceptable margin of error exists for angle determinations from the Kinect for use in a rehabilitative context. This result then allows for the use of the Kinect in a virtual rehabilitation system. As a direct result, home-based therapy can then be used to provide quantitative feedback to patients and therapists in an inexpensive way. By using such systems, therapists could treat many more patients and increase their overall efficiency. Through more meaningful feedback patients can not only gain functional recovery much more expeditiously, but also increase their aptitude for motor learning and perhaps an increase in engagement. All this ultimately leads to a better patient quality of life.

From our assessment, we have formed a quantitative measure of the accuracy of the MS Kinect for the elbow flexion angle, shoulder flexion angle, shoulder abduction/adduction angle, and the 3-dimensional shoulder and elbow angles observed in random reaching activities. We have also created a method for translating reach into measurable clinically-based shoulder angles.

Defined Angles

We have termed and validated clinical angle measurements that can be used to classify motion of the arm. Specifically, we term them: Shoulder Flexion, Shoulder Abduction, and Elbow Flexion (See *Angle Calculation*). Using these angle definitions, everyday arm motion may more easily be quantitatively defined and assessed for therapeutic or other purposes especially in a virtual context.

Defined Metrics

We have confirmed the utility of our metrics in *Overall Metrics Assessment* through a comparison between our subject groups. Specifically, we have confirmed there is a significant difference in MT, PATH, MUs, and ROM between children and adults. PAV between these groups may warrant a revision in the thinking that it will definitely increase from children to adults. And although we only specifically see evidence for significant differences in shoulder ROM and shoulder abduction PAV between typical children and children with CP, and we believe that more testing is necessary to definitively prove its difference, we anticipate that the differences in a larger sample of children with CP would show significance in the other metrics as well based on the differences observed between the children and adults.

We also see a trend toward improvement of MT and MUs in children with CP in *Children with CP*. This result holds promise in that we are able to induce progress in clinically defined metrics using the program. If we assess the RAS literature, then the next logical step would be to attempt a long-term intervention using RAS in order to determine if there is a statistically relevant real effect.

Defined Protocol

Although our protocol to test the differences between a rhythm present condition and a rhythm absent condition has yet to be definitively proven effective, we believe what we have defined is the next logical step based on the results of all of our testing. We believe this protocol can provide an adequate foundation for any future testing in this domain. And based on the literature in the RAS field, we believe this experimentation holds much promise and could hold dramatic effects for children with CP as it has with patients with PD, post-CVA, and other motor-deficiencies.

Survey Responses

Adult P1

Using our results from the adult surveys from Protocol 1 and considering the data only with the least deviation (≤1 STD), we take the following main points from the data. Our participants were, on average, experienced with some type of game play, whether that be on a computer or otherwise. Most found the game to be intuitive and lacking in ambiguity and stated that they enjoyed playing the game. The group was also pleased to have themselves appear in the game. The participants for the most part believed they did well. They also believed the game was not too fast and were neutral about it being too slow. Most of the adults also disagreed that they could pop bubbles faster with the music playing. They were neutral in whether they would like to play the game more often and in that the game was so engaging that they lost track of time. They seemed to believe there were delays in the game's response times.

We believe that overall these results are positive. We have attempted to address the issue of game response time and are hopeful that this shows in our children testing. The belief that game was slow makes sense when we relate this to the fixed tempo we use, which was slower than all of the participants' natural tempos. Even though this is not from our primary demographic (children or children with CP), they still promising results as we move forward in our study.

Children P1

Using our results from the child surveys from Protocol 1 and considering the data only with the least deviation (≤1 STD), we can glean the following main points from the data. Of the children tested, most agreed that they liked the game. Most children found the objects in the game to be interesting and attractive. They, on average, agreed that they could hear the sound from the game very well and knew where the sound was coming from. Most agreed the movements used in the game were not too fast or slow.

We see a direct change in the perception of the game speed here and we expected this since we made the tempo exactly equal to the child's natural tempo. The children found the objects in the game to be interesting and attractive which might indirectly allude to engagement. These results coupled with the findings in the comparison in *Typical Children Vs. Typical Adults* regarding the significant higher PAV in the child group leads us to believe that children were very engaged in the game play. This is crucial for an effective therapeutic treatment as we have found from our survey of the literature on therapy in *Virtual Systems for Therapy*.

Overall from our defined angular measurements, the quantified amount of error in our sensor, the validation of the metrics used, and the results of our surveys we believe that we have developed an effective system for use as a foundation for a long-term RAS therapeutic regime. Clearly further testing is needed to prove the system's effectiveness in improving motor function, but this testing is also warranted based on our and other's findings. We also believe the system could provide an excellent foundation for other upper-extremity therapies. We illustrate several potential uses of the findings in this study in the following section on Future Work.

CHAPTER 7

FUTURE WORK

Kinect Skeleton Joint Angles

From our quantification of the error in the Kinect data, we believe that with an appropriate filter method (such as the one we prescribe) the Kinect provides an accurate enough measurement of joint angles. This opens the doors for use of the Kinect in all types of rehabilitative contexts including, but most definitely not limited to: virtual rehabilitation, home-based assessments, home-based therapies, and home-based monitoring. Having a remote assessment method could potentially allow for therapists to be much more productive and to cater to many more patients than they would have been able to otherwise. Using our defined angles of Shoulder Flexion, Shoulder Abduction, and Elbow Flexion one could also better quantify the progress of the patient in therapy. Furthermore, the metrics we enlist could possibly provide for a great technique for determination of the effectiveness of different therapies. We believe the findings of this study warrant the use of these tools which we prescribe and provide a foundation for further studies in the area of upper extremity therapy with a particular emphasis on children with CP.

Greater Number of Subjects

Future studies on the effect of Rhythm versus No Rhythm can use our work as a foundation. The next step in this assessment would be to confirm the system and the metrics with a population already shown to be positively affected by Rhythmic Auditory Stimulation (such as PD or post-CVA). Thereafter, we believe that studies involving many more subjects (both typical children and children with CP) should be performed to provide more conclusive evidence to an effect of rhythm using the metrics we have defined. From our findings and based on the broad array of literature in the space of Rhythmic Auditory Stimulation, there is promise in its utility as a therapeutic augmentation that has yet to be realized in the research communities. These types of studies should also explore long-term interventions as prescribed in the RAS literature. Studies should also explore the use of home-based assessments in these demographics as well since studies as such are limited.

APPENDIX

Metrics Tests

Adults P1

			Subject1	Subject2	Subject3	Subject4	Subject5	Subject6	Subject7	Subject8	Subject11	Subject12	Subject14	Subject16	Subject17	Subject18
		Tempo	57	52	55	44	35	34	51	71	47	48	33	47	33	54
REPETITIVE		AVG MT	1.576846	1.373285	1.572492	0.796592	2.089155	1.794226	1.799367	1.650176	2.540799	1.441816	2.624083	1.883233	1.621833	1.376165
W/ Music		Trend	0.015388	0.008116	0.034077	-0.00611	0.029675	0.018385	0.034321	-0.0366	0.093436	0.003685	0.050412	0.008623	0.068801	0.008852
		Total PATI	355.0563	168.0728	182.7207	222.2468	250.2452	459.8178	22.07463	421.0179	237.0875	225.0975	336.6034	276.7487	280.4077	174.9341
		Trend	-0.13142	0.025285	0.146686	-0.09192	-0.39709	-0.14715	0.028078	-2.08526	0.181845	-0.21998	0.131511	-0.32901	0.510267	-0.11502
		AVG MU	5.111111	3.310345	3.962963	2.8125	6.904762	6.307692	5	5.5	7.176471	5.034483	9	7.347826	5.035714	4.766667
		Trend	0.032357	-0.0867	-0.02991	-0.05748	-0.21688	0.004103	-0.04522	-0.42261	0.120098	-0.03695	-0.56071	-0.00198	0.214833	-0.02336
		STV	0.963795	0.945444	0.900622	0.97143	0.944588	0.972858	0.931508	0.896316	0.970091	0.961482	0.979122	0.970736	0.986277	0.950289
	AVG PAV	ELBOW	390.9228	325.4947	486.2121	289.5445	380.8731	547.3451	104.2239	1074.671	403.1528	324.8178	336.3001	480.2808	641.8657	415.3854
		Trend	11.07429	-13.7475	1.208153	-3.00717	-39.5443	-30.6899	-1.30472	48.52185	-17.3654	-3.49148	17.30038	2.60243	-1.64111	-47.1544
		SA	745.9213	768.6609	1193.427	318.9138	363.0319	841.6078	122.1273	1588.395	734.6962	528.8928	2266.605	429.5285	197.6084	402.0482
		Trend	-18.6437	59.8347	-79.0775	3.277015	-19.0733	-15.9983	5.74283	-44.1278	-101.984	22.44025	-130.342	-4.16411	8.067889	11.66286
		SF	284.8253	167.2265	459.5	211.6043	595.875	466.7808	101.8967	834.5654	230.4603	235.8358	638.4835	424.9661	876.2988	367.5442
		Trend	11.99577	-10.2207	21.13998	-6.09891	32.36894	-37.9898	-6.8784	3.715027	-8.98177	-8.79522	-63.8114	16.53457	123.0889	-5.4907
		S3D	543.5565	392.8238	814.8925	275.1102	689.0177	499.9923	236.1525	1326.408	339.7097	461.0577	660.2478	326.9296	336.7788	604.0474
		Trend	-18.3755	4.18096	-39.5404	3.157319	-12.4967	24.52763	14.4002	-20.348	4.935114	19.1629	59.24363	-7.94993	-13.0101	9.879144
	Peak ROM	ELBOW	20.02649	16.19363	27.59793	17.08903	18.37483	53.58402	6.591259	33.58946	33.43911	17.80864	20.82948	19.68297	22.49984	15.54491
		SA	42.02107	29.12579	50.03924	16.65499	19.73812	56.38757	7.842027	50.22684	53.78905	44.38851	118.6837	22.95793	16.56722	27.96889
		SF	27.44378	8.583663	29.64053	15.414	35.69528	63.61361	4.209331	43.64725	29.46361	20.21716	59.60252	25.70548	38.76504	26.7228
		S3D	48.3578	22.76269	55.12117	22.82816	41.98969	73.18539	16.02866	63.62949	41.73762	40.81275	74.18196	26.93637	34.3608	39.3916
RANDOM		AVG MT	1.67148	1.618008	2.014032	1.411645	2.144271	1.890675	2.172596	1.396496	2.072089	1.454075	1.772912	1.721865	1.413098	1.390406
W/ Music		Trend	0.003737	0.021501	0.032019	0.003667	0.09779	0.126977	-0.04083	0.031898	0.014415	0.022069	0.056417	0.041028	0.00987	0.017363
		Total PATI	243.7894	186.7145	135.6752	108.8113	100.2996	64.2835	257.6252	114.7578	191.5372	135.4567	224.7256	155.9671	128.1815	121.6742
		Trend	-0.41865	-0.05306	-0.88657	-0.06703	-0.02115	0.037118	-1.40283	0.13209	-0.53671	0.078671	0.115911	0.165979	0.088345	0.109996
		AVG MU	5.576923	3.653846	6.95	5.066667	5.666667	6.541667	8.6	3.8	7.736842	5.206897	6.916667	5.76	4.666667	4.580645
		Trend	0.001026	-0.02974	-0.33459	-0.097	0.122078	0.441304	-0.42105	0.041935	-0.35439	0.069458	0.069565	0.138462	0.057842	0.050403
		STV	0.894482	0.938218	0.649851	0.794438	0.657985	0.886771	0.937314	0.88472	0.912644	0.919321	0.928526	0.940822	0.831538	0.88318
	AVG PAV	ELBOW	217.0621	244.6096	338.4177	617.8203	184.9479	206.8882	558.1241	450.7055	506.6515	188.2375	355.2584	296.2699	403.5965	70.18603
		Trend	7.539123	0.106884	9.99757	-21.4844	-8.28985	1.615987	18.32789	-5.15287	21.60404	2.74477	14.39578	-3.328	7.233577	13.05751
		SA	170.7066	393.3885	390.6893	492.5778	152.9108	66.3023	165.7323	1360.177	516.8198	420.9064	617.2904	580.579	327.3304	226.0286
		Trend	-10.1265	8.370256	37.14766	-8.59472	1.113272	-7.75414	56.66422	-37.4529	34.14768	-0.688	-6.21032	-7.70786	4.526892	-8.62792
		SF	132.3159	1322.983	326.7692	718.5869	209.4886	590.1866	1042.73	756.0085	875.7469	331.8464	1039.2	520.0195	623.7594	94.9525
		Trend	-36.4165	-11.1628	-2.35111	-21.0558	-25.9054	0.019471	-5.57319	-4.07803	27.17703	-8.44957	8.593183	21.43185	-0.64973	-23.1355
		S3D	113.1594	197.0196	221.76	432.1636	178.2882	147.8151	609.2015	1215.927	725.2687	179.7203	407.4557	233.6055	376.5584	163.6018
		Trend	10.21953	8.920426	-15.7206	5.468283	14.40815	5.148027	30.62365	1.133281	16.3162	2.659697	-9.38883	10.50164	6.754431	10.09061
	Peak ROM	ELBOW	19.43159	19.31222	22.68438	29.66468	14.18042	13.86508	28.40064	27.2245	27.35257	14.34161	17.38037	24.54205	19.35548	17.871
		SA	31.30451	42.65991	20.52414	23.88285	15.88519	11.59173	51.10268	37.6379	38.55515	30.29262	32.2809	38.68031	29.63693	14.38357
		SF	30.81059	32.49002	15.99522	32.38695	16.32524	16.41673	54.48697	35.50163	37.38081	24.92689	42.20411	36.44102	40.18077	20.04548
		S3D	15.29193	18.68752	15.74421	18.81703	12.1862	10.66531	25.34411	20.34294	23.63996	15.85274	17.33223	19.69239	19.54267	11.42276

			Subject1	Subject2	Subject3	Subject4	Subject5	Subject6	Subject7	Subject8	Subject11	Subject12	Subject14	Subject16	Subject17	Subject18
		Tempo	57	52	55	44	35	34	51	71	47	48	33	47	33	54
REPETITIVE		**AVG MT**	2.15475847	1.542092	1.076734	1.14684	0.895443	0.947933	1.324965	0.858959	1.644272	1.136107	2.503916	1.763557	1.322478	0.831095
W/O Music		**Trend**	-0.0017871	0.021501	-0.01047	0.007485	0.00013	0.003357	0.00247	-0.0036	0.000977	-0.00894	0.075841	0.028913	-0.00111	-0.01652
		Total PATI	36.2041157	323.8941	149.7983	17.31081	12.19949	80.10877	218.5974	139.2643	238.2224	236.0282	257.8831	287.5742	317.8781	171.1251
		Trend	-0.2063368	-0.08775	-0.06775	-0.03893	-0.01397	-0.0611	-0.12528	-0.13034	-0.30431	-0.44921	-0.05065	0.233258	-0.33996	-0.3443
		AVG MU	1.65	5.035714	3.487179	2.810811	2.065217	2.325581	4.419355	2.4375	5.461538	3.055556	9.166667	4.5	4.21875	2.541667
		Trend	-0.0022556	-0.00575	-0.05688	-0.03817	-0.00278	-0.01102	-0.02661	-0.03696	-0.09094	-0.14003	0.050568	-0.00348	-0.11345	-0.10356
		STV	0.65869825	0.900282	0.882091	0.378898	0.768943	0.777487	0.967375	0.848802	0.972613	0.800547	0.980604	0.948016	0.942678	0.751538
	AVG PAV	**ELBOW**	74.4453286	600.0836	256.1384	148.7813	76.58595	293.032	267.8387	151.9412	201.9353	529.1184	308.6731	280.4828	370.7235	225.0077
		Trend	-2.0208242	24.4605	-4.37204	0.123908	0.668409	-7.18781	7.276005	-0.02329	-3.09962	4.601725	22.3585	-12.0276	15.74413	-1.31161
		SA	208.318868	439.0805	220.5133	175.9618	50.24053	214.119	700.8237	183.0657	139.1131	4166.949	434.6285	725.2464	1863.124	136.0209
		Trend	-2.0101673	32.04711	-1.71016	4.43583	-0.27636	1.206124	-16.8385	-0.01549	-0.29064	-76.6321	14.72975	-43.0441	-34.5055	-3.78616
		SF	62.0623179	286.1952	151.001	119.12	75.76419	351.6089	391.3257	188.4048	237.7724	255.5884	333.4472	450.9542	295.3444	168.9399
		Trend	0.31434742	6.196432	1.511083	-0.71701	-0.49572	-0.7241	-4.22997	-1.9896	-5.40505	-9.34719	-1.71442	-19.3249	-8.43873	3.543221
		S3D	172.414244	394.0537	114.2918	227.1022	86.00991	380.5459	516.0371	262.7132	197.6911	1082.083	400.8075	624.2969	881.0449	272.946
		Trend	0.15538873	30.80451	-0.99376	-0.96128	0.442521	0.95152	-9.15114	0.723831	8.185642	15.4841	-8.69303	-3.65129	13.68035	-4.37957
	Peak ROM	**ELBOW**	5.71812069	27.39699	21.15743	6.878737	2.493408	7.803889	10.83507	8.245153	9.360078	16.22117	22.8551	16.13865	15.2346	6.498711
		SA	15.1739563	18.63579	25.96076	7.391137	1.652291	7.395833	29.73377	15.34987	8.009007	63.17968	37.82975	43.44956	86.38571	10.32174
		SF	4.80195459	14.87547	18.79785	5.285092	2.803226	12.92005	31.6184	17.21998	17.64579	10.97218	28.14787	24.45231	23.28896	10.94746
		S3D	11.2425494	22.36397	12.24126	11.34874	2.548191	14.56573	43.62139	23.22515	16.26068	39.84651	42.4104	39.87819	51.49296	14.4686
RANDOM		**AVG MT**	1.22079559	1.422229	1.006491	1.069452	1.367542	1.538921	1.210487	1.053857	1.146298	1.412007	2.424327	2.10365	1.253763	0.97361
W/O Music		**Trend**	0.00938926	-0.0137	-0.00049	0.012767	0.007635	0.030734	0.026233	0.002723	0.014906	0.060457	0.094116	0.155114	0.006325	0.015434
		Total PATI	271.652276	181.0119	152.0204	93.40396	109.4941	179.6084	181.9124	232.3086	131.7926	351.1497	209.8361	162.1892	170.2304	141.2222
		Trend	-0.2799252	-0.12054	-0.11137	0.074529	0.343897	0.118087	0.176185	-0.08014	0.019099	0.851038	0.255517	0.770333	0.002691	0.020116
		AVG MU	4.55555556	5.1	2.609756	3.170732	2.967742	6.142857	3.777778	3.871795	4.027778	5.4	9.75	5.4	5.060606	3.428571
		Trend	0.02162162	-0.01846	-0.05331	-0.02979	0.031855	0.091407	0.036808	0.002632	0.037967	0.206897	0.218797	0.285714	-0.02406	0.062232
		STV	0.78350167	0.946365	0.860977	0.74351	0.677516	0.941702	0.89927	0.885502	0.901713	0.924894	0.956667	0.986086	0.92148	0.885513
	AVG PAV	**ELBOW**	280.061238	367.4626	603.5933	261.619	148.4187	289.8103	262.3994	399.4059	371.6204	466.6198	636.145	399.9359	509.3096	308.1181
		Trend	6.40355111	15.37638	2.844182	-1.73917	-7.45313	9.990374	1.906198	10.98933	2.856055	-15.9399	-35.6299	17.34648	4.762726	0.250905
		SA	411.429878	428.5392	318.4906	374.95	138.596	331.9065	500.7608	513.2776	489.1172	1160.874	737.5154	554.3188	1276.153	436.6658
		Trend	-7.7232907	-0.29405	4.181771	-7.85114	5.675665	5.293144	-0.76513	-20.9341	-6.37472	28.8363	-7.2172	-21.0996	30.09929	-9.45057
		SF	526.913441	455.6263	290.817	363.1336	190.8569	765.656	1078.726	503.994	423.8259	509.7961	610.6086	557.1574	765.5938	584.0362
		Trend	9.20242733	22.4482	-0.6546	-7.53302	4.411395	3.194366	64.32381	-8.93844	-0.19366	-2.34564	-36.9491	14.45305	24.96077	-21.7551
		S3D	282.620993	419.867	551.3361	167.3975	117.419	304.6073	345.1974	306.2914	255.4393	326.0702	558.2188	406.3666	498.3523	255.5176
		Trend	-12.05179	-24.4548	-1.45805	1.385966	6.807062	-9.94879	-2.01977	5.697063	-0.83299	-4.74902	19.48107	5.115927	-7.5087	2.188269
	Peak ROM	**ELBOW**	18.7038003	23.65108	21.59218	11.16673	13.39279	14.68823	15.9641	24.22409	16.33076	13.96582	29.62507	20.27166	15.70353	13.07304
		SA	27.7589629	35.58517	22.84833	14.61892	15.50716	20.62457	38.09265	34.86261	24.31796	46.39181	39.97915	40.37687	46.01166	24.27999
		SF	44.0372536	42.91045	16.10953	15.16432	20.94274	30.14998	53.33386	36.27421	23.04491	28.37704	33.87186	36.18067	34.03825	28.82722
		S3D	24.5425879	28.2031	32.99065	7.854815	10.01431	13.89749	23.94276	22.22755	12.21013	23.16669	25.73848	24.42298	19.67123	14.88853

Children P1

W/ Music			Subject1	Subject2	Subject3	Subject4	Subject7	Subject8
		Tempo	20	43	25	17	20	33
REPETITIVE		AVG MT	3.379711	1.486694	1.817053	2.54275	2.480303	0.892052
		Trend	0.363704	0.010902	0.192538	0.060923	0.131897	0.016086
		Total PATI	368.0172	232.7448	131.4746	391.9524	193.0871	187.4696
		Trend	3.74003	0.007173	2.454534	-0.22144	0.618785	-0.01364
		AVG MU	13.66667	5.142857	9	9.823529	11.35294	3.130435
		Trend	1.5	0.006568	-0.25	0.17402	0.416667	-0.00012
		STV	0.967643	0.987754	0.972916	0.956186	0.95397	0.908907
	AVG PAV	ELBOW	1141.167	374.8327	353.0982	505.0093	502.9696	451.0313
		Trend	194.4397	30.93752	-8.98986	27.6999	-73.6208	-14.7177
		SA	1014.157	414.1271	774.2074	580.1767	803.8294	607.3951
		Trend	101.1938	24.90502	-3.76705	26.26073	-109.731	-21.5383
		SF	541.6393	385.0095	426.7292	494.2801	371.1453	353.1741
		Trend	-60.3492	-35.5139	-4.84527	8.238618	-67.9951	-10.1224
		S3D	530.0575	412.9408	308.3889	330.726	422.5214	460.4046
		Trend	27.36627	21.93476	-16.2742	-16.3488	-7.15057	18.00542
	Peak ROM	ELBOW	66.92115	34.8841	45.89537	32.30824	32.15347	33.0818
		SA	54.12351	37.54522	68.86291	31.41995	60.31992	24.69732
		SF	44.9707	32.76988	36.5812	22.94875	34.18249	26.13559
		S3D	40.55055	46.33149	50.43086	36.0784	50.41745	34.24334
RANDOM		AVG MT	2.287862	1.513298	1.380864	1.825194	2.023111	1.348867
		Trend	0.074418	0.066941	0.03688	0.017517	0.013675	-0.00246
		Total PATI	177.0866	303.8804	314.7327	214.9271	225.0238	257.3076
		Trend	-0.29082	0.858262	0.220421	-0.11229	0.047666	-0.47301
		AVG MU	10.45455	5.7	5.4	8.086957	9.47619	6.448276
		Trend	-0.34545	0.217353	0.111235	-0.05731	-0.04286	-0.1399
		STV	0.953806	0.906992	0.972083	0.931057	0.942791	0.893295
	AVG PAV	ELBOW	548.6473	584.2447	810.6156	283.6294	951.6775	969.3878
		Trend	122.3928	21.36087	-59.0458	20.59864	-87.5374	36.88837
		SA	1875.451	728.7516	910.5654	1066.143	77.16354	724.6089
		Trend	94.57911	-15.2805	9.453257	-62.9353	-39.501	-29.9461
		SF	531.7333	187.6029	202.2632	232.7423	347.7728	559.6334
		Trend	-172.398	-1.34981	-15.1017	-21.1189	-11.692	-17.6493
		S3D	744.5953	550.7401	879.5386	342.1773	431.7649	6.664898
		Trend	66.49223	1.329077	11.80222	-9.18423	66.4897	25.43441
	Peak ROM	ELBOW	33.42015	36.90768	24.21539	15.41265	25.13327	28.39881
		SA	57.75864	53.58067	47.51109	43.9804	65.3986	63.4525
		SF	44.22083	45.54374	44.2699	15.46421	31.44988	30.71948
		S3D	60.80029	35.8035	42.05743	21.22264	38.84825	44.57228

W/O Music			Subject1	Subject2	Subject3	Subject4	Subject7	Subject8
		Tempo	20	43	25	17	20	33
REPETITIVE		AVG MT	4.895089	1.188776	1.589742	2.059506	1.551871	1.446275
		Trend	0.600631	0.013596	0.020171	0.036736	-0.01237	-0.01329
		Total PATI	357.7269	188.6023	289.6159	191.019	143.7519	194.0179
		Trend	3.800363	0.01939	-0.01594	-0.27747	-0.15735	-0.46475
		AVG MU	19.5	4.342857	6.037037	9.388889	5.407407	5.344828
		Trend	2.066667	0.052941	-0.00794	-0.3808	-0.10317	-0.1798
		STV	0.987234	0.957898	0.903207	0.944964	0.915361	0.906567
	AVG PAV	ELBOW	683.416	525.6837	723.1195	783.6593	321.418	591.1456
		Trend	0.543337	5.48358	-44.4382	-63.6151	1.064218	5.055359
		SA	662.7576	785.7954	693.1182	1118.952	1129.109	985.917
		Trend	-39.528	11.87261	-4.72436	48.35551	-13.3763	-16.5074
		SF	502.6864	526.315	504.881	749.901	171.9136	536.9032
		Trend	20.2175	2.304969	-15.5556	14.01967	-3.01697	0.200702
		S3D	532.3626	759.5439	556.535	803.9363	540.0437	663.41
		Trend	36.1593	28.33053	11.67776	18.94335	-9.89323	-2.11825
	Peak ROM	ELBOW	68.22163	27.30333	49.7945	48.12155	13.60527	39.1375
		SA	65.43441	33.30316	35.05764	54.38655	58.03432	44.4415
		SF	56.74509	27.47552	33.79994	38.14141	11.74688	42.29776
		S3D	74.36995	42.92788	40.80826	36.03724	35.67561	55.97183
RANDOM		AVG MT	1.373298	1.95237	1.57674	4.222725	3.649156	1.763885
		Trend	0.023102	0.056552	0.014818	0.233482	0.41624	0.032897
		Total PATI	265.5605	383.7059	291.9194	369.261	357.6708	291.5816
		Trend	0.087573	0.238672	-0.05919	1.657489	2.762262	0.397749
		AVG MU	5.966667	7.88	6.071429	17.4	15.66667	7.458333
		Trend	0.097219	0.166923	-0.0093	0.448485	1.643357	0.046522
		STV	0.949214	0.973068	0.954607	0.945769	0.988635	0.944498
	AVG PAV	ELBOW	298.1694	987.7634	863.87	898.5141	685.3552	591.395
		Trend	-23.8178	-13.449	20.98278	-130.119	-55.2849	25.93564
		SA	561.0383	1293.465	937.9132	836.5178	1377.127	1490.086
		Trend	-5.75293	-43.5107	-34.2456	-18.4327	367.8552	55.28227
		SF	406.232	1021.661	1090.121	1432.725	955.4166	780.0182
		Trend	-44.3589	-64.7587	-77.8013	538.2978	-111.707	-5.34427
		S3D	354.7764	757.7907	764.151	713.9077	702.9742	681.2903
		Trend	11.53788	33.5549	15.84893	-254.437	43.30188	2.381475
	Peak ROM	ELBOW	20.64205	42.19457	36.46644	66.98678	41.25196	35.02649
		SA	45.46106	68.256	59.38118	66.28576	75.13399	94.4827
		SF	36.02418	47.28779	61.74144	77.71431	52.80585	49.6566
		S3D	29.06412	46.04564	43.46017	41.31871	47.02762	54.58018

Adults P2

W/ Music			Subject1	Subject2	Subject3	Subject4	Subject5	Subject6	Subject7
		Tempo	44	47	57	55	46	38	47
		AVG MT	0.822008	0.775152	0.957163	0.753803	0.764643	1.105866	1.31036
		Trend	0.010481	0.007878	0.029635	0.016622	0.01201	0.030705	-0.01279
		Total PATI	92.38528	94.08669	67.51835	119.1834	89.26364	137.3859	58.07037
		Trend	0.0171	0.02507	0.05495	0.054069	0.037511	0.090867	-0.08428
		AVG MU	2.647059	2.88	1.833333	2.192982	2.057692	4.27027	2.580645
		Trend	0.017195	0.024202	0.053723	0.061641	0.000555	0.128023	-0.08548
		STV	0.89665	0.91278	0.87616	0.962255	0.909248	0.929252	0.856736
	AVG PAV	ELBOW	379.8065	313.5665	211.9485	175.2806	56.88209	64.27372	33.47663
		Trend	3.125657	-11.0944	-2.98305	-0.15556	-2.15552	-0.89349	0.702939
		SA	261.7243	261.4518	163.3026	344.6298	45.55589	41.14298	18.13869
		Trend	0.773732	-1.15734	-0.008	-7.62947	0.746371	0.089366	0.141818
		SF	438.9828	368.2824	203.4476	392.5221	33.53995	30.33207	15.61068
		Trend	7.557337	-6.71551	-2.50176	-8.4908	-1.75663	1.33075	-0.05472
		S3D	256.9906	229.1601	108.9029	156.5961	38.404	53.43884	25.14258
		Trend	-5.3509	5.042799	3.462353	-0.04392	0.863844	-0.54521	-0.20894
	Peak ROM	ELBOW	17.93836	12.76938	11.79693	14.95251	16.19025	31.29492	12.35001
		SA	18.52546	13.792	13.47172	26.25524	15.43772	33.21311	20.90002
		SF	31.1121	17.95367	18.79974	30.56308	23.13381	37.84499	18.27034
		S3D	11.53555	10.53771	8.664879	11.12773	9.622639	17.92586	9.621043

W/O Music			Subject1	Subject2	Subject3	Subject4	Subject5	Subject6	Subject7
		Tempo	44	47	57	55	46	38	47
		AVG MT	0.841204	0.748677	0.789163	0.987239	0.736204	1.233202	0.651703
		Trend	0.006231	0.002816	0.01931	0.027028	0.010971	-0.00487	0.002964
		Total PATI	71.3271	77.13821	95.25995	120.486	101.7802	147.9665	93.83108
		Trend	0.006628	-0.01609	0.040289	0.104115	0.031416	-0.10091	0.004249
		AVG MU	2.12	2.089286	2.254902	3.166667	2.111111	4.088235	1.953125
		Trend	-0.02497	-0.02334	0.02733	0.07625	0.032628	-0.00321	0.002633
		STV	0.911258	0.916225	0.940108	0.940219	0.952821	0.94295	0.874404
	AVG PAV	ELBOW	329.548	203.5065	488.9908	341.8705	3.310827	81.40649	21.07715
		Trend	-16.0747	-1.45862	-8.12809	-6.68615	0.012319	0.469772	-0.42601
		SA	277.073	212.0609	276.9184	579.8358	7.141501	40.50834	10.36324
		Trend	-8.75579	-0.80998	3.651793	-12.3429	0.163222	-0.68687	0.22448
		SF	489.8629	229.1582	296.2008	693.376	4.64191	32.72653	9.08377
		Trend	-15.6326	-2.17632	6.105327	-19.4582	-0.11112	-0.33399	-0.14301
		S3D	225.7739	140.9222	204.0103	282.584	6.820989	37.98289	11.7358
		Trend	9.174798	-0.79466	-5.58785	3.093287	0.088872	-1.28144	0.227865
	Peak ROM	ELBOW	17.84931	9.23403	19.91693	19.10704	16.01153	27.17305	8.833039
		SA	14.06001	11.7116	12.07495	32.83612	14.41996	21.12799	19.28546
		SF	28.67311	11.13369	13.31266	38.50451	22.40054	32.81606	17.80792
		S3D	10.18537	6.578795	8.394032	17.34332	9.105664	13.12839	7.36667

Children P2

First/Last Trials

After			Subject1	Subject2	Subject3
		Tempo	21	49	41
		AVG MT	0.635015	0.886652	0.853014
		Trend	-8.2E-05	0.01073	0.004682
		Total PATI	66.10194	131.2371	83.22579
		Trend	-0.00709	0.037657	0.005792
		AVG MU	2.33871	3.162791	2.791667
		Trend	-0.00905	0.015363	0.012484
		STV	0.916078	0.882527	0.874953
	AVG PAV	ELBOW	184.9384	61.18012	331.6117
		Trend	0.673217	0.91233	-10.3546
		SA	197.1024	51.2414	219.6146
		Trend	1.283081	1.276778	-4.45285
		SF	197.2532	69.44456	363.77
		Trend	0.940308	0.144368	1.700421
		S3D	163.1654	106.2563	191.9187
		Trend	-0.2285	2.840609	-1.76383
	Peak ROM	ELBOW	9.975539	9.007314	19.68228
		SA	11.0808	21.3934	18.02352
		SF	11.60865	27.57253	27.50921
		S3D	8.831685	14.79637	12.67745

Before			Subject1	Subject2	Subject3
		Tempo	21	49	41
		AVG MT	0.89115	1.383691	1.527032
		Trend	0.019702	0.007523	0.023033
		Total PATI	40.43001	82.29826	56.8212
		Trend	0.052218	-0.04759	0.0181
		AVG MU	5.375	3.129032	2.821429
		Trend	-0.25293	0.002597	0.009031
		STV	0.944211	0.909865	0.823229
	AVG PAV	ELBOW	325.2172	305.6719	138.6515
		Trend	26.85558	-3.95788	3.375126
		SA	426.8633	410.3855	151.7652
		Trend	22.08086	-5.36188	-4.32718
		SF	322.2261	294.5595	206.8912
		Trend	13.58094	0.095533	-8.10424
		S3D	152.5131	227.6312	93.6346
		Trend	-3.78091	-0.99997	2.52222
	Peak ROM	ELBOW	14.83643	15.99514	19.91528
		SA	19.84015	33.76972	23.24315
		SF	16.57712	31.61762	29.35477
		S3D	10.06443	23.82178	15.17127

First/No Rhythm Trials

After			Subject1	Subject2	Subject3
		Tempo	21	49	41
		AVG MT	0.635015	1.285997	0.853014
		Trend	-8.2E-05	0.005988	0.004682
		Total PATI	66.10194	80.50928	83.22579
		Trend	-0.00709	-0.00694	0.005792
		AVG MU	2.33871	3.030303	2.791667
		Trend	-0.00905	-0.00635	0.012484
		STV	0.916078	0.905029	0.874953
	AVG PAV	ELBOW	184.9384	275.7784	331.6117
		Trend	0.673217	15.70941	-10.3546
		SA	197.1024	162.8577	219.6146
		Trend	1.283081	-10.7195	-4.45285
		SF	197.2532	155.2153	363.77
		Trend	0.940308	-3.42493	1.700421
		S3D	163.1654	252.3173	191.9187
		Trend	-0.2285	3.010331	-1.76383
	Peak ROM	ELBOW	9.975539	10.20966	19.68228
		SA	11.0808	23.94422	18.02352
		SF	11.60865	22.91688	27.50921
		S3D	8.831685	16.59439	12.67745

Before			Subject1	Subject2	Subject3
		Tempo	21	49	41
		AVG MT	0.89115	1.383691	1.527032
		Trend	0.019702	0.007523	0.023033
		Total PATI	40.43001	82.29826	56.8212
		Trend	0.052218	-0.04759	0.0181
		AVG MU	5.375	3.129032	2.821429
		Trend	-0.25293	0.002597	0.009031
		STV	0.944211	0.909865	0.823229
	AVG PAV	ELBOW	325.2172	305.6719	138.6515
		Trend	26.85558	-3.95788	3.375126
		SA	426.8633	410.3855	151.7652
		Trend	22.08086	-5.36188	-4.32718
		SF	322.2261	294.5595	206.8912
		Trend	13.58094	0.095533	-8.10424
		S3D	152.5131	227.6312	93.6346
		Trend	-3.78091	-0.99997	2.52222
	Peak ROM	ELBOW	14.83643	15.99514	19.91528
		SA	19.84015	33.76972	23.24315
		SF	16.57712	31.61762	29.35477
		S3D	10.06443	23.82178	15.17127

First/Rhythm Trials

After			Subject1	Subject2	Subject3
		Tempo	21	49	41
		AVG MT	1.695021	0.886652	0.987925
		Trend	0.001896	0.01073	0.015406
		Total PATI	41.10969	131.2371	121.1163
		Trend	-0.00016	0.037657	0.019709
		AVG MU	5.5	3.162791	3.883721
		Trend	-0.23739	0.015363	0.073694
		STV	0.926332	0.882527	0.912255
	AVG PAV	ELBOW	411.6582	61.18012	294.1755
		Trend	-0.64661	0.91233	6.289908
		SA	473.6158	51.2414	447.0878
		Trend	-7.97014	1.276778	-7.56096
		SF	232.6815	69.44456	661.4226
		Trend	-15.3521	0.144368	-3.78217
		S3D	398.0372	106.2563	275.1798
		Trend	-2.64147	2.840609	4.056971
	Peak ROM	ELBOW	18.86107	9.007314	15.15875
		SA	29.84167	21.3934	23.53071
		SF	14.63935	27.57253	31.52909
		S3D	18.79269	14.79637	12.98568

Before			Subject1	Subject2	Subject3
		Tempo	21	49	41
		AVG MT	0.89115	1.383691	1.527032
		Trend	0.019702	0.007523	0.023033
		Total PATI	40.43001	82.29826	56.8212
		Trend	0.052218	-0.04759	0.0181
		AVG MU	5.375	3.129032	2.821429
		Trend	-0.25293	0.002597	0.009031
		STV	0.944211	0.909865	0.823229
	AVG PAV	ELBOW	325.2172	305.6719	138.6515
		Trend	26.85558	-3.95788	3.375126
		SA	426.8633	410.3855	151.7652
		Trend	22.08086	-5.36188	-4.32718
		SF	322.2261	294.5595	206.8912
		Trend	13.58094	0.095533	-8.10424
		S3D	152.5131	227.6312	93.6346
		Trend	-3.78091	-0.99997	2.52222
	Peak ROM	ELBOW	14.83643	15.99514	19.91528
		SA	19.84015	33.76972	23.24315
		SF	16.57712	31.61762	29.35477
		S3D	10.06443	23.82178	15.17127

Children with CP P2

First/Last Trials

After			Subject1	Subject2
		Tempo	15	48
		AVG MT	3.236369	0.752032
		Trend	0.060603	0.012869
		Total PATI	125.3834	99.19959
		Trend	0.222748	0.045582
		AVG MU	12.92857	2.592593
		Trend	0.173626	0.048485
		STV	0.969661	0.851419
	AVG PAV	ELBOW	425.2624	229.8103
		Trend	14.53718	-2.1316
		SA	329.683	226.4305
		Trend	35.24641	-5.97052
		SF	287.8133	169.4139
		Trend	-10.2875	-2.37289
		S3D	410.699	142.7245
		Trend	-19.6626	-2.14664
	Peak ROM	ELBOW	39.80542	10.95746
		SA	20.4927	15.43715
		SF	24.27029	16.48099
		S3D	30.04841	11.2624

Before			Subject1	Subject2
		Tempo	15	48
		AVG MT	4.24172	1.28284
		Trend	0.613314	0.031808
		Total PATI	201.2274	121.3019
		Trend	2.512964	-0.0024
		AVG MU	14.16667	3.914286
		Trend	2.027972	0.022129
		STV	0.974246	0.866233
	AVG PAV	ELBOW	593.4668	401.3523
		Trend	-32.2852	3.113549
		SA	579.7932	328.3453
		Trend	15.15749	-3.6432
		SF	885.3412	308.1198
		Trend	-124.883	8.9034
		S3D	793.8723	261.1161
		Trend	213.1941	0.840926
	Peak ROM	ELBOW	35.19153	18.99085
		SA	21.2944	20.01457
		SF	31.41474	21.64927
		S3D	27.63241	15.66482

First/No Rhythm Trials

After			Subject1	Subject2
		Tempo	15	48
		AVG MT	3.236369	0.745544
		Trend	0.060603	0.000338
		Total PATI	125.3834	128.6981
		Trend	0.222748	-0.01882
		AVG MU	12.92857	2.132075
		Trend	0.173626	-0.00701
		STV	0.969661	0.898876
	AVG PAV	ELBOW	425.2624	422.4492
		Trend	14.53718	11.95693
		SA	329.683	360.1616
		Trend	35.24641	-10.8284
		SF	287.8133	334.3854
		Trend	-10.2875	-2.01309
		S3D	410.699	202.8734
		Trend	-19.6626	0.300498
	Peak ROM	ELBOW	39.80542	23.63943
		SA	20.4927	28.99616
		SF	24.27029	27.7663
		S3D	30.04841	20.4657

Before			Subject1	Subject2
		Tempo	15	48
		AVG MT	4.24172	1.28284
		Trend	0.613314	0.031808
		Total PATI	201.2274	121.3019
		Trend	2.512964	-0.0024
		AVG MU	14.16667	3.914286
		Trend	2.027972	0.022129
		STV	0.974246	0.866233
	AVG PAV	ELBOW	593.4668	401.3523
		Trend	-32.2852	3.113549
		SA	579.7932	328.3453
		Trend	15.15749	-3.6432
		SF	885.3412	308.1198
		Trend	-124.883	8.9034
		S3D	793.8723	261.1161
		Trend	213.1941	0.840926
	Peak ROM	ELBOW	35.19153	18.99085
		SA	21.2944	20.01457
		SF	31.41474	21.64927
		S3D	27.63241	15.66482

First/Rhythm Trials

After			Subject1	Subject2
		Tempo	15	48
		AVG MT	2.027392	0.752032
		Trend	0.006454	0.012869
		Total PATI	96.49426	99.19959
		Trend	-0.02134	0.045582
		AVG MU	7.65	2.592593
		Trend	-0.27293	0.048485
		STV	0.784922	0.851419
	AVG PAV	ELBOW	520.2121	229.8103
		Trend	36.8878	-2.1316
		SA	219.0634	226.4305
		Trend	-3.67983	-5.97052
		SF	400.9167	169.4139
		Trend	-8.59137	-2.37289
		S3D	292.5033	142.7245
		Trend	28.00159	-2.14664
	Peak ROM	ELBOW	33.54496	10.95746
		SA	15.52854	15.43715
		SF	29.22185	16.48099
		S3D	20.26661	11.2624

Before			Subject1	Subject2
		Tempo	15	48
		AVG MT	4.24172	1.28284
		Trend	0.613314	0.031808
		Total PATI	201.2274	121.3019
		Trend	2.512964	-0.0024
		AVG MU	14.16667	3.914286
		Trend	2.027972	0.022129
		STV	0.974246	0.866233
	AVG PAV	ELBOW	593.4668	401.3523
		Trend	-32.2852	3.113549
		SA	579.7932	328.3453
		Trend	15.15749	-3.6432
		SF	885.3412	308.1198
		Trend	-124.883	8.9034
		S3D	793.8723	261.1161
		Trend	213.1941	0.840926
	Peak ROM	ELBOW	35.19153	18.99085
		SA	21.2944	20.01457
		SF	31.41474	21.64927
		S3D	27.63241	15.66482

Between Groups

Children to Adults

Adult P1 RANDOM W/O Music			Subject1	Subject2	Subject3	Subject4	Subject5	Subject6	Subject7	Subject8	Subject11	Subject12	Subject14	Subject16	Subject17	Subject18
		Tempo	57	52	55	44	35	34	51	71	47	48	33	47	33	54
		AVG MT	1.220796	1.422229	1.006491	1.069452	1.367542	1.538921	1.210487	1.053857	1.146298	1.412007	2.424327	2.10365	1.253763	0.97361
		Trend	0.009389	-0.0137	-0.00049	0.012767	0.007635	0.030734	0.026233	0.002723	0.014906	0.060457	0.094116	0.155114	0.006325	0.015434
		Total PATI	271.6523	181.0119	152.0204	93.40396	109.4941	179.6084	181.9124	232.3086	131.7926	351.1497	209.8361	162.1892	170.2304	141.2222
		Trend	-0.27993	-0.12054	-0.11137	0.074529	0.343897	0.118087	0.176185	-0.08014	0.019099	0.851038	0.255517	0.770333	0.002691	0.020116
		AVG MU	4.555556	5.1	2.609756	3.170732	2.967742	6.142857	3.777778	3.871795	4.027778	5.4	9.75	5.4	5.060606	3.428571
		Trend	0.021622	-0.01846	-0.05331	-0.02979	0.031855	0.091407	0.036808	0.002632	0.037967	0.206897	0.218797	0.285714	-0.02406	0.062232
		STV	0.783502	0.946365	0.860977	0.74351	0.677516	0.941702	0.89927	0.885502	0.901713	0.924894	0.956667	0.986086	0.92148	0.885513
	AVG PAV	ELBOW	280.0612	367.4626	603.5933	261.619	148.4187	289.8103	262.3994	399.4059	371.6204	466.6198	636.145	399.9359	509.3096	308.1181
		Trend	6.403551	15.37638	2.844182	-1.73917	-7.45313	9.990374	1.906198	10.98933	2.856055	-15.9399	-35.6299	17.34648	4.762726	0.250905
		SA	411.4299	428.5392	318.4906	374.95	138.596	331.9065	500.7608	513.2776	489.1172	1160.874	737.5154	554.3188	1276.153	436.6658
		Trend	-7.72329	-0.29405	4.181771	-7.85114	5.675665	5.293144	-0.76513	-20.9341	-6.37472	28.8363	-7.2172	-21.0996	30.09929	-9.45057
		SF	526.9134	455.6263	290.817	363.1336	190.8569	765.656	1078.726	503.994	423.8259	509.7961	610.6086	557.1574	765.5938	584.0362
		Trend	9.202427	22.4482	-0.6546	-7.53302	4.411395	3.194366	64.32381	-8.93844	-0.19366	-2.34564	-36.9491	14.45305	24.96077	-21.7551
		S3D	282.621	419.867	551.3361	167.3975	117.419	304.6073	345.1974	306.2914	255.4393	326.0702	558.2188	406.3666	498.3523	255.5176
		Trend	-12.0518	-24.4548	-1.45805	1.385966	6.807062	-9.94879	-2.01977	5.697063	-0.83299	-4.74902	19.48107	5.115927	-7.5087	2.188269
	Peak ROM	ELBOW	18.7038	23.65108	21.59218	11.16673	13.39279	14.68823	15.9641	24.22409	16.33076	13.96582	29.62507	20.27166	15.70353	13.07304
		SA	27.75896	35.58517	22.84833	14.61892	15.50716	20.62457	38.09265	34.86261	24.31796	46.39181	39.97915	40.37687	46.01166	24.27999
		SF	44.03725	42.91045	16.10953	15.16432	20.94274	30.14998	53.33386	36.27421	23.04491	28.37704	33.87186	36.18067	34.03825	28.82722
		S3D	24.54259	28.2031	32.99065	7.854815	10.01431	13.89749	23.94276	22.22755	12.21013	23.16669	25.73848	24.42298	19.67123	14.88853

Kids P1 RANDOM W/O			Subject1	Subject2	Subject3	Subject4	Subject7	Subject8
		Tempo	20	43	25	17	20	33
RANDOM		AVG MT	1.373298	1.95237	1.57674	4.222725	3.649156	1.763885
		Trend	0.023102	0.056552	0.014818	0.233482	0.41624	0.032897
		Total PATI	265.5605	383.7059	291.9194	369.261	357.6708	291.5816
		Trend	0.087573	0.238672	-0.05919	1.657489	2.762262	0.397749
		AVG MU	5.966667	7.88	6.071429	17.4	15.66667	7.458333
		Trend	0.097219	0.166923	-0.0093	0.448485	1.643357	0.046522
		STV	0.949214	0.973068	0.954607	0.945769	0.988635	0.944498
	AVG PAV	ELBOW	298.1694	987.7634	863.87	898.5141	685.3552	591.395
		Trend	-23.8178	-13.449	20.98278	-130.119	-55.2849	25.93564
		SA	561.0383	1293.465	937.9132	836.5178	1377.127	1490.086
		Trend	-5.75293	-43.5107	-34.2456	-18.4327	367.8552	55.28227
		SF	406.232	1021.661	1090.121	1432.725	955.4166	780.0182
		Trend	-44.3589	-64.7587	-77.8013	538.2978	-111.707	-5.34427
		S3D	354.7764	757.7907	764.151	713.9077	702.9742	681.2903
		Trend	11.53788	33.5549	15.84893	-254.437	43.30188	2.381475
	Peak ROM	ELBOW	20.64205	42.19457	36.46644	66.98678	41.25196	35.02649
		SA	45.46106	68.256	59.38118	66.28576	75.13399	94.4827
		SF	36.02418	47.28779	61.74144	77.71431	52.80585	49.6566
		S3D	29.06412	46.04564	43.46017	41.31871	47.02762	54.58018

Children with CP to Children

Kids P1 RANDOM W/O			Subject1	Subject2	Subject3	Subject4	Subject7	Subject8
		Tempo	20	43	25	17	20	33
RANDOM		AVG MT	1.373298	1.95237	1.57674	4.222725	3.649156	1.763885
		Trend	0.023102	0.056552	0.014818	0.233482	0.41624	0.032897
		Total PATI	265.5605	383.7059	291.9194	369.261	357.6708	291.5816
		Trend	0.087573	0.238672	-0.05919	1.657489	2.762262	0.397749
		AVG MU	5.966667	7.88	6.071429	17.4	15.66667	7.458333
		Trend	0.097219	0.166923	-0.0093	0.448485	1.643357	0.046522
		STV	0.949214	0.973068	0.954607	0.945769	0.988635	0.944498
	AVG PAV	ELBOW	298.1694	987.7634	863.87	898.5141	685.3552	591.395
		Trend	-23.8178	-13.449	20.98278	-130.119	-55.2849	25.93564
		SA	561.0383	1293.465	937.9132	836.5178	1377.127	1490.086
		Trend	-5.75293	-43.5107	-34.2456	-18.4327	367.8552	55.28227
		SF	406.232	1021.661	1090.121	1432.725	955.4166	780.0182
		Trend	-44.3589	-64.7587	-77.8013	538.2978	-111.707	-5.34427
		S3D	354.7764	757.7907	764.151	713.9077	702.9742	681.2903
		Trend	11.53788	33.5549	15.84893	-254.437	43.30188	2.381475
	Peak ROM	ELBOW	20.64205	42.19457	36.46644	66.98678	41.25196	35.02649
		SA	45.46106	68.256	59.38118	66.28576	75.13399	94.4827
		SF	36.02418	47.28779	61.74144	77.71431	52.80585	49.6566
		S3D	29.06412	46.04564	43.46017	41.31871	47.02762	54.58018
CP Kids P2 W/O			Subject1	Subject2				
		Tempo	15	48				
		AVG MT	4.24172	1.28284				
		Trend	0.613314	0.031808				
		Total PATI	201.2274	121.3019				
		Trend	2.512964	-0.0024				
		AVG MU	14.16667	3.914286				
		Trend	2.027972	0.022129				
		STV	0.974246	0.866233				
	AVG PAV	ELBOW	593.4668	401.3523				
		Trend	-32.2852	3.113549				
		SA	579.7932	328.3453				
		Trend	15.15749	-3.6432				
		SF	885.3412	308.1198				
		Trend	-124.883	8.9034				
		S3D	793.8723	261.1161				
		Trend	213.1941	0.840926				
	Peak ROM	ELBOW	35.19153	18.99085				
		SA	21.2944	20.01457				
		SF	31.41474	21.64927				
		S3D	27.63241	15.66482				

Survey Questions

Adults P1

Gender				Age				
M	F	None Listed		17-	18-24	25-31	32+	None Listed
8	6	5		0	8	9	1	1

Question	Strongly Agree	Agree	Neutral	Disagree	Strongly disagree	N/A
1. I have a lot of experience playing video or computer games.	7	8	3	1	0	0
2 The game interface is easy to understand.	9	10	0	0	0	0
3 The rules of the game are clear from the current presentation.	8	7	4	0	0	0
4 I found the moving things / objects in the game very interesting.	4	4	5	6	0	0
5 There was no delay in what I did and what I saw in the game.	1	3	2	11	2	0
6 I found it nice to see myself in the game.	5	6	7	1	0	0
7 I enjoyed playing the game overall.	5	13	0	1	0	0
8 I think I performed well in the game.	4	9	5	1	0	0
9 I would like to play this game more often.	1	7	8	2	1	0
10 I would be willing to play the game every day for a few minutes.	1	12	3	1	2	0

11 I would be willing to play the game twice a week for at least 30 minutes.	0	7	4	6	2	0
12 It would be nice if I could play the game with other children at the same time.	9	7	1	1	0	1
13 The game was so engaging that I lost track of the time.	1	6	5	7	0	0
14 Training with the ‘Super Pop’ game is less fun than with regular physiotherapy.	1	1	1	3	5	8
15 If repeatedly played, I believe the speed and accuracy of my movements when playing the game would improve.	8	8	2	0	0	1
16 The game was too fast. I would have liked to play a slower version of the game.	0	1	1	13	4	0
17 The game was too difficult. I would have liked to play an easier version of the game.	0	0	4	9	6	0
18 I could predict what was going to happen after I had made a movement.	1	9	2	7	0	0
19 I found it hard to play the game by moving my arms.	0	0	1	14	4	0
20 I have heard the songs before and I am very familiar with them.	14	1	0	0	1	3
21 I could hear all the songs very well.	14	2	0	0	0	3
22 The sounds I heard out of the game were	2	7	4	2	1	3

very attractive.						
23 The music was distracting.	1	2	3	5	5	3
24 I was more focused when playing with no sound.	1	5	4	5	1	3
25 I was more focused when playing with just the bubble popping sound.	1	2	2	4	1	9
26 I was more focused when playing with the "Twinkle Twinkle Little Star" song.	1	6	4	2	0	6
27 I was more focused when playing with the "Für Elise" song.	0	0	1	1	0	17
28 I was more focused when playing with the "Row Row Row Your Boat" song.	0	0	1	0	0	18
29 I was more focused when playing with the "Tetris" song.	0	0	1	0	0	18
30 I was more focused when playing with music overall than I was without music.	3	5	1	4	2	4
31 The songs played were too fast for me to keep up.	0	1	1	11	3	3
32 The songs played were too slow.	0	5	0	10	1	3
33 I popped the bubbles faster when the music was playing.	0	2	4	5	4	4
34 I popped the bubbles slower when the music was	2	4	4	3	2	4

playing.						
35 The metronome tone allowed me to keep my focus.	2	8	1	3	1	4
36 I think that my accuracy was better when the music was playing during the game.	1	4	5	5	1	3
37 Having more songs to choose from would have made the game more interesting.	8	3	3	1	0	4
38 I become more tired from playing this game than from regular physiotherapy.	0	0	4	2	2	11
39 I have learned new movements by playing this game.	0	1	6	6	3	3
40 I think I could learn new movements by playing the game more often.	2	8	3	3	2	1
Question	Strongly Agree	Agree	Neutral	Disagree	Strongly disagree	N/A

Children P1

Subject	1	2	3	4	5	6	7
Questions							
I could see all my movements from the screen very well	4	5	5	5	4	4	2
I found the objects in the game very interesting	3	4	4	4	5	3	3
The objects I saw in the game were very attractive	2	2	3	4	4	4	4
I could hear all music in the game very well	5	5	5	5	5	4	5
The music I heard out of the game was very attractive	5	3	1	3	4	4	2
I could not hear where all of the sounds out of the game came from	1	1	1	1	2	2	2
The movements to play the game were too hard	3	1	1	3	2	1	4
The movements used to touch objects in the game were so fast, they were not too easy; but also were not too hard	4	5	2	3	3	4	4
I must still learn a lot before I can play the game well	4	1	1	4	2	2	4
I could predict what was going to happen after I had made a movement	2	2	5	2	4	4	2
I had the feeling I could accomplish the game	2	5	5	3	4	4	4
I would find it nice if I could play the game together with more friends at the same time	2	5	5	5	5	4	4
The game was so attractive that I lost all count of time	2	4	4	4	2	2	4
I would like to play the game more often	3	4	5	3	4	4	2
The game training is less fun than regular computer/video games	4	5	-	2	2	2	4
The request from the game was easy to understand	5	5	4	4	4	4	2
The request from the game was easy to follow	5	5	5	4	4	4	4
It was very logical playing the game by popping the objects	4	5	5	4	4	4	4
I found it hard to follow the game by moving my hands	4	1	1	4	2	2	4
I become more tired from playing with the game than from the regular computer/video games	1	1	4	4	2	2	4
I like playing the game	4	4	5	3	4	5	4

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