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## Upper Extremity Motion Assessments in Virtual Reality Environments

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# Upper Extremity Motion Assessments in Virtual Reality Environments



Honors Thesis

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Department: Mechanical and Aerospace Engineering

Advisor: Megan Reissman, Ph.D.

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## Abstract

Traditional upper extremity rehabilitation techniques often utilize tedious and repetitive reaching motions. Fully immersive virtual reality (VR), involving a VR headset, is a technology with the potential to have non-gaming uses and applications, specifically as an upper extremity rehabilitation tool. This study was designed with the long-term goal of evaluating immersive VR as an upper extremity rehabilitation tool. The purpose of this research is to quantify different movement deficits that may arise due to MS or Parkinson's, and to understand how the motions of patients with MS or Parkinson's may differ from healthy controls. This thesis documents the first step in that process: the development of a baseline standard for upper extremity reaching motions within this experimental rehabilitation method.

The virtual environment utilized in this study is the game "Beat Sabers". Custom levels were designed and coded to examine the impact of factors of Vertical Position, Horizontal Position, and Direction of the movement task on the outcome metrics. Additionally, three type of movements were tested: Unilateral, Bilateral, and Contralateral. A healthy control group of 16 young adults was recruited. Using an XSens Awinda motion capture suit, motion data was collected while participants performed roughly 500 movement tasks per person. Initial statistical assessment of the Unilateral movements showed that the factor of Direction was strongly significant for all joint angle and velocity metrics examined. Vertical Position was significant for most of the metrics examined. Finally, average range of motion for each joint was established. These results and motion profiles will serve as a control baseline for upper extremity motions, which will be later used in the evaluation of movement deficits in clinical populations including multiple sclerosis and Parkinson's disease.

## Disclaimer

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# Table of Contents

Abstract	Title Page
Introduction	1
Methods	4
Results	9
Discussion	11
Conclusion	16
References	18

# 1. Introduction

## 1.1 Understanding Motor Control

An individual's level of motor control has a considerable effect on their ability to complete most of the tasks within their daily life and maintain independence. There are two main facets of motor control, lower extremity and upper extremity motor control. Lower extremity motor control is related to the movement of the legs and details a person's ability to walk, dance, and run. Upper extremity motor control is used in other daily tasks of living, such as brushing teeth or reaching to grab objects. When individuals develop conditions that impact their upper extremity motor control, these daily tasks either require much more effort, must be accomplished using assistive devices, or are not able to be performed as well and the individual's independence suffers. Therefore, any rehabilitation aimed at improving an individual's upper extremity motor control will have an immense impact on their daily life and independence.

The focus of this study is on movement ability, particularly upper extremity reaching motions. Upper extremity motor control has a widespread impact on activities of daily living and ability to live independently. While the intricacies involved in studying hand movements are also of considerable importance, in this study we focus solely on the overall movements of the arm (shoulder, elbow, and wrist) during reaching motions. The study of how persons complete reaching tasks will allow for an increased understanding of human motor control and eventually lead to improvements in rehabilitation practices. The aim of this research is to understand how reaching movements differ when the movement involves one or both arms, for different directions of movement, and for different locations in the movement workspace.

## 1.2 Control vs Future Populations

In studying these movements across the factors listed above, we are hoping to develop a better understanding of how motor control may differ between groups with movement impairment and healthy controls. The first step in this study involved developing a baseline for upper extremity reaching motions by testing a healthy control group. The control group

will serve future work as the group against which pathological groups are compared to understand what movement differences or deficits are present. Groups targeted for future study include multiple sclerosis, Parkinson's, and stroke.

The purpose of this research is to quantify different movement deficits that may arise due to Multiple Sclerosis (MS) or Parkinson's, and to understand how the motions of patients with MS or Parkinson's may differ from healthy controls. This research study has a long-term purpose of determining whether virtual reality can be used as an effective upper extremity rehabilitation tool.

### 1.3 A Review of Prior Research

Fully immersive virtual reality (VR) utilizes a headset and hand controllers to artificially display a virtual environment to its users. While it is primarily recognized as a mode of entertainment, is a technology with the potential to have non-gaming uses and applications. Specifically, it may be useful as a rehabilitation tool for those with upper extremity afflictions. This VR technology may be uniquely beneficial in rehabilitation due to the growing accessibility and at-home nature of VR systems, as well as their entertainment value. If VR can be shown to provide effective challenge and variety in movement tasks, then it can potentially provide rehabilitation benefit. This may result in a more engaging at-home rehabilitation option compared to simply completing movements or exercises in the real-world environment. Prior work suggests that therapy that includes virtual environments and games (such as Nintendo Wii) can yield effects akin to aerobic exercise, including increased heart rate (Bosch, 2012, Mellecker, 2008), particularly an increase in heart rate among Cystic Fibrosis (CF) patients that meets the required level for rehabilitation (Carbonera, 2016).

Multiple Sclerosis is a disease that leads to muscle atrophy similar to that which occurs from muscle disuse (Kent-Braun, 1997). Due to the similarities between muscle atrophy caused by MS and muscle atrophy caused by a lack of physical exercise, common treatments for MS involve some form of physical exertion (Mark, 2008, Ortiz-Rubio, 2016,

Scheidler, 2018, Taylor, 2006). Interactive gaming, or 2D VR, has been combined with gait training in rehabilitation measures for MS (Russo, 2018).

It is fairly common for stroke survivors to experience some impairment in the upper extremities (Williams, 2018). Therapy methods for post-stroke loss of mobility often incorporate some form of reaching or tracing task (Ho, 2019, Williams, 2018). 2D VR is effective as a therapeutic tool to restore balance after stroke (Llorens, 2015) and to imitate reaching or tracing motions required for rehabilitation (Ho, 2019).

Patients with Parkinson's disease will often perform motor tasks slower than control groups, particularly if multiple tasks are in sequential order (as opposed to stand-alone tasks) (Agostino, 1992). Physical exercise is supported as an effective countermeasure concerning areas such as physical functioning or strength in Parkinson's patients (Goodwin, 2008, Scandalis, 2001). Parkinson's patients have also been shown to respond positively to some 2D VR training (Mendes, 2012).

The 2D gaming methods utilized in these studies are less advanced versions of virtual reality technology, and immersive VR studies are not as common. 3D immersive VR (with a headset and hand controllers) as a therapeutic tool, specifically for upper extremity rehabilitation, has great potential and could be just as effective as 2D VR rehabilitation, if not more. Therapeutic motions, such as reaching or tracing, have been achieved in 2D VR (Ho, 2019), and similar motions can easily be achieved within immersive VR.

When studying movement ability in any population it is important to understand that the challenge level of a task is dependent on both movement ability and skill level (prior experience or training). A movement task at the appropriate challenge level will generate the greatest gains in learning and ability. Thus, in rehabilitation, the goal is to aim the exercises for a patient-specific challenge level to maximize learning (Guadagnoli, 2004). The utilization of immersive VR rehabilitation allows the attributes of the movement task and the person's performance to be easily recorded. Over time this would provide a method

for quantifying and tracking these challenge points for patients, allowing for greater efficiency and personalized approaches to rehabilitation.

Various conditions or afflictions have successfully applied dance rehabilitation, including cancer patients (Ho, 2005), multiple sclerosis (Scheidler, 2018), and cerebral palsy (Lopez-Ortiz, 2016). Thus, in addition to presenting the task in virtual environments we also included music alongside the presentation of the movement tasks. Like in dance, the participants performed movements in sync to the beat of the song. In prior work with dance programs, it is possible to modify various dance motions to suit the abilities of the patients and fit individual challenge points. This is particularly applicable to Beat Saber, the virtual environment used for this study's movement tasks. Much like in dance classes, Beat Saber aligns specified movements with the beat of a song. Motion capture data is collected as study participants perform these reaching movement tasks within Beat Sabers, creating a reaching movement database.

## **2. Methods**

### **2.1 Description of Movement Tasks**

The movement task assessed was a swiping or cutting motion of the endpoint (hand). Successful completion of the task required the end point to move to a certain location in the upper extremity workspace and travel through that portion of the workspace in a specified direction (along a line).

The upper extremity movement tasks in this study were categorized into 3 overarching trial types, based on the arm movements involved. For all trials both left arm and right arm tasks were be presented. The first trial type was unilateral testing, in which subjects perform motion tasks using one arm at a time, alternating in a randomized pattern. The second trial type was bilateral testing, which requires subjects to achieve the same task with both arms simultaneously. The final trial type was bilateral opposing testing, which requires subjects to perform tasks with both hands simultaneously, but with motion tasks that are presented in opposing directions.

Participants selected a song from several options to accompany the level. All songs had a steady BPM within the range of 119 to 139 BPM. Movement tasks aligned with the beat of the music and were spaced out evenly with 4 beats in between tasks. Movement tasks involved swiping motions directed in the 4 cardinal directions. These tasks were labeled as UP, DOWN, IN, and OUT. Where IN was a movement toward the centerline of the body and OUT was a movement away from the centerline of the body regardless of the arm used.

Movement tasks were located within a 2x4 grid within the virtual environment, shown in Figure 1. This grid was located with the center of the bottom row at approximately elbow height for the subject and the center of the top row at shoulder level. The two leftmost columns presented tasks only for the left hand, while the two rightmost columns presented tasks only for the right hand. None of the movement tasks involved crossing the medial line, however this can be easily added in future study. Movement tasks were color coded to distinguish left arm tasks (red) from right arm tasks (blue). Tasks within the two inner columns were differentiated as “medial” tasks. Tasks within the two outer columns were labeled “lateral” tasks.

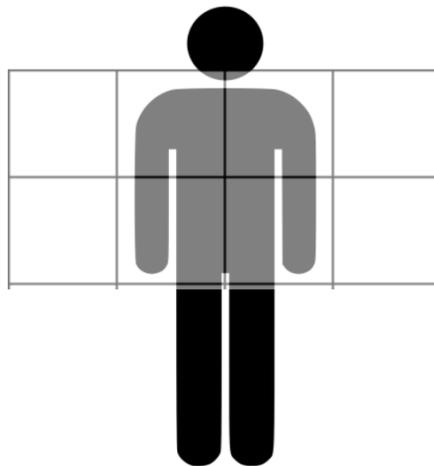


Figure 1: Approximate Positioning of Virtual Movement Grid

## 2.2 Data Collection Procedures

All procedures were approved by the university IRB.

For the baseline study, 16 healthy participants (9 Male 7 Female, aged 21.9 years) were consented to participate. The long-term continuation of the study will also include up to 20 participants with MS and 20 participants with Parkinson's. Participants were required to complete the Basic Health Questionnaire and a basic visual acuity test with a Snellen Eye Chart read from 20 feet to confirm that the inclusion and exclusion criteria were met.

Movement data was collected using an XSens MTw Awinda System. The XSens system included 17 inertial measurement units in the full body setup. Sensors were placed on the head, sternum, both shoulders, pelvis, lateral upper arms, lateral forearms, hands, lateral thighs, lateral shanks, and feet. Body measurements were also taken of the knee height, hip height, hip width, shoulder height, shoulder width, wingspan, wingspan distance between wrists, wingspan distance between elbows, and overall height. These measurements were then used to appropriately size the motion capture avatar as well as the body segments within the data analysis software (Visual 3D, C-Motion).

After sensors were placed, subjects completed a brief calibration procedure. Participants were instructed to stand in a starting pose with both arms and legs straight and head facing forward. Participants then performed a predetermined amount of walking. The accuracy of the final calibrated body model was then verified by having the participant first touch their hands together in front of them and then to their chest. This informal procedure indicated the validity of the model's arm positioning. A brief UE range of motion test was then performed to record participants' starting abilities. This test was repeated upon completion of all movement trials.

The VR system used to create the virtual environment in the study is the commercially available HTC Vive Pro. The headset uses AMOLED display with a 90Hz refresh rate, 110-degree field of view, and synchronized audio. Study staff assisted participants in adjusting the headset fit to allow a clear display of the virtual environment.

After fitting the headset properly and placing the participant in the virtual environment, a brief tutorial was completed to introduce participants to the movement tasks used in the Beat Saber trials. Participants were in a standing position during the data collection trials, although the option to sit during data collection is available for those that may request to do so. Participants were instructed to return to a resting position with their arms straight and by their sides in between each movement task. This starting position was used during the tutorial as well as during the data collection trials.

Upon successful completion of the tutorial, participants began the 6 movement trials. Each trial contained 72-96 tasks, depending on the category of trial (unilateral, bilateral, and bilateral opposing). Movement task combinations within the trials were presented in an overall randomized order but any particular task combination (ex: right hand, medial high position, inner direction task) was repeated 3 times sequentially. Participants completed the three categories of trials in a randomized order with breaks as needed, and then completed those three trials again with a different randomization pattern.

Following each completed trial, participants completed the NASA Task Load Index to record participant perception of the difficulty of the preceding trial with respect to mental demand, physical demand, temporal demand, performance, effort, and frustration.

### 2.3 Analysis Procedures

Biomechanics software (Visual 3D, C-Motion) was used to further analyze segment motions and determine joint angles for the shoulder, elbow, and wrist. Wrist extension was defined as movement of the back of the hand towards the forearm in the sagittal plane (Figure 2). Medial and lateral deviation was defined as wrist movement in the frontal plane. Shoulder flexion was defined as arm movement in the anterior direction, which is represented as a positive joint angle.

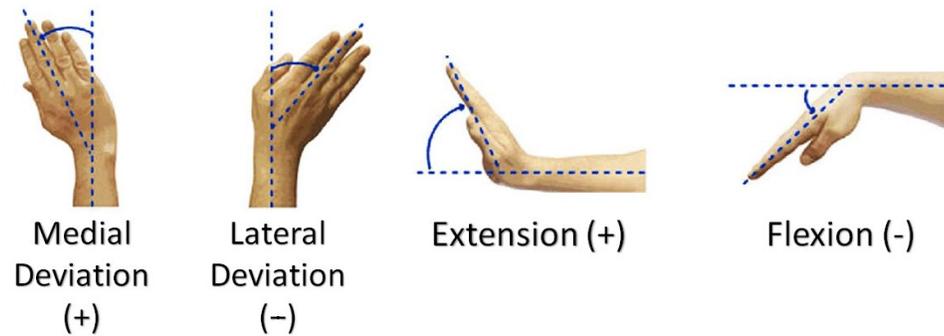


Figure 2: Joint Movement Definitions and signs  
*(edited from Krawczyk et. al. 2018)*

Trials were divided into “beat profiles,” with the approximate completion of the motion tasks located in the center of the profile. Beat profiles were tagged according to which hand performed the motion, which height the task was positioned at, the horizontal position of the task, and the direction in which the task was oriented. Several metrics were then collected from within each beat profile. Metrics that were gathered included maximum shoulder angle in the sagittal plane, maximum and minimum wrist angles in the frontal and sagittal planes, maximum velocity of the hand throughout the motion, and velocity of the hand at the center of each beat profile.

Unilateral datafiles were processed for 10 of the 16 subjects that participated in data collection. Beat profiles were found for all reaching motions within the 10 selected unilateral trials.

All statistical processing was performed with commercially available statistics software (NCSS v.2020). A repeated measures ANOVA was used with significance set at alpha ( $p$ )  $< 0.05$ . The within factors examined were Vertical Position with levels of High and Low, Horizontal Position with levels of Medial and Lateral, and Direction with levels of Up, Down, In, and Out. Tukey Kramer post hoc testing was used to determine significance between levels of the Direction factor. There were no between factors. Ten subjects were included, each contributing 96 left hand data points and 96 right hand data points. For the group overall, 54 data points were included for each possible combination of factors/levels.

### 3. Results

Statistical analysis was performed for the ten control participants for the Unilateral movement tasks. Left and right arm outcomes were assessed separately. Summary of results for the wrist, shoulder, and velocity metrics can be found in Table 1.

**Table 1:** Statistical analysis of metrics, with significant factors in bold

		Vertical Position		Horizontal Position		Direction	
		p (significance)	P (power)	p (significance)	P (power)	p (significance)	P (power)
Wrist Extension	Left	0.251	0.209	0.924	0.051	<b>0.000</b>	1.000
	Right	<b>0.000</b>	0.978	<b>0.006</b>	0.785	<b>0.000</b>	1.000
Wrist Flexion	Left	<b>0.032</b>	0.573	<b>0.010</b>	0.729	<b>0.000</b>	1.000
	Right	0.818	0.056	<b>0.000</b>	0.988	<b>0.000</b>	1.000
Wrist Medial Deviation	Left	<b>0.000</b>	0.998	0.274	0.194	<b>0.000</b>	1.000
	Right	<b>0.000</b>	0.983	0.054	0.486	<b>0.000</b>	1.000
Wrist Lateral Deviation	Left	<b>0.000</b>	0.999	0.052	0.495	<b>0.000</b>	1.000
	Right	<b>0.000</b>	0.999	0.237	0.219	<b>0.000</b>	1.000
Shoulder Flexion Maximum	Left	<b>0.000</b>	1.000	0.529	0.096	<b>0.000</b>	1.000
	Right	<b>0.000</b>	1.000	0.168	0.281	<b>0.000</b>	1.000
Hand Velocity at Beat	Left	<b>0.002</b>	0.860	0.755	0.061	<b>0.000</b>	1.000
	Right	0.886	0.052	0.686	0.069	<b>0.000</b>	1.000
Hand Velocity Maximum	Left	<b>0.000</b>	1.000	0.592	0.083	<b>0.000</b>	1.000
	Right	<b>0.000</b>	1.000	0.577	0.086	<b>0.000</b>	1.000

#### *Factor: Direction*

Direction was found to be a significant factor across all metrics for both left and right hands, with  $p=0.000$  and  $P=1.000$  for all metrics and levels.

#### *Factor: Horizontal Position*

The factor of Horizontal Position of the movement tasks (Medial/Lateral) was significant in regard to wrist flexion for the left and right arm,  $p=0.010$ ,  $P=0.729$  and  $p=0.000$ ,  $P=0.988$

respectively. Horizontal Position was also significant for wrist extension of the right arm, with  $p=0.006$  and  $P=0.785$ , but was not significant for the left arm.

*Factor: Vertical Position*

The factor of Vertical Position of the movement tasks was also significant for most metrics, excluding left-hand wrist extension, right-hand wrist flexion and right-hand velocity at beat. Vertical Position for right-hand wrist extension was significant with  $p=0.000$  and  $P=0.978$ . Left-hand wrist flexion Vertical Position was significant with  $p=0.032$  with a lower power;  $P=0.573$ . Vertical Position for left and right medial wrist deviation was significant, with  $p=0.000$  for both and  $P=0.998$  and  $P=0.983$ , respectively. Vertical Position was significant for left and right lateral wrist deviation, with  $p=0.000$  and  $P=0.999$  for both hands. Vertical Position was significant for shoulder flexion for both left and right arms, with  $p=0.000$  and  $P=1.000$ . Vertical Position was also significant for left hand beat velocity ( $p=0.002$ ,  $P=0.860$ ), as well as for left and right maximum hand velocities (both  $p<0.001$ ,  $P=1.000$ ).

*Average Range of Motion*

Average range of motion for the control group was also determined and can be viewed in Table 2. This gives the average maximum and minimum joint angles for each type of joint movement (wrist flexion, extension etc.) for each factor/level. The most extreme joint angle values are highlighted in each row.

Table 2: Average Range of Motion for Healthy Controls

	High	Low	Lateral	Medial	Down	In	Out	Up
Wrist Extension	31.5	33.1	32.7	31.9	36.7	34.9	26.1	31.6
Wrist Flexion	-7.7	-6.9	-8.7	-5.9	1.1	-17.6	-7.6	-5.1
Wrist Medial Deviation	24.3	22.0	23.3	23.1	21.5	24.8	20.3	26.0
Wrist Lateral Deviation	-9.4	-12.2	-11.3	-10.3	-19.7	-4.0	-6.7	-12.8
Shoulder Flexion Maximum	48.1	33.9	40.8	41.2	39.8	36.9	39.0	48.4

Movements that are oriented in the Down direction were found to produce the highest amounts of wrist extension, while movements oriented in the In direction produce the most extreme amounts of wrist flexion. Up movements generally incite the most wrist medial deviation, while “down” movements incite the most lateral wrist deviation. Up movements also tend to encourage the most shoulder flexion, at 48.4° of flexion. It should also be noted that movement tasks that are positioned on the top row of the virtual movement grid tend to also produce a comparable amount of flexion at 48.1°, which is considerably more than movements that were presented on the lower row of the movement grid.

#### 4. Discussion

The Vertical Position at which the movement tasks were presented had a significant effect on most joint angles achieved during motions. The effect of movement task Vertical Position on joint angles may be attributed to the increased distance between the starting position (arms at sides) and the final objective. Because the hand must travel a greater distance to achieve the motion, the participant must compensate their motions with more exaggerated joint angles and velocities. Any difference in significance of Vertical Position between left and right sides could be due to differences in the dominant hand of the control

subjects, however further study would be required and conflicting outcomes for motions such as wrist extension and flexion should be treated as inconclusive.

The beat profile of a control group subject, which can be considered representative of the joint angle profiles of most control group participants, is shown in Figure 3. Graphs for S08's beat profile were found to be representative of most beat profiles within the baseline study and will be used for any of the following motion examples within the discussion section. This profile shows shoulder flexion angles for IN motions, where the red line represents the mean of the 6 left arm movements within that subject's data trials and the blue line represents the mean of the 6 right arm movements.

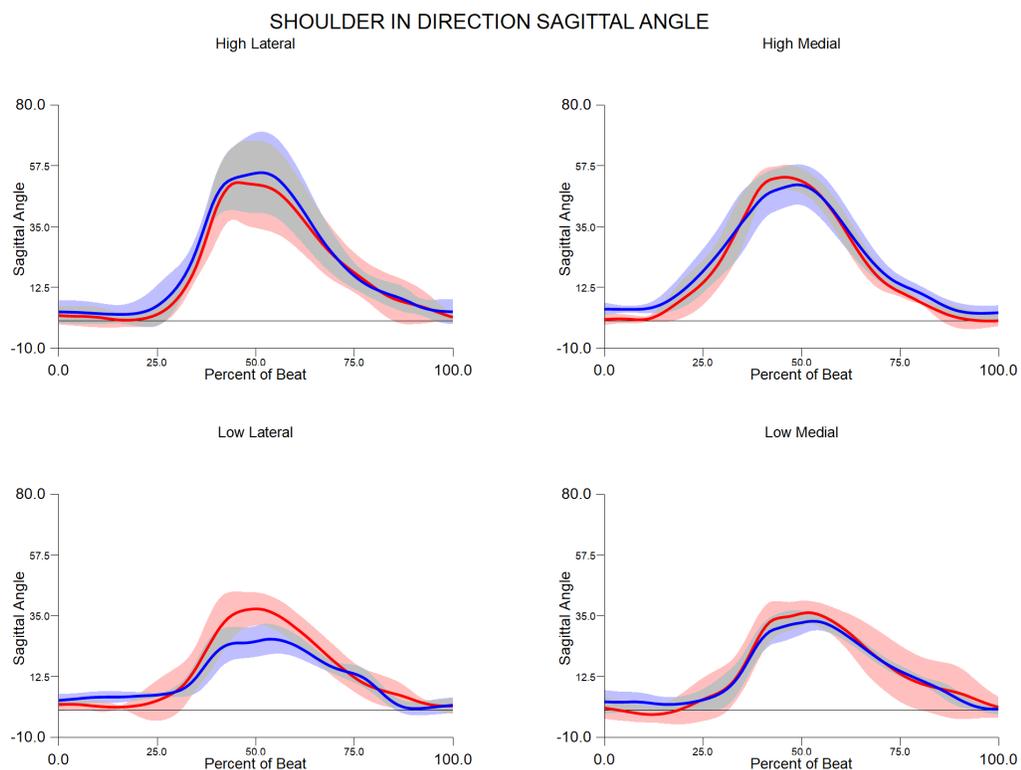


Figure 3: S08 Sagittal Shoulder Angle, “In” Direction Joint Angle Profile  
*Red represents mean and STDev for the left arm, blue is right arm*

As can be observed within the joint angle profiles, this subject achieved a higher average shoulder flexion for the same tasks at the High level (shoulder height) compared to the

Low-level (elbow height). Visually, the joint angle profiles of High-level tasks demonstrate more extreme shoulder flexion angles than the Low-level tasks, supporting the conclusion that Vertical Position plays a significant role in the extent of joint angles within similar motions. In Figure 2 and in general, participants attained a max joint angle near the middle of the movement task (50% point). Also, the left and right arms had very similar movement patterns which was anticipated as the control group does not have any major pathological differences between their arm movement ability.

The factor of Horizontal Position (medial/lateral) is not indicated as significant for most joint angles (Table 1). Examination of individual movement profiles (Figure 3) supports this conclusion, showing minor visual differences between medial and lateral beat profiles at either Vertical Position. However, Horizontal Position was suggested to be a significant factor for wrist flexion and potentially wrist extension.

The factor of Direction was significant for all joint angle metrics and for both left and right sides. This may be contributed to the required differences in approach patterns for various direction of movement tasks. When all else is kept the same, differences in movement task direction will require participants to approach the movement tasks from entirely different locations, altering the motion involved in the preparatory phases of the motion, the execution of the motion, and returning to the starting position.

A sample from an individual participant (Figure 4) illustrates the frontal wrist angle (medial and lateral deviation of the wrist) during movements in the high lateral location for the 4 different movement orientations (Up, Down, In, Out). When comparing the opposing task directions of Up and Down, the beat profiles appear to be mirrored. This is due to the start and end positions of the two movements being switched, which flips the order that the motions occur in.





rehabilitation task set if a certain joint movement has a deficit. We also expect that certain pathological groups will have differences in the range of joint motion or in what joint movements are expressed for particular movement tasks.

## 5. Conclusion

If proven to be an effective upper extremity rehabilitation method, virtual reality and Beat Saber could greatly advance the current state of at-home rehabilitation. If successful, these methods could provide a fun, engaging, and effective at-home rehabilitation option for individuals with conditions that affect their upper extremity motor control. These methods could be life-changing for patients that are unable to attend regular in-person rehabilitation visits, or individuals that aren't particularly motivated to complete standard rehabilitation movements unless there is the added benefit of a game.

The average range of motion for baseline subjects has the potential to be an incredibly helpful tool for assessing movement ability within impaired populations and personalizing rehabilitation approaches based on individual need. Specifically, the intended outcome is to determine which motions are strong for any given participant and which motions require increased intervention. Using this knowledge, we then hope to design personalized and targeted rehabilitation interventions that target specific motor control deficiencies. This individualized movement knowledge will also be beneficial in providing another method of tracking and quantifying individual improvements or changes in movement abilities.

These reaching motions also have the potential to be individualized, allowing patients and their physical therapists to focus more effort on specific motions and personalize their rehabilitation plan. Using the baseline statistical analysis data and average range of motion, algorithms can be developed to create patient-specific Beat Saber programs based on previously demonstrated movement deficits. The algorithms will allow physical therapists to create and assign personalized Beat Saber programs with a focus in movement tasks that are shown to encourage increased movement in the joint motions that require additional repetition and practice.

The utilization of VR as an at-home rehabilitation tool sounds like a lofty and unattainable goal, since VR is still an uncommon technology in most households. However, background research into the topic shows parallels between the past development of “Wii-habilitation” for at home-rehabilitation purposes and the future that virtual reality rapidly seems to be approaching.

Virtual reality is becoming increasingly accessible to the general public, through one variation or another. Whether users implement a cardboard headset or a high-end VR system, it is necessary to realize the potential of this rapidly developing technology. Research such as the kind described above takes time to complete, so it is important to begin studying these possibilities now so that these life-changing methods are ready and available by the time that VR becomes a common everyday technology.

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