ABSTRACT

Quality Assessment of Limb Tracking within a
Therapy-Based Exergaming System

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The use of exercise-based video games (exergaming) in physical therapy can improve rehabilitation outcomes. A clinically useful exergaming system requires precise motion tracking and accurate determinations of the correctness of the performed exercise. In this study, both elements were analyzed for a custom exergaming system using Kinect and a custom game, Vitalize. Using a large number of exercises, broad trends about the tracking abilities of a Kinect-based system were discovered: (1) Kinect performs significantly better in the frontal plane than in the sagittal plane; (2) error and variance are both positively correlated with range of motion in the sagittal plane; and (3) every exercise has a unique error profile for each joint involved. In this study, reference tables of errors specific to joint and exercise were created and a custom exergaming software was shown to accurately identify correct motions for use in clinical exergaming applications.

Quality Assessment of Limb Tracking within a Therapy-Based Exergaming System

by

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A Thesis

Approved by the Department of Mechanical Engineering

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Submitted to the Graduate Faculty of
Baylor University in Partial Fulfillment of the
Requirements for the Degree
of

Master of Science in Biomedical Engineering

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December 2016

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ACKNOWLEDGMENTS

I would like to first thank my advising professor Dr. Jonathan Rylander. I greatly appreciate his support and guidance; I'm also deeply appreciative of his willingness to be flexible with me as Eric and I were married, had Lillia and moved across the country in the time I was working on this project. Thank you.

I would also like to thank Dr. Chris Rábago for the vital work he did in the origination and previous phases of this study. Without the work completed at the CFI this research would not have been possible. I would also like to thank Alex Wiley, Jenifer Whitehead and Kelly Rodriguez for the work they did in setting up the initial coding in Visual 3D and Matlab and for collecting the amputee data for the next phase of the study.

I thank all of the undergraduate students in the Biomotion Lab at Baylor who have worked on this project. Di Lu and Zach Hostetler, thank your help with data collections. Danny Spaulding, thank you for your work on the software decisions analysis. Grant Drewelow, thank you for your work in compiling the error tables. Tyler Jost, thank you for so willingly giving your coding expertise to this project. Marie Smith, you have been a great friend; thank you for your help with data collection, coding, data processing and presenting this project at the ORS conference while I was having Lillia.

Finally, I must express my very profound gratitude to my husband, Eric, for giving me constant encouragement and support through the high points and low points of this project over the last two years. Thank you for encouraging me to keep going when I didn't want to; thank you also for taking care of Lil so I could focus on finishing up analysis and writing. This wouldn't have happened without you. Thank you.

CHAPTER ONE

Introduction

Physical Therapy and the Home Exercise Program

According to the American Physical Therapy Association, physical therapy seeks to optimize movement to improve the health of society. This involves evaluating and managing an individual's movement system to both identify and improve activity and participation restrictions. Physical therapists offer a unique outlook on purposeful, precise and efficient movement by combining their knowledge and expertise of the human movement system. They examine and evaluate movement to create a personalized care plan to help the patient achieve their desired goals. Physical therapy uses movement-related interventions to maximize the patient's functional capacity and performance [1], [2].

Approximately 50% of American adults suffer a musculoskeletal injury that lasts over three months [3], resulting in 150 million people annually who could benefit from physical therapy. A condition that requires extensive physical therapy and retraining is an amputation. Nearly 1800 service members returning from fighting in the Middle East now live with at least one amputation [4]. These service members have to relearn many tasks of everyday life; physical and occupational therapy are very important for their rehabilitation.

However, the number of clinical visits physical therapists are able to provide to a patient is limited by insurance companies. Home exercise programs (HEPs) are used by physical therapists to extend the therapy into the patient's home and spare the clinical visits; they consist of therapeutic exercises to increase the range of motion and muscle strength and to decrease pain. These programs are taught to the patient in the clinic and often given to the patient in written form to complete at home between clinic visits. Studies comparing HEPs to clinic treatment have shown that home exercise programs increase the functional capacity of patients, but not as much as clinical treatment [5], [6]. One clinical trial has shown that after four weeks of treatment, a 26% improvement was seen in the group using home exercise programs; whereas a 52% improvement was seen in the control group receiving clinical physical therapy [6]. Because of the limited number of clinical visits allowed by insurance, physical therapists must use HEPs; but there are limitations in the effectiveness of HEPs as compared to in-clinic therapy. Research is needed to improve the effectiveness of HEP.

This project was developed to support the rehabilitation of wounded warriors as they move from initial injury to living an active daily life by researching, designing, developing and testing an exercise-based video game for use as an HEP. The design and development of the video game, Vitalize, was conducted by Blitz Games Studio (Lemington Spa, UK) with funding from US Army Medical Research and Material Command Award Number W81XWH-11-C-0066 in collaboration with Blue Marble Game Company (Los Angeles, CA) and the Center for the Intrepid (CFI), Brooke Army Medical Center, JBSA Ft. Sam Houston, TX. The initial validations of motion tracking were started at the CFI under Christopher A. Rábago, PT Ph.D. and Jason Wilken MPT, Ph.D. The focus of this thesis research is to determine the tracking accuracy of the Vitalize exergaming system. While this project was developed for the benefit of wounded warriors, the findings presented in this research extend beyond that population to the broader use of motion capture-based exergames to improve the effectiveness of HEPs within physical therapy.

Challenges of the Home Exercise Program

The HEP is widely used because of the limited number of clinic visits allowed by insurance; however, the positive outcomes from using an HEP were lower than the outcomes from clinical therapy [6]. This is likely due to the most prominent challenge of the HEP, compliance. The success of physical therapy, and especially with the HEP depends greatly on the commitment and motivation of the patient performing the exercises [7]. Research suggests that inadequate adherence to the HEP may decrease the effectiveness of the treatment [8], [9]. It is widely acknowledged that patient compliance with a home exercise program is typically low [10]–[14]. Physical therapists have estimated that up to 77% of their patients are not compliant with their prescribed program [12]. Such a high rate of noncompliance is concerning because correct adherence to prescribed therapy regimes is essential for safe and effective therapy [15].

Types of Noncompliance

There are different types of noncompliance; three categories are considered here. The first type of noncompliance is the patient not performing the correct dose. This includes the patient not performing the correct number of repetitions per set of an exercise; not performing the correct number of sets of an exercise; not performing the exercises the correct number of times per day; or not performing the exercises the correct number of days per week.

Another type of noncompliance is the patient not performing the exercises correctly. There are two primary parts of correct exercise performance: range of motion and body positioning. If the patient performs the exercise with incorrect range of motion or incorrect body positioning it can be classified as not being compliant with the prescribed exercise regime.

The last type of noncompliance referenced here is the patient not performing the exercises at all. This is the type of noncompliance that is most commonly referenced. It is likely due to the patient not wanting to complete their exercises.

Reasons for Noncompliance

There are several possible reasons for the high reported rates of noncompliance with home exercise programs; one of which is poor memory of exercises. This could result from the patient not remembering which exercises were prescribed to them and in what dose. It could also result from the patient not remembering how to correctly perform the exercises they were taught in the clinic.

Another possible reason for the high rates, especially with the noncompliance due to not performing the exercises correctly, is the lack of external feedback during the home exercise program. In the clinic, the physical therapist tells the patient if the exercises are being performed correctly or not. During the HEP, the patient does not receive any outside feedback as to whether they performed the exercise correctly or incorrectly.

A third possible reason for high noncompliance rates during the HEP is a lack of patient motivation, the patient simply not wanting to complete the exercises. This lack of patient motivation is intensified by the lack of accountability. In the clinic, the patient is directly accountable to the therapist for completing the assigned exercises. However, for the HEP, the physical therapists must rely on the patient's report on whether the exercises were completed. This is concerning because either failing to perform the exercises or performing them incorrectly will not help the patient's rehabilitation and may lead to additional injury.

High noncompliance rates are concerning for the effectiveness of treatment and ultimately the success of the patient's rehabilitation. The addition of exergaming to the home exercise program may increase patient compliance with their prescribed exercise regime.

Exergaming and the Home Exercise Program

Exergaming is a portmanteau of exercise and gaming; in short it can be defined as video games that require physical exercise [16]. These exergames are controlled by the user's motion either through a motion-sensitive controller or through tracking of the user's body. In the last several years there has been much interest in using exergames to augment physical therapy [15], [17]–[22].

Benefits of Exergaming

One of the primary attractions of using exergames in therapy is that the games have the ability to increase patient motivation by introducing an element of entertainment into the home exercise program. This leads to more enjoyment of therapy which leads to improved adherence to the prescribed therapy regime [22]. But there are several additional benefits to using exergames in therapy.

Software Instructs Execution of Exercises. One advantage is the ability to create and use specialize software which would allow the physical therapist to manipulate the game to target specific movements. The physical therapist selects exercises to be included and the software instructs the patient how to correctly perform the exercise. This will likely improve compliance because the patient is actively being instructed how to correctly complete the exercise; thus diminishing the noncompliance due to incorrect performance of exercises.

This introduces the idea that the physical therapist may be able to program the exergame software to specialize the therapy for their specific patient at the exact point in their rehabilitation, which greatly increases the effectiveness of using the exergame in the HEP.

Physical Therapist Assigns Correct Dose. By using the exergaming software to assign the HEP, the patient has much less responsibility about remembering the correct dose. The physical therapist can program the desired number of repetitions and sets into the exergame. This ensures that by simply playing the exergame, the patient will perform the correct dose of exercises for that day. The patient will need to remember to play the game a certain number of times per week, but otherwise the game will take care of all the exercise dosages.

Immediate Feedback about Correctness of Motion. An exergaming system at the patient's home will be able to facilitate proper performance of the exercise by providing continuous feedback during the HEP [15]. This is important because it is crucial that the patient not only performs the exercises, but does so correctly. Accurate decisions made by the exergame regarding the correctness of motion will provide the external feedback that is otherwise lacking during the home exercise program. Positive, immediate feedback given by the exergame may also help to keep the patient involved and interested in the therapy [20].

Physical Therapist receives Report. Traditionally the only quantitative gauge of the effectiveness of a home exercise program available to the therapist is the improvement from one clinic visit to the next. With the use of an exergaming system, data about the correctness and completion of exercises can be collected during the HEP and made available to the physical therapist. This will give the therapist the ability to correct errors in exercise performance and view the patient's adherence to the HEP [20]. The therapist will easily be able to discern if and how well the patient performed their home exercise program.

An additional benefit of the therapist receiving this "report card" of the exercises completed with the HEP is that it increases patient accountability which could further increase patient compliance.

Clinical Studies

Studies incorporating exergames into physical therapy, both in-clinic [23], [24] and as part of an HEP [25], [26], show positive results. Figure 1, on the next page, is from a study that complemented traditional physical therapy with exergames using the XBOX Kinect [23]. The subject represented in this case study has severe cerebral palsy and participates in regular rehabilitative therapy.

During the baseline phase, the therapist instructed the participant and ensured correct movements; then the subject completed 10 repetitions for each of three movements without correction from the therapist. During the intervention phase, the subject completed the same repetitions taking cues from the prescribed exergame. It is easily seen that the number of correct movements greatly increased when physical therapy was augmented with the Kinect.

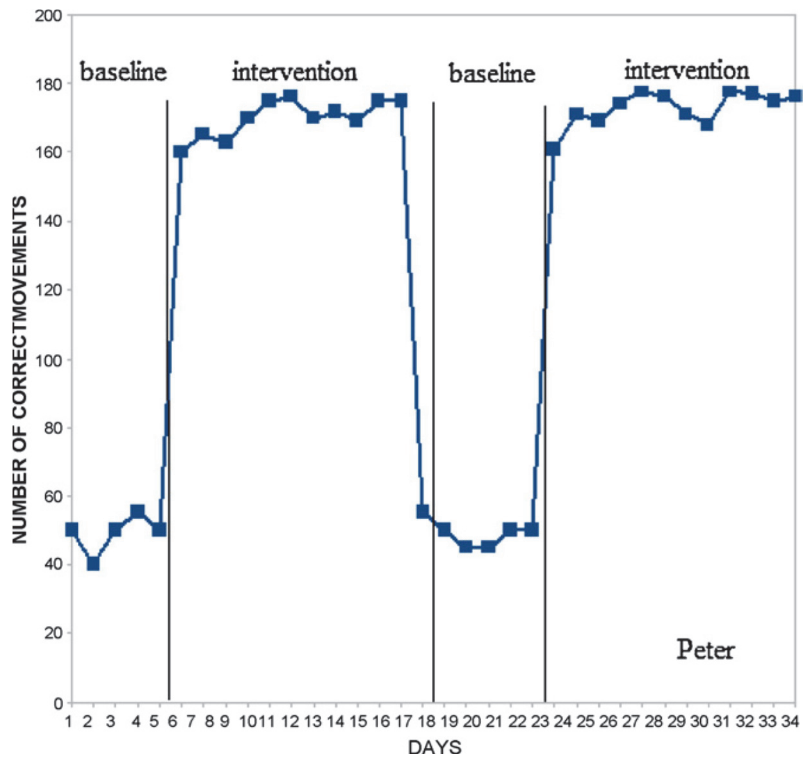


Figure 1. Results of a Clinical Study: Correct Movements in Therapy augmented with an Exergaming System [23]

This study clearly showed that when the exergame intervention was being used patient motivation was increased which improved exercise performance. This type of augmented therapy during home exercise programs may be particularly impactful for a population of young, previously highly active patients such as wounded warriors. It is likely that a nearly instantaneous change from a very active life to prescribed therapy being the only physical activity leads to frustration and noncompliance with prescribed therapy.

Exergaming Hardware and Software

Hardware and software are the two components to consider in an exergaming system. The hardware is the physical gaming console that is used to play the game; the software is the game that is being played. They correspond to the two critical elements for clinical use of an exergaming system. The system must be able to accurately track the motion, which is primarily a hardware issue. It must also be able to decide if the motion was performed correctly, a software issue. Both of these conditions must be met before exergaming systems are used clinically.

Hardware

There are currently three competitive motion-based video game hardware systems on the market: the Nintendo Wii, the PlayStation MOVE and the XBOX Kinect. Both the Wii and MOVE require the user to move a controller; the system tracks the motion of the controller which translates into the motions in the video game. The Kinect has no controller. Instead, the Kinect makes use of a simple motion capture system which uses the body of the user as the controller for the video game. In the context of rehabilitation, the Wii and MOVE are not viable options because they do not require or register any motions of the lower body. The Kinect is more difficult to "trick" into thinking the correct motion was completed because it tracks the entire body. Microsoft, which owns XBOX, has publicly released the drivers for the Kinect and has provided a free developer kit and full programming support [27], which provides additional incentive to choose the Kinect because it enables programmers to easily use the Kinect in nontraditional ways. This study uses the Kinect for XBOX 360 as the hardware for the exergaming system.

Software

Quickly after starting to use exergames in physical therapy, it was discovered that off-the-shelf games were not suitable; standard games for the Kinect console were too difficult for patients to perform and lacked the flexibility required in physical therapy [28]. This highlights the need for custom exergaming software for use in physical therapy. There are many benefits to creating a specialized exergame software, the primary one being the ability to highly specialize the game for the specific patient's exact point in their rehabilitation. The exergames can also be customized for a specific patient demographic and their interests, which may further increase patient compliance with prescribed therapy. There have been several studies into developing and testing games for clinical use [7], [29]–[31]. A custom game should include the ability to choose which exercises should be performed and to set the sensitivity of the game to avoid patient frustration. Ideally, the game will also decide if the motion was performed correctly in order to provide immediate feedback to the patient. This study uses a custom exergaming software, Vitalize.

Current State of Research

The academic community quickly recognized the potential of the Kinect technology as a medical tool. Since its debut in 2010, many researchers have explored the accuracy of the Kinect in the context of clinical rehabilitation [15], [19], [32]–[42]. Most studies performed have compared the performance of the Kinect to a marker-based system, which is commonly considered the gold standard in motion capture.

Two validation studies that determined the accuracy of the Kinect by using manual measurements were referenced [19], [33]. Mobini et al. [19] used a 2-dimensional wooden model of the upper body and found that the Kinect's estimation of joint centers was between 1 and 2 cm; this is an extremely simplified model, but shows the high potential of the Kinect. Bonnechère et al. [33] physically measured the body segments of their subjects and found excellent reproducibility by the Kinect, but that the accuracy of this system depends on the segment being studied.

Research has also been performed studying the suitability of the Kinect for use in gait analysis [34], [40], [41]. These studies do not agree which aspects of gait can be accurately collected by the Kinect. Clark et al. [34] reports that the temporal measurements of gait were the least valid. Interestingly, as a result of their research, Pfister et al. [40] states that the Kinect is not accurate enough for clinical analysis with the possible exception of the same temporal gait measurements. The study done by Xu et al. [41] found that the Kinect follows motion trends well, but lacks the ability to accurately measure magnitudes of motions. There is significant disagreement among these studies, but they all conclude that the Kinect displays varied levels of accuracy for different gait parameters.

Several validation studies have considered the accuracy of the Kinect with respect to specific motions, often related to the rehabilitation of a specific condition [32], [35], [36], [38], [39]. Bonnechere et al. [32] performed a study with 48 able-bodied subjects using four simple motions; it was found that the difference between the Kinect and the marker-based system was within 11 degrees with less error in the upper body than lower body. Galna's study [35] used a mixture of able-bodied subjects and patients with Parkinson's disease. This study concluded that the Kinect can accurately measure timing and gross spatial characteristics of motion, but lacks the accuracy to correctly report smaller motions. Kuster et al. [36] is one of the early validation studies using the KinectOne; they reported average error for shoulder motions under five degrees, but also found large discrepancy between the accuracy of tracking the shoulder and the trunk.

It can easily be seen that there is much interest in validating the Kinect for possible clinical use. However, researchers are not in agreement because the validation results have been widely varied depending on the motions used and the joints analyzed. This highlights the need for a comprehensive study that uses a large number of therapeutic motions to discover broad trends in the tracking abilities and limitations of the Kinect to determine which motions and which joints can be tracked with enough accuracy for clinical use.

Purpose

The purpose of this study was to determine the tracking accuracy and limitations of a single depth camera exergaming system. Motion capture data from a large number of exercises was collected and analyzed with the goal of making a comprehensive reference database of errors associated with the various body segments and exercises. This will inform both exergaming software developers and clinicians of which exercises perform well in a simple depth tracking system and which exercises have large error associated with the system and so should not be assigned for home exercise programs. Analysis of the database was initiated to determine trends in the accuracy of the Vitalize system. The following are the primary aims of this research:

Aim 1: Effect of plane of motion on error. Is there more error associated with motions that are primarily in the frontal plane versus motions that are primarily in the sagittal plane? It is hypothesized that the Vitalize system will perform better in the frontal plane than in the sagittal plane because there is no depth measurement required for frontal plane motions.

Aim 2: Effect of range of motion on error. Does the range of motion of an exercise have an effect on the error associated with that exercise? If so, what is the effect and when is it observed? It is hypothesized that the range of motion will not have an effect on the tracking accuracy of the system; as reported in previous research [32], [36], [38].

Aim 3: Effect of the involved joint in the motion on error. Does the Vitalize system's tracking ability depend on which joint is being tracked? Are hip motions tracked with more accuracy than shoulder motions? It is hypothesized that there will be minimal differences between the tracking accuracy of various joints.

Aim 4: Effect of complexity of motion on error. Does the tracking error associated with a specific joint during an exercise increase when additional components are added to the exercise? It is hypothesized that adding complexity will not have an effect on the error of the primary joint involved in the exercise.

Aim 5: Observations on the Decision made by Vitalize. How does Vitalize decide if a motion was performed correctly? Are those decisions clinically valid? It is hypothesized that the Vitalize software will occasionally reject a correct motion, but that it will perform well in making these decisions.

CHAPTER TWO

Methods

This study was completed in collaboration with the CFI. Institutional Review Board approval was given at Baylor University ("Multiple Plane Motion Tracking Quality Assessment of a Therapy-Based Exergaming System." Protocol Number: 755134-5. Principle Investigator: Jonathan Rylander, Ph.D.) and Brooke Army Medical Center ("Vitalize - Game Based Wellbeing Research Initiative", Protocol Number: C.2011.057, Principle Investigator: Jason Wilken, MPT, Ph.D.). Two motion capture systems (Vitalize and Vicon) simultaneously collected the exercise data; the Vitalize exergaming system was compared to the Vicon marker-based system which was used as the gold standard. The Vitalize data was collected from the Kinect sensor through the custom Vitalize software. The Vicon data was collected using a passive marker-based system and the Nexus software; then the model was created in Visual 3D. The two datasets were time-synced together to directly compare the repetitions. Any difference between the datasets was reported as error of the Vitalize system. After creating an error database, analyses addressing each aim of this study were completed.

Subjects

Data from 15 able-bodied, adult subjects was collected at the Baylor University BioMotion Lab at the Baylor Research and Innovation Collaborative. A homogeneous subject group was selected to control for variation in the tracking ability of the Kinect sensor due to body type. Of the subjects, 7 were female; the average age was 22.6 years with a standard deviation of 3.5 years; the average BMI was 22.1 with a standard deviation of 2.3. All of the subjects gave their informed consent. All were able to maintain moderate, intermittent physical activity for an extended period of time and had no condition or prior injury which would potentially alter normal motion. Matching clothing was provided for all the subjects at Baylor because it is unknown how different clothes affect the accuracy of the Kinect sensor. All the subjects wore small black shorts and a black tank top that was tucked up to expose the lower torso; subjects wore their own running shoes. Figure 2 shows an example of the clothing used.

Figure 2. Example of the clothing worn during collections by all subjects

Data from 1 able-bodied and 8 disabled adult subjects was collected at the CFI. Of these subjects, 1 was female; the average age was 30.6 with a standard deviation of 4.1 years; the average BMI was 26.4 with a standard of deviation of 4.4. These subjects gave their informed consent. The disabled subjects had varied degrees of limb salvage and amputations. The amputee data has been collected but not yet analyzed. Though this study was designed for an amputee population, it was decided that additional research was needed to validate the performance of the Vitalize system in a more controlled way by using able-bodied subjects before adding the variability of amputee subjects. Research into the data from the amputee group will include the influence of carbon fiber limbs and body asymmetry on the tracking ability, but a solid understanding of the abilities of the system with able-bodied subjects was needed before that analysis could be properly completed. The young, able-bodied population was chosen due to the similarity to the young, amputee population. The following work presented here was completed using only the data from the able-bodied subjects collected by the Baylor group.

Exercises

Each subject performed ten repetitions each of 69 exercises used in physical therapy. These exercises ranged from simple arm raises to complex motions involving multiple body segments and multiple planes of motion such as a dodge and cross punch with a squat. The exercises were selected with accessibility in mind; including a range of exercises that patients with 1-4 missing limbs could successfully complete. A list of the exercises is included in Appendix A, the descriptions of every exercise are included in Appendix B.

Double Motion Capture

All data was simultaneously collected by a gold standard motion marker-based capture system (Vicon System) and the experimental system (Vitalize System) in order to directly compare the results. Figure 3, shows data being collected simultaneously by the two systems.

Figure 3. Double Motion Capture set-up for Data Collection

Vicon System

The Vicon system consisted of a 14-camera Vicon Vantage infrared system at the BioMotion Lab at Baylor University. The data was collected at 120 Hz. 57 reflective markers were placed on critical landmarks and various body segments to track the kinematics of the whole body as exercises were performed. All markers were placed directly on the subject's skin with the exception of four markers on the headband and the thigh and shank markers which were placed on rigid plates and secured to the respective body segments. The marker set [43], [44] is shown in Figure 4 below, details of the marker set are included in Appendix C.


Figure 4. Markerset used with the Vicon System

Passive markers were used with the Vicon system, meaning the Vantage cameras emit infrared rays via bright LEDs, which are reflected back to the camera by the reflective markers on the subject, as seen below in Figure 5. Through proper calibration of the camera array, the Vicon system is able to triangulate the 3-dimensional location of all the reflective markers on the subject.

The marker locations recorded allow for local coordinate systems to be defined for each limb segment of the subject's body. These local coordinate systems are used to calculate limb global angles, for example: the global shoulder angle, the orientation of the upper arm relative to the global y-axis; as well as relative angles between adjacent body segments, for example: the relative knee angle, the angle between the thigh and shank.

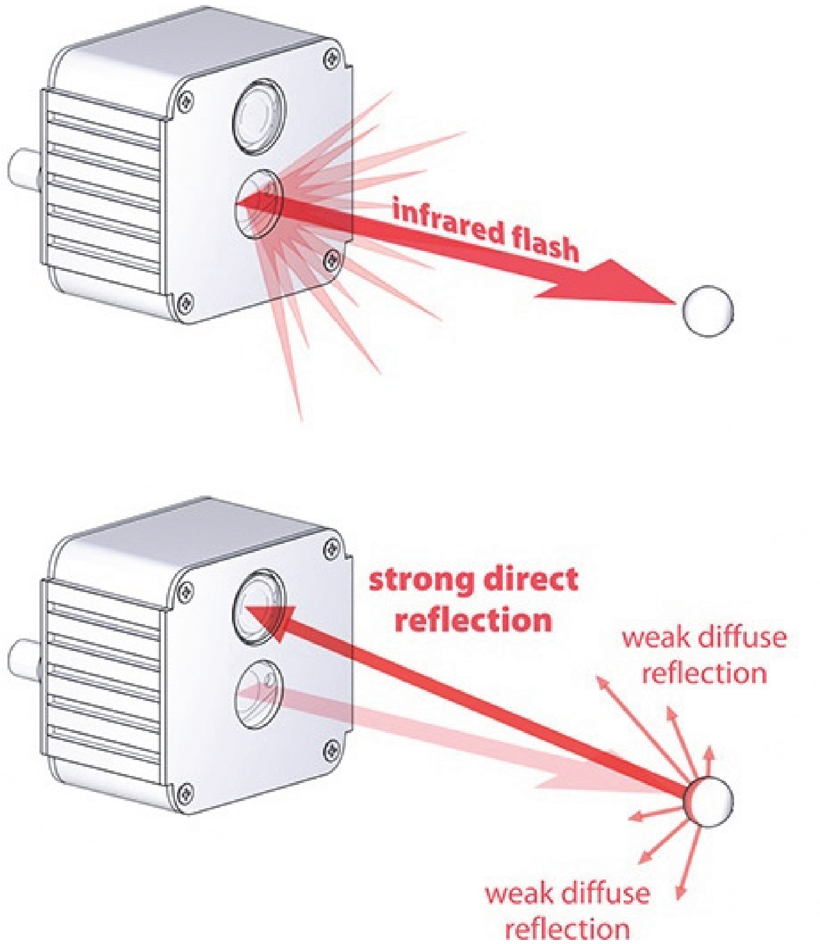


Figure 5. Description of Vicon Cameras. Infrared rays reflected from marker back to camera; adapted from [45]

In addition to the physical reflective markers, twenty bony landmarks on the subject were found by manual palpation and recorded using a digitizing pointer to create virtual markers. These virtual markers were referenced back to the physical markers on the body and used to derive the joint centers of the ankle, knee, hip, shoulder and elbow. The marker placement and palpation were always performed by the primary researcher to minimize variation between subjects.

Vicon Nexus 2.2.3 was the software used to track and record the 3D coordinates for each marker — 120 measurements per second for every marker on the subject.

Vitalize System

The Vitalize system consisted of a Microsoft Kinect [46] and a custom exergame application, Vitalize. This system was used to determine the accuracy and limitations of a single depth camera motion tracking system for possible use in physical therapy.

Kinect Hardware. Microsoft released the Kinect in 2010 as a USB accessory to the Xbox 360 system. In 2014, Microsoft debuted the second generation Kinect, the KinectOne. This version claims improved motion tracking and voice recognition as well as the addition of a high definition camera. This study used the first generation Kinect, as described below, since the Vitalize software was written to be compatible with this Kinect.

The Kinect uses the combination of an infrared laser speckle pattern emitter and a depth camera to enable three-dimensional whole-body motion recognition. The Kinect has five basic components as shown below in Figure 6.

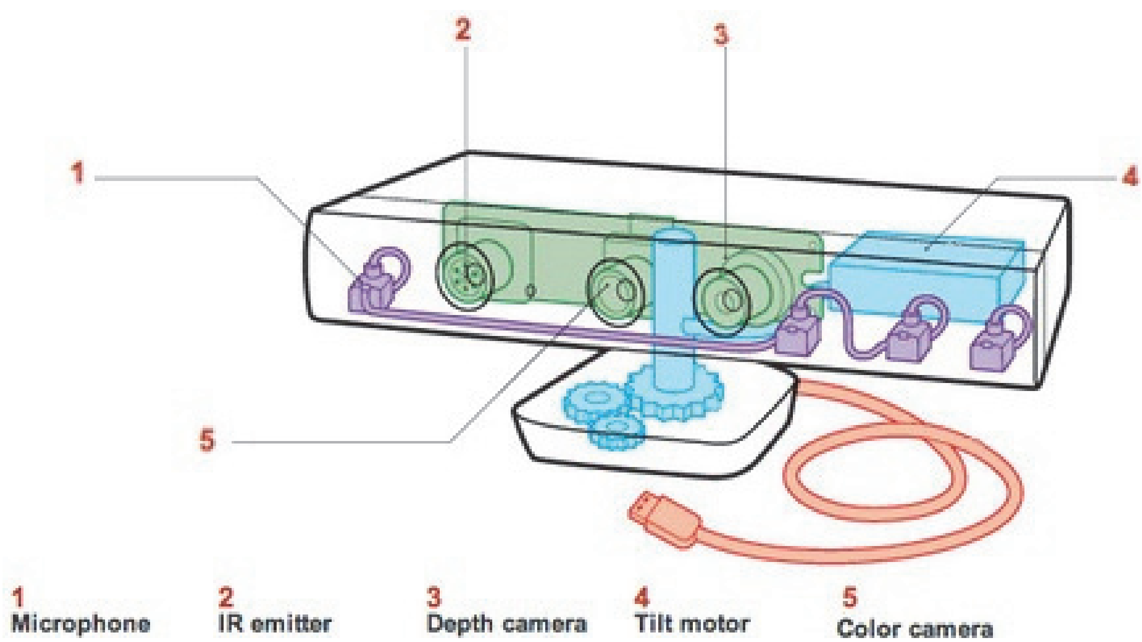


Figure 6. Five Basic Components of the Kinect [47]

1. The microphone array, which consists of four microphones that can separate the voices of the players from the other noise in the room. This allows players to use the voice controls in the system.

2. The IR emitter, which projects infrared light into the room. As the IR light hits surfaces it becomes distorted, this distortion information is read by the depth camera.

3. The depth camera, which uses the distortion in the infrared patterns to build a 3-dimensional mapping of the room and the players.

4. The tilt motor, which adjusts the position of the box based on the height of the player. The tilt motor will angle up for a tall player and down for a shorter player; this optimizes the cameras for any height of player.

5. The color camera, which is similar to a webcam, captures video images that the Kinect uses to make a more accurate picture of the room and the players.

The IR emitter releases an infrared speckle array and the depth camera captures the distortion of the array caused by objects in the room, specifically the distortion caused by the body of the person in front of the Kinect. Software in the Kinect combines the depth information with information from the color camera to create a model of the user. By tracking the form of the subject, the Kinect infers the joint location to create a virtual skeleton abstraction. The Kinect can reports movement of all the primary joints in the human body, see Figure 7. These tracked motions inform the movement of the avatar inside the video game.

The skeleton tracking is designed to recognize a user when they are facing the sensor [48], so all subjects directly faced the sensor standing around 2 meters from the Kinect. The Kinect was placed directly under the television in the BioMotion Lab, approximately 1 meter from the ground. Both distances are within the ranges suggested by Microsoft [49]. Subjects wore matching clothes, black shorts and a black tank top (tucked up to avoid obscuring markers), to reduce possible variability of the tracking ability of the Kinect due to clothing.

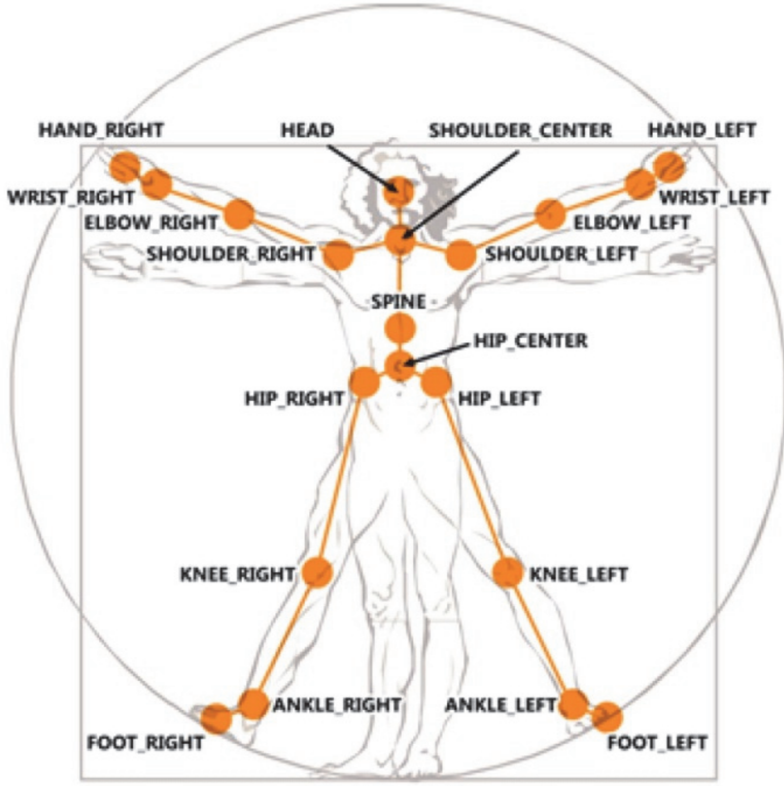


Figure 7. Joints Tracked by the Kinect [27]

The Kinect tracks at a variable frame rate near 30Hz. For this study, the Vitalize collection computer was optimized with a fast video card and solid state hard drive and reserved only for data collection for this study. Therefore, the collection frame rate was as near 30Hz as possible.

Vitalize Software. The software used for the experimental system is a custom 3rd-person shooter exergame called Vitalize, which was developed by Blitz Gaming Studios as part of this study [50]. The game was developed for the wounded warrior population, the 3rd person shooter interface was the preferred game among this group. Within the game, the player performs exercises to charge and fire their weapon at enemy drones.

One of the primary goals of this software was accessibility; therefore several customizable options were built into the game.

The exercises used in gameplay can be specified and customized for the user. Filters are in place that enable the exercises to be sorted according to the needs of the patient. For example, if the filters "Hip" and "Shoulder" are both selected, only exercises that use the hip and shoulder will be used in gameplay. The sensitivity can also be adjusted to allow for varying degrees of "correctness" to be accepted by the system. Various limbs can be switched off from the exercise detection system to allow better tracking of patients with missing limbs; the user can also play in "wheelchair" mode which makes it easier for a patient in a wheelchair to navigate the game. The game controls can also be customized, see Figure 8, below.

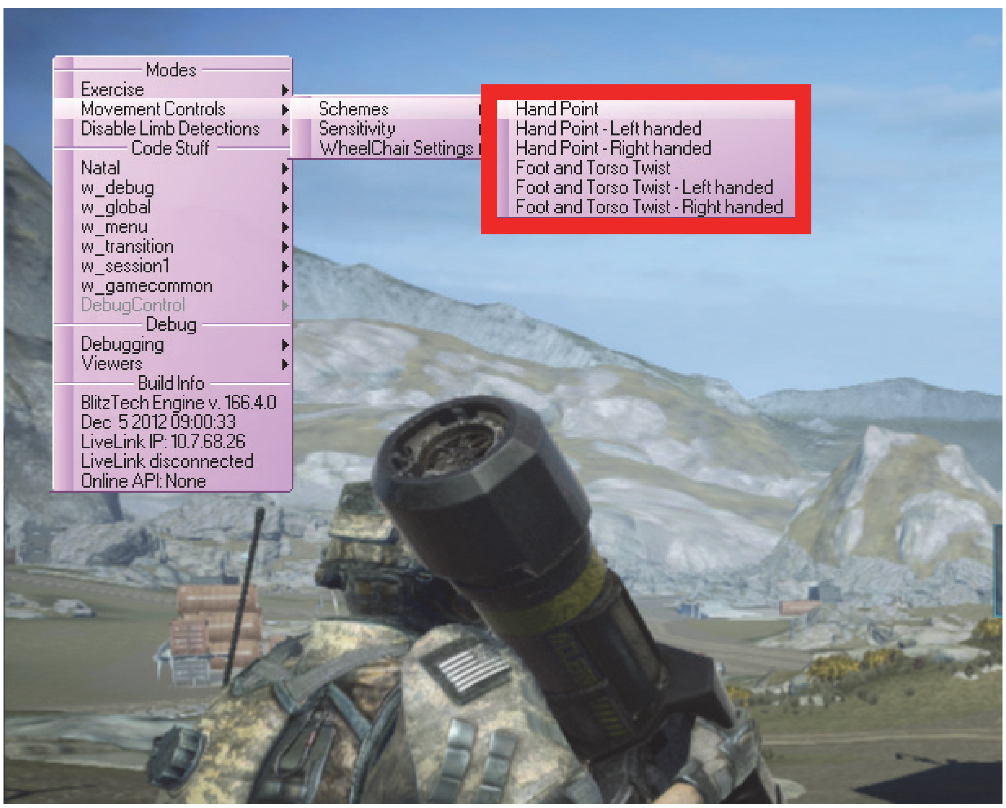


Figure 8. Customization for Navigation within Vitalize Software

By default, the soldier in the game is controlled by the player pointing their hand in different directions. However, this can be changed (all control options are shown within the red box in Figure 8) to allow for increased accessibility for players missing limbs.

When an exercise needs to be performed to charge or fire a weapon, a figure appears on the bottom right of the screen to instruct and guide the subject through the required exercise. A screenshot of Vitalize is included below in Figure 9, the exercise instructor is highlighted by the red box.

Figure 9: Screenshot of Vitalize during Gameplay. Highlighting motions being instructed to user.

Vitalize not only instructs the motion to be performed, but also decides if the motion was performed correctly. The ability of the software to make the decision about the correctness of a motion is something that has only been minimally seen in prior research validating the Kinect for use in physical therapy [23]. This advanced detection and decision making process is a very important part of the current study because the patient will rely on the decisions made by the exergame software to gauge whether or not they are doing the exercises included in their home exercise program correctly.

The data used to track the skeleton by the Kinect is collected through Vitalize. The 3-dimensional coordinates that infer the location of the 20 joints tracked by the Kinect are collected by Vitalize for further processing and analysis.

Nexus Processing

There are multiple steps required to process the data from the Vicon system. The first step is to clean the data after the collection. This is done in Nexus by correcting marker labels and filling gaps. Each of the 57 markers has a distinct label, see Appendix C; the researcher must ensure that all the markers are labelled correctly before proceeding. Gaps in the data must also be addressed. Gaps occur when a marker is occluded from the cameras. If a marker cannot be seen by at least two cameras, the data is not collected. Gaps smaller than 35 frames were filled and visually checked in post-processing. At the 120 Hz. collection rate, this represents just over a ¼ of a second worth of data. Gaps that occurred on the head, pelvis or leg plates were filled with the Rigid-Body Gap fill algorithm provided by Vicon Nexus. The Rigid-Body fill uses data from three reference markers on the same rigid body as the marker containing the gap to fill the gap; under the assumption that the relative distances between the markers on the rigid body is constant. Figure 10, below, is an example of a Rigid-Body fill. The gap is on the marker Shank4, the markers Shank1, Shank2 and Shank3 are used for reference as to the location of Shank4 as the motion continues. The trajectories of the reference markers are seen in orange, the blue trajectory is the proposed fill for the missing frames of the Shank4 marker.

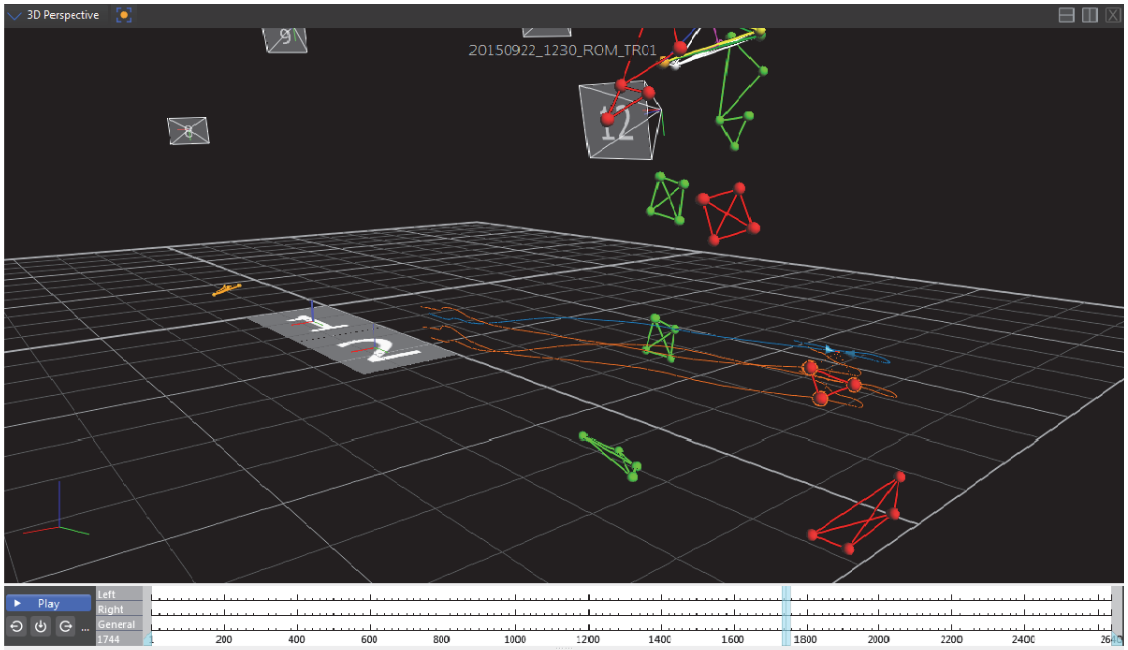


Figure 10: Example of a Rigid-Body Gap Fill in Nexus. The blue trajectory is the proposed fill for the missing marker.

Gaps that occurred on any other body segment were filled with the Spline fill or Pattern fill, with the Pattern fill preferred. The Spline fill (simple interpolation) uses a numerical fit on the order of 3 to fill gaps that are under 14 frames. The Pattern fill is similar to the Rigid Body fill, but uses only one reference marker.

Visual 3D Processing

Visual 3D was used for most of the post-processing involved in this project. In Visual 3D the Vicon data was transformed to match the coordinate system of the Kinect data and filtered using a low-pass filter with a cutoff frequency of 6Hz. Then a custom model was built for each subject. In addition to the physical markers, virtual markers were placed on bony landmarks of the subject's body, using manual palpation and the digitizing wand; these are also called digitizing points. These markers are listed in Table 1 below.

Table 1. Virtual Markers (digitizing points) added to the Model

Bony Landmark:	Name
Left Lateral Malleolus	LANL
Left Medial Malleolus	LANM
Left Lateral Knee Center	LKNL
Left Medial Knee Center	LKNM
Left Greater Trochanter	LGTR
Left Iliac Crest	LILL
Right Lateral Malleolus	RANL
Right Medial Malleolus	RANM
Right Lateral Knee Center	RKNL
Right Medial Knee Center	RKNM
Right Greater Trochanter	RGTR
Right Iliac Crest	RILL
Left Anterior Shoulder Center	LSHA
Left Posterior Shoulder Center	LSHP
Left Lateral Humoral Epicondyle	LELL
Left Medial Humoral Epicondyle	LELM
Right Anterior Shoulder Center	RSHA
Right Posterior Shoulder Center	RSHP
Right Lateral Humoral Epicondyle	RELL
Right Medial Humoral Epicondyle	RELM

The model created in Visual 3D used the physical (seen in Figure 4) and virtual markers to create 12 body segments that define the custom model for each subject. The x-axis corresponds to the Anterior/Posterior direction, the y-axis corresponds to the Axial direction, and the z-axis corresponds to the Mediolateral direction. The markers used and the coordinate definitions for each body segment are included in Table D.1 found in Appendix D.

Along with the physical and virtual markers, additional virtual landmarks were added in post-processing to match the joint centers tracked by the Kinect sensor. The additional landmarks are shown below in Figure 11. The teal landmarks are used to make the models as similar as possible to enable direct comparisons to be made between the systems

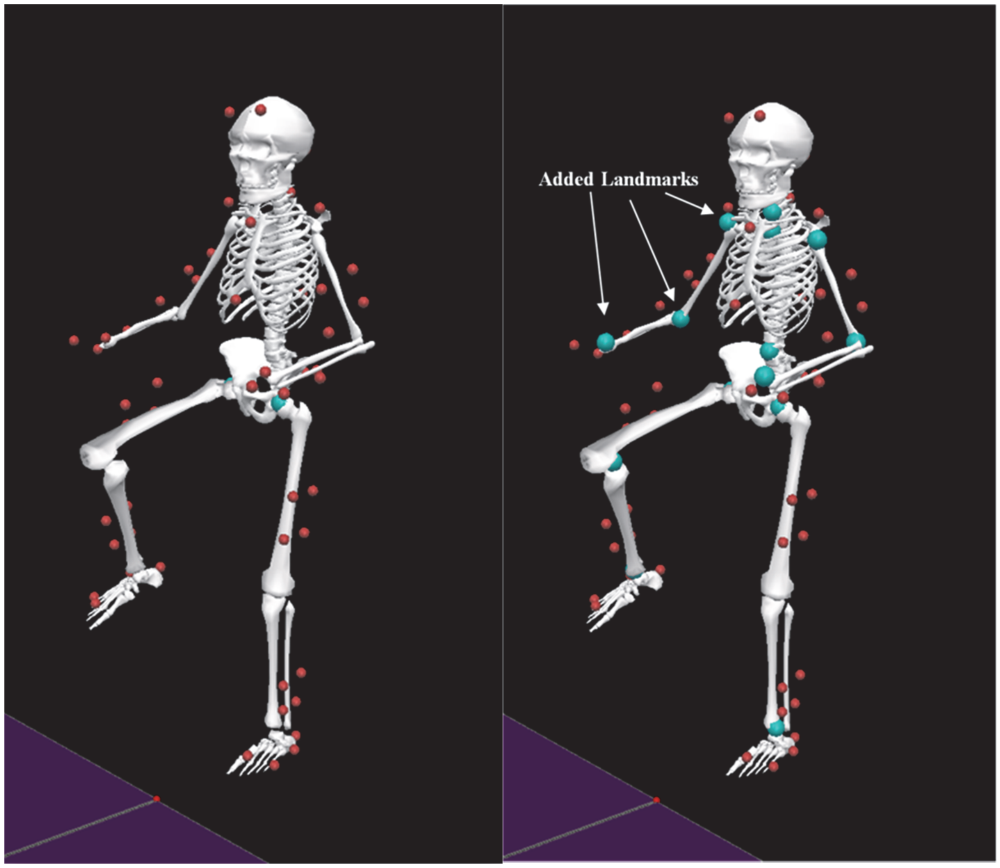


Figure 11: Original Vicon Skeleton (left) and Skeleton with Added Landmarks (right) to mirror the joints tracked by the Kinect

The two systems used in this study track motion in very different ways. The Vitalize system uses the Kinect sensor to track the form of the user's body and infer positions of joint centers. The Vicon system, on the other hand, tracks the individual reflective markers and with the addition of virtual digitizing points calculates the locations of body segments and joint centers to create the model. Table 2, on the next page, lists these additional landmarks and provides the definitions used to create them in Visual 3D.

Table 2. Landmarks added to Visual 3D Model Comparable to ones tracked by the Kinect

Kinect Landmarks	V3D Model Additions	Definitions
Hand_Right		
Wrist_Right	RWJC	Midpoint between the radial and ulnar wrist markers (RWRR & RWRU)
Elbow_Right	REJC2	Midpoints between the medial and lateral elbow digitizing points (RELL & RELM)
Shoulder_Right	RSJC2	Midpoints between the anterior and posterior shoulder digitizing points (RSHA & RSHP))
Hip_Right	RIGHT_HIP	
Knee_Right	RKJC2	Midpoints between the medial and lateral knee digitizing points (RKNL & RKNM)
Ankle_Right	RAJC2	Midpoints between the medial and lateral ankle digitizing points (RANL & RANM)
Hand_Left		
Wrist_Left	LWJC	Midpoint between the radial and ulnar wrist markers (LWRR & LWRU)
Elbow_Left	LEJC2	Midpoints between the medial and lateral elbow digitizing points (LELL & LELM)
Shoulder_Left	LSJC2	Midpoints between the anterior and posterior shoulder digitizing points (LSHA & RSHP)
Hip_Left	LEFT_HIP	
Knee_Left	LKJC2	Midpoints between the medial and lateral knee digitizing points (LKNL & LKNM)
Ankle_Left	LAJC2	Midpoints between the medial and lateral ankle digitizing points (LANL & LANM)
Foot_Left		
Foot_Right		
Hip_Center		
Spine	LUMBAR2	Midpoint between XYPH and T8 markers, on a plane creaed by the Illiac Crest digitizing points (LILL & RILL); and a point projected laterally from the Left Illiac Crest Landmark (LASI_2)
Shoulder_Center	NECK	Placed at the origin of the Thoraz/Ab segment
Head	HEAD	Placed at the origin of the Head segment

The data was screened and visually time-synced in Matlab; neither sampling rate from the Vicon or Vitalize data was changed [35], [38] . The manual time sync ensured that each repetition in the Vicon data was correctly matched to the corresponding repetition in the Vitalize data to enable direct comparison. An example of the data-sync can be seen below in Figure 12.

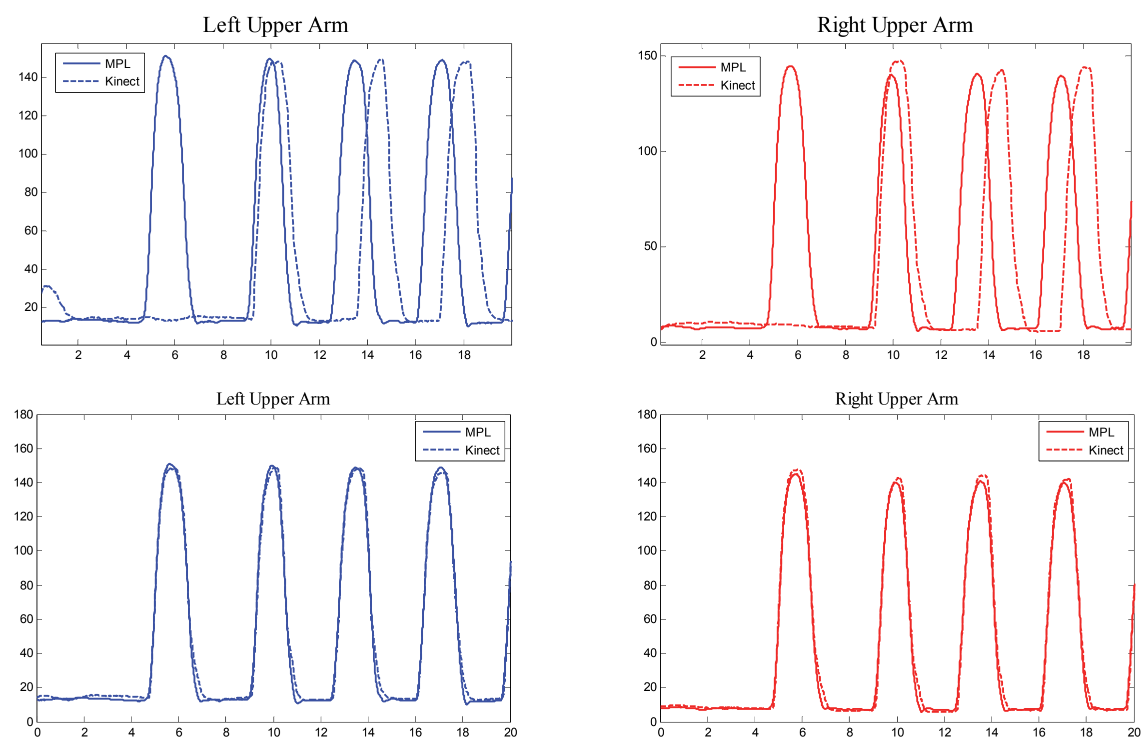


Figure 12. Sample Data before (top figures) and after (bottom figures) Time-Sync

After the datasets were synced together, an automated process, with manual corrections as needed, was used to split the exercise trials into repetitions by adding a "Start" and "End" event to each repetition. This enables each repetition to be used independently. In this study, the repetitions for each subject were averaged together for each exercise performed. In Figure 13 below, the red marks indicate "Start" events and the yellow marks indicate "End" events used.

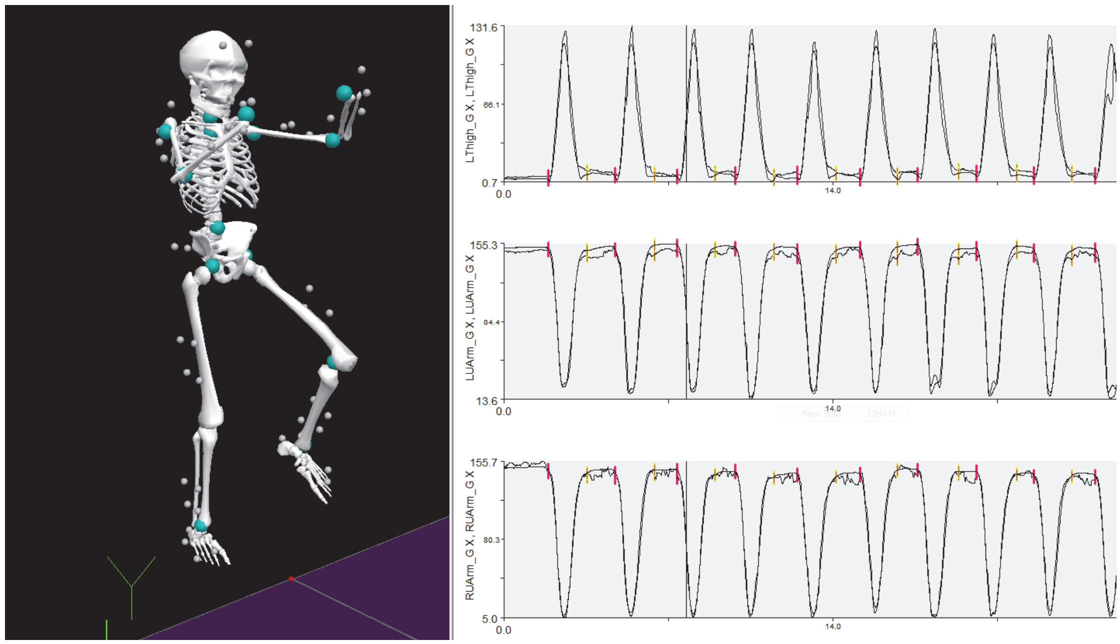


Figure 13. Adding "Start" and "End" events to split the trial into repetitions

Angles and segment lengths were calculated for both the Vicon and Vitalize datasets in Visual 3D. The following values (included in Table 3) were calculated and stored for analysis. Two types of angles were calculated: global angles and relative angles. The global angles represent the location of the limb segment relative to the global coordinate system. For example, the global shoulder angle is defined as the position of the upper arm segment relative to the global y-axis. The relative angles are calculated as the angle between two adjacent body segments. For example, the relative knee angle is defined as the angle between the thigh segment and the shank segment. All the angles were included in the large database created; but for this phase of the project, only the global angles (the first nine angles in Table 3) were analyzed [35]. The segments lengths were not analyzed because the focus of this study was on body angles which are traditionally the more clinically useful measure. However, the length values may be very important in future work, possibly with the next phase of software development.

Table 3. Descriptions of Angles and Segment Lengths Calculated

Calculated Value	Description of value
LFore_G	Orientation angle of left forearm segment with respect to the global Y-Axis (deg.)
LShank_G	Orientation angle of the left shank segment with respect to the global Y-Axis (deg.)
LThigh_G	Orientation angle of the left thigh segment with respect to the global Y-Axis (deg.)
LUArm_G	Orientation angle of the left upper arm segment with respect to the global Y-Axis (deg.)
RFore_G	Orientation angle of the right forearm segment with respect to the global Y-Axis (deg.)
RShank_G	Orientation angle of the right shank segment with respect to the global Y-Axis (deg.)
RThigh_G	Orientation angle of the right thigh segment with respect to the global Y-Axis (deg.)
RUArm_G	Orientation angle of the right upper arm segment with respect to the global Y-Axis (deg.)
Trunk_G	Orientation angle the trunk segment with respect to the global Y-Axis (deg.)
Forearms_Agl	Angle between the two forearm segments in local coordinates (deg.)
LElbow_Agl	Angle formed between the left forearm and left upper arm segments in local coordinates (deg.)
LKee_Agl	Angle formed between the left thigh and left shank segments in local coordinates (deg.)
RElbow_Agl	Angle formed between the right forearm and right upper arm segments in local coordinates (deg.)
RKnee_Agl	Angle formed between the right thigh and right shank segments in local coordinates (deg.)
Shanks_Agl	Angle formed between the two shank segments in local coordinates in local coordinates (deg.)
Thighs_Agl	Angle formed between the two thigh segments using the hip_center landmark in local coordinates deg.)
UArms_Agl	Angle formed between the two upper arm segments using the shoulder_center landmark in local coordinates(deg.)
LFore_Len	Length of left forearm segment (cm.)
LShank_Len	Length of left shank segment (cm.)
LThigh_Len	Length of left thigh segment (cm.)
LUArm_Len	Length of left upper arm segment (cm.)
RFore_Len	Length of right forearm segment (cm.)
RShank_Len	Length of right shank segment (cm.)
RThigh_Len	Length of right thigh segment (cm.)
RUArm_Len	Length of right upper arm segment (cm.)
Trunk_Len	Length of trunk segment (cm.)

Analysis

Immense amounts of data were collected for use in this project. To begin sorting through the data, the analysis was split into two parts. The first was to create a database of values for each subject, exercise, angle and repetition used; as well as reference tables of error for hip, shoulder, knee and elbow. The second was to analyze trends in the errors observed in the reference tables to determine the effect of

- Plane of Motion
- Range of Motion
- Joint Involved in Motion
- Complexity of Motion

An additional analysis examined the decisions made by Vitalize about the correctness of the motions to determine how well the system identified correct and incorrect motions.

Creation of Database and Reference Tables

Using the angles calculated from the raw datasets, the values of interest were calculated. These values include the speed, the maximum value and location, start value and location, and end value and location for each repetition in the Vitalize and Vicon datasets.

Four measures of error were calculated for analysis in this research, all are reported in degrees:

- Error at Start
- Error at Peak
- Range of Motion (ROM) Error
- Root Mean Square (RMS) Error

For each repetition, the “start” value and “peak” value were calculated, as seen below in Figure 14.

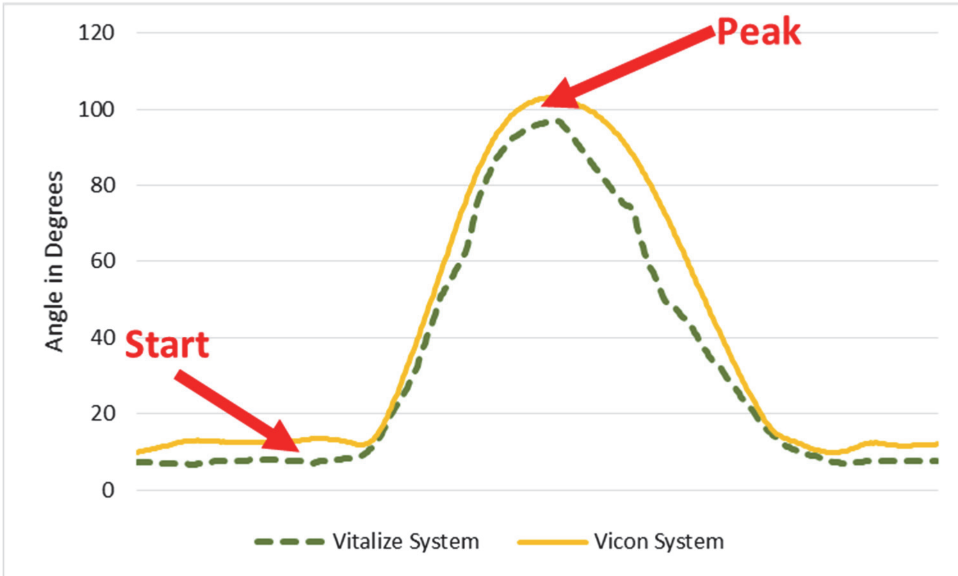


Figure 14. Exemplar Data to describe "Start" and "Peak" Errors

The error at the start is defined as the difference between the Vicon and the Vitalize system at the start of the repetition. Start errors were reported, but not analyzed in this study. The error at the peak is the difference between systems at the peak of the repetition, which was analyzed in this study. This is a very clinically important value because the physical therapist needs to know if the system is accurately reporting the peak angle reached in a motion. For example, if the subject is instructed to raise the arm to 50 degrees before lowering it; the system needs to accurately determine if the arm reached 50 degrees.

The ROM of each system was calculated as “Peak-Start”. Figure 15, below, shows the ROM for the Vicon system (solid red line) and for the Vitalize system (dashed red line). The ROM Error is defined as the difference between the ROM of the Vicon system and the ROM of the Vitalize system. The ROM Error, Error at Start and Error at Peak are all independent of time. The ROM Error is heavily used in this study because ROM is very commonly used in physical therapy exercise descriptions.

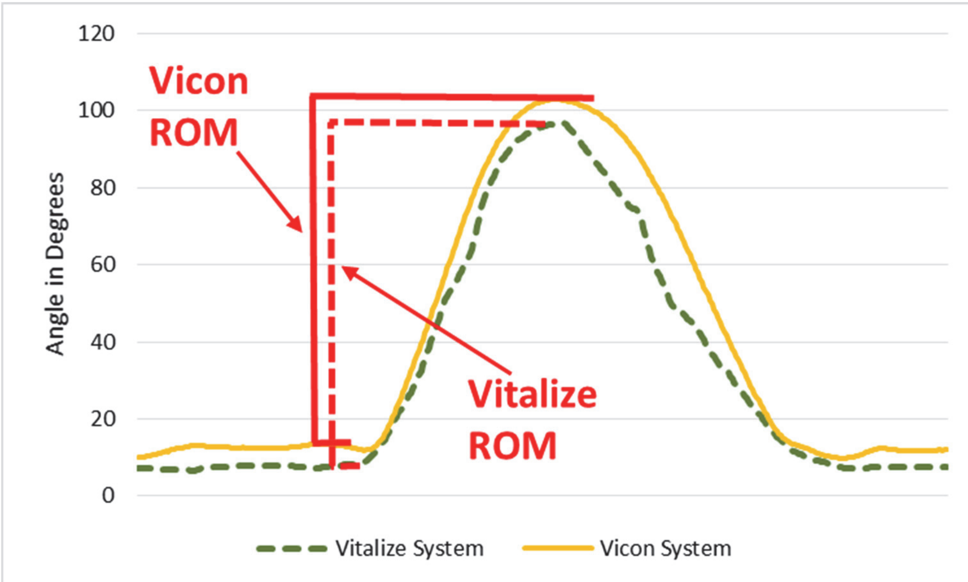


Figure 15. Exemplar Data to describe ROM Error

Finally, the RMS error was calculated for each repetition; it is defined as the square root of the average of the square of difference between the systems, see Figure 16. Unlike the other errors, RMS Error is time-dependent and considers the entire waveform.

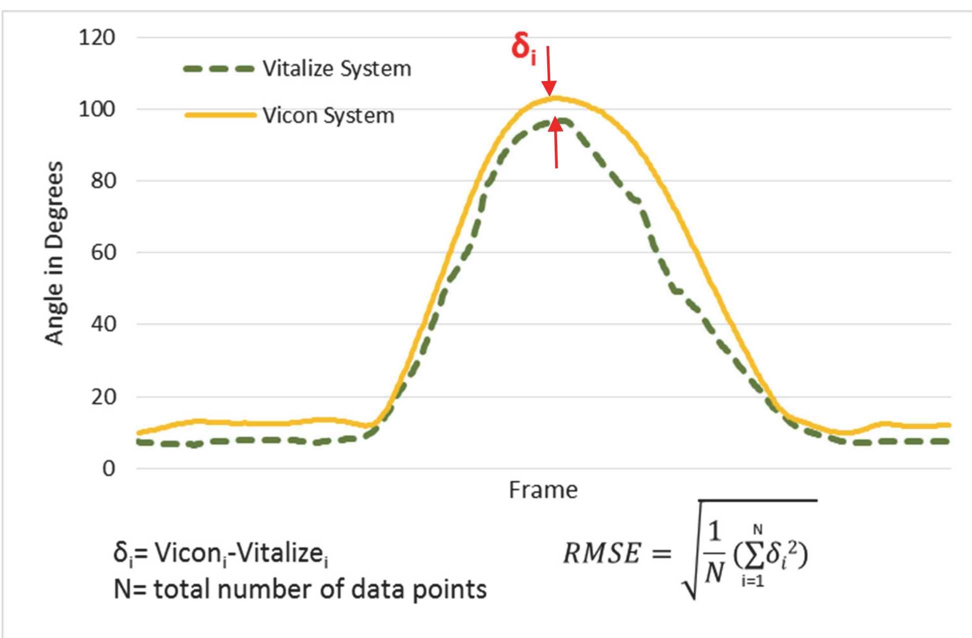


Figure 16. Exemplar Data to describe RMS Error

All of these values were calculated for each repetition, angle, and exercise for each subject; which is over 3 million values included in the large error database.

From this database, reference tables of errors were created. Four tables were made; for the hip, shoulder, knee and elbow joints (see Tables F.1-F.4 in Appendix F). Each of these tables included all the exercises in this study that used the joint of interest. Each table included ROM Error, Error at Start, Error at Peak, RMS Error, ROM, Plane of Motion, and the Category of Motion. The repetitions for each subject were averaged, then the subjects were averaged together, which created a single reported value for each exercise included in the table. The data from the elbow was included but not analyzed in this study because this study is heavily based on plane of motion and the plane of motion of the elbow is difficult to analyze because it is dependent on the orientation of the shoulder.

Data Analysis

For each aim, all the repetitions were averaged for each subject, but each subject was kept separate for the statistical analyses. The repetitions were averaged to help control for variation seen in a single repetition. Averaging the repetitions in this way results in a single value being assigned to each subject for each exercise for each type of error reported.

Aim 1: Effect of the Plane of Motion. Analyses were completed comparing the frontal to sagittal plane at both the hip and the shoulder to determine if there was a difference between the error in the sagittal plane of motion and in the frontal plane of motion.

Aim 2: Effect of the Range of Motion. Analyses were completed for the knee, hip and shoulder in the sagittal plane and for the hip and shoulder in the frontal plane to determine if and how the error of the Vitalize system was related to the ROM of the exercise. These analyses were controlled for plane of motion because it is suspected that the plane has an effect on the error observed.

Aim 3: Effect of Different Joints. Analyses were completed in the sagittal and frontal planes to determine if there was a relationship between the joint being tracked and the error of the Vitalize system. The first part of this aim controlled for range of motion and plane of motion. The second part of the aim was completed examining the error associated with multiple joints within the same exercise.

Aim 4: Comparison of Simple to Complex Motions. A case study was completed for the Knee Strike variations (see Appendix B for descriptions):

- Full Knee Strike
- Seated Knee Strike
- Knee Strike with Overhead Arms
- Knee Strike with Row

These were analyzed to determine if adding complexity to the motion has an effect on the tracking error observed at the primary joint.

Aim 5: Observations on the Decisions made by Vitalize. This final analysis consisted of a case study on the decisions made by the software, Vitalize. For a select subset of exercises using data from a single subject, the decision made by the software was compared to both the Vitalize and Vicon data to determine why the software made the decision and if that decision was correct.

Statistics

For all statistical analyses, the significance level was set at $\alpha=0.05$. For each analysis that directly compared two things, two-tailed t-tests assuming unequal variance were used. For analyses that compared more than two things, a one-way ANOVA was used. Post hoc testing was completed with a series of t-tests and a Bonferroni correction for all comparisons within the ANOVA to determine where significance existed. Correlations were completed using a Pearson's product-moment correlation. For all correlation analyses, the suggestion by Evans [51] is followed for explaining the absolute value of r:

- .00-.19 "very weak"
- .20-.39 "weak"
- .40-.59 "moderate"
- .60-.79 "strong"
- .80-1.0 "very strong"

For all boxplots, the lower whisker indicates the first quartile of the data, the bottom half of the box indicates the second quartile, the top half of the box indicates the third quartile and the upper whisker indicates the fourth quartile. The black bar in the box indicates the median of the data and the red bar in the box indicates the mean of the data.

CHAPTER THREE

Results

To begin sorting through the data, the analysis was split into two parts. The first part was to create a database of values for each subject, exercise, angle and repetition used; as well as reference tables of error for hip, shoulder, knee and elbow. The second part was to analyze trends in observed error to determine the effect of

- Plane of Motion
- Range of Motion
- Joint Involved in Motion
- Complexity of Motion

An additional analysis examined the decisions made by Vitalize for correctness of motion to determine how well the system identified correct and incorrect motion.

Master Database

A sample of the database created is included on the next page as Table 4. The far left column indicates the subject, this sample only shows data from Subject 2; however the database extends to include data from 15 subjects. The next column indicates the angle, data from 17 different angles is included for each exercise. The third column is the exercise, the data from 69 different exercises is included in the database; a list of all the exercises is included in Appendix A, the descriptions of every exercise is found in Appendix B. The fourth column indicates the repetition; ten repetitions of each exercise were performed by each subject. All the column headings indicate values that were either directly pulled from the raw data or calculated from the data. These values are listed and explained in Appendix E.

Table 4. Sample of the Error Database Created

Subject	Marker	Ex	Rep	MaxKinect	MaxK_Loc	MaxVicon	MaxV_Loc	StartKinect	Start Vicon	EndKinect	EndVicon	ROMKinect	ROMVicon	ExerSpeed	ROMError	StartError	MaxError	MaxError_Loc	RMSE
2	'Forearms_Agl'	1	1	34.9	254.0	25.2	269.0	3.3	6.9	5.7	3.7	31.7	18.3	8.2	13.4	3.7	-9.7	15.0	6.4
2	'Forearms_Agl'	1	2	39.5	271.0	24.2	275.0	6.8	1.7	8.0	8.5	32.7	22.5	9.9	10.2	-5.1	-15.3	4.0	6.2
2	'Forearms_Agl'	1	3	40.2	99.0	29.2	97.0	5.9	2.9	7.4	7.2	34.3	26.4	33.0	7.9	-3.1	-10.9	-2.0	6.7
2	'Forearms_Agl'	1	4	41.2	279.0	33.5	290.0	3.7	2.3	9.9	10.1	37.5	31.2	13.0	6.3	-1.4	-7.7	11.0	7.6
2	'Forearms_Agl'	1	5	45.6	99.0	37.6	95.0	6.0	6.3	8.1	8.0	39.6	31.4	40.0	8.2	0.3	-7.9	-4.0	7.2
2	'Forearms_Agl'	1	6	44.3	305.0	31.1	313.0	10.1	9.8	7.6	4.8	34.3	21.2	8.2	13.0	-0.2	-13.2	8.0	6.4
2	'Forearms_Agl'	1	7	46.1	279.0	37.0	308.0	5.8	3.7	8.8	16.5	40.3	33.4	13.0	7.0	-2.1	-9.1	29.0	8.3
2	'Forearms_Agl'	1	8	45.5	88.0	35.8	100.0	6.0	5.1	16.7	21.4	39.6	30.7	37.2	8.9	-0.9	-9.8	12.0	7.0
2	'Forearms_Agl'	1	9	48.2	91.0	38.5	88.0	11.1	14.2	9.6	11.2	37.0	24.3	33.5	12.7	3.1	-9.6	-3.0	7.0
2	'Forearms_Agl'	1	10	47.9	96.0	38.9	92.0	10.1	11.1	6.9	4.9	37.7	27.7	36.6	10.0	1.0	-9.0	-4.0	7.3
2	'LElbow_Agl'	1	1	-8.6	316.0	-21.3	337.0	-20.0	-24.9	-14.2	-22.4	11.4	3.6	1.3	7.8	-4.9	-12.8	21.0	7.6
2	'LElbow_Agl'	1	2	-3.9	271.0	-20.2	366.0	-18.1	-23.5	-13.1	-21.0	14.2	3.2	1.1	11.0	-5.4	-16.3	95.0	7.4
2	'LElbow_Agl'	1	3	-6.6	106.0	-19.0	48.0	-15.2	-22.3	-12.0	-21.2	8.6	3.3	8.4	5.3	-7.2	-12.4	-58.0	7.3
2	'LElbow_Agl'	1	4	-7.4	291.0	-20.2	347.0	-18.5	-23.8	-14.0	-21.2	11.1	3.6	1.2	7.5	-5.3	-12.8	56.0	7.8
2	'LElbow_Agl'	1	5	-5.4	100.0	-19.7	43.0	-16.6	-23.1	-20.1	-23.9	11.2	3.4	9.7	7.8	-6.6	-14.4	-57.0	7.7
2	'LElbow_Agl'	1	6	14.2	440.0	23.5	439.0	15.1	20.6	14.2	23.5	-1.0	2.8	0.8	3.8	5.5	9.3	-1.0	7.7
2	'LElbow_Agl'	1	7	-9.8	299.0	-20.3	338.0	-19.0	-24.7	-12.0	-21.3	9.2	4.5	1.6	4.8	-5.8	-10.5	39.0	7.3
2	'LElbow_Agl'	1	8	-7.5	305.0	-19.8	301.0	-16.6	-23.2	-14.8	-22.9	9.1	3.4	1.3	5.7	-6.6	-12.3	-4.0	7.3
2	'LElbow_Agl'	1	9	-6.4	332.0	-19.7	363.0	-19.1	-25.8	-14.9	-22.7	12.7	6.1	2.0	6.6	-6.6	-13.3	31.0	7.7
2	'LElbow_Agl'	1	10	-10.5	97.0	-20.4	180.0	-16.8	-24.2	-13.1	-23.0	6.3	3.8	2.5	2.6	-7.4	-10.0	83.0	7.0
2	'LFore_G'	1	1	135.9	166.0	136.7	158.0	25.2	22.4	24.6	22.1	110.8	114.4	87.4	3.6	-2.8	0.8	-8.0	13.0
2	'LFore_G'	1	2	144.7	179.0	141.9	184.0	25.0	22.4	25.5	26.0	119.7	119.5	78.4	0.2	-2.6	-2.8	5.0	10.9
2	'LFore_G'	1	3	146.3	223.0	145.1	199.0	23.5	23.0	20.0	19.7	122.8	122.1	74.0	0.7	-0.5	-1.2	-24.0	10.2
2	'LFore_G'	1	4	148.0	195.0	146.5	196.0	23.4	20.8	23.0	21.1	124.6	125.8	77.4	1.1	-2.6	-1.5	1.0	11.5
2	'LFore_G'	1	5	151.2	201.0	149.6	197.0	22.4	20.9	20.2	14.1	128.8	128.7	78.8	0.1	-1.4	-1.6	-4.0	10.8
2	'LFore_G'	1	6	157.4	205.0	154.2	209.0	17.8	15.8	18.5	17.8	139.6	138.4	79.9	1.2	-2.0	-3.2	4.0	10.0
2	'LFore_G'	1	7	151.1	206.0	149.5	207.0	23.2	19.8	19.1	21.0	127.9	129.6	75.5	1.7	-3.3	-1.6	1.0	11.7
2	'LFore_G'	1	8	155.4	211.0	151.9	207.0	21.1	18.1	16.6	16.2	134.3	133.7	77.9	0.6	-2.9	-3.5	-4.0	11.2
2	'LFore_G'	1	9	156.2	212.0	150.0	217.0	23.1	22.5	17.9	17.9	133.1	127.4	70.8	5.7	-0.5	-6.2	5.0	10.0
2	'LFore_G'	1	10	153.6	224.0	150.6	208.0	24.1	22.2	18.5	18.6	129.5	128.4	74.4	1.1	-1.9	-3.0	-16.0	9.7
2	'LKnee_Agl'	1	1	-7.5	312.0	-7.5	239.0	-7.9	-8.3	-7.4	-8.1	0.4	0.8	0.4	0.4	-0.4	-0.1	-73.0	0.5
2	'LKnee_Agl'	1	2	-6.8	22.0	-7.6	90.0	-7.0	-8.2	-8.4	-8.2	0.2	0.6	0.8	0.3	-1.2	-0.8	68.0	0.6
2	'LKnee_Agl'	1	3	-6.9	373.0	-7.6	303.0	-8.4	-8.3	-7.8	-8.3	1.5	0.7	0.3	0.8	0.1	-0.7	-70.0	0.7
2	'LKnee_Agl'	1	4	-6.6	206.0	-7.5	97.0	-8.3	-8.1	-8.4	-8.2	1.8	0.6	0.7	1.2	0.2	-1.0	-109.0	0.8
2	'LKnee_Agl'	1	5	-6.4	225.0	-7.5	286.0	-7.0	-8.3	-7.5	-7.8	0.5	0.8	0.3	0.3	-1.3	-1.1	61.0	0.9
2	'LKnee_Agl'	1	6	7.6	372.0	10.3	418.0	7.6	7.8	7.0	8.1	0.0	2.5	0.7	2.4	0.3	2.7	46.0	1.0
2	'LKnee_Agl'	1	7	7.5	396.0	8.6	386.0	7.4	8.1	7.5	8.5	0.1	0.5	0.2	0.4	0.7	1.1	-10.0	1.0
2	'LKnee_Agl'	1	8	-5.8	229.0	-6.9	310.0	-7.4	-8.4	-6.9	-7.7	1.7	1.5	0.6	0.2	-1.0	-1.2	81.0	1.2
2	'LKnee_Agl'	1	9	-5.4	207.0	-7.4	77.0	-6.5	-7.8	-7.3	-7.9	1.2	0.5	0.7	0.7	-1.3	-2.0	-130.0	1.5
2	'LKnee_Agl'	1	10	-5.9	241.0	-7.4	327.0	-7.5	-8.0	-7.1	-7.8	1.6	0.6	0.2	1.0	-0.5	-1.4	86.0	1.0

Reference Tables of Errors

Tables that consolidate data from the database into a more usable form were made. A table was made for each of the four major joints: hip, shoulder, knee and elbow; these four tables are included in Appendix F. The tables for the hip and shoulder are presented and discussed here. Table 5 is the reference table of errors for the hip. The values are sorted by ROM Error (indicated by the red box on Table 5), the exercises higher on the table have lower error.

Table 5. Reference Table of Errors for the Hip

Exercise Name	ROM Error	Error at Start	Error at Peak	RMS Error	ROM	Plane	Category
Side Step (Full)	3.4	2.9	0.5	3.4	13.1	Frontal	Step
Jumping Jack (Full)	3.5	2.3	0.9	3.4	14.3	Frontal	Jumping Jack
March with No Arms (Partial)	3.9	1.9	0.9	3.9	26.0	Sagittal	March
Squat (Partial)	4.0	1.7	2.1	3.9	27.1	Sagittal	Squat
Side Jump (Full)	4.0	1.7	0.9	3.6	16.2	Frontal	Jump
Jumping Jack (Mid)	4.1	2.3	-0.6	3.5	13.7	Frontal	Jumping Jack
Lunge (mid)	4.5	3.5	3.5	4.9	42.4	Sagittal	Lunge
Jumping Jack (No Arms) (Full)	4.6	2.1	-1.8	3.4	14.8	Frontal	Jumping Jack
Squat (Mid)	4.9	1.0	1.1	5.0	42.2	Sagittal	Squat
Step Forward and Back	5.5	3.4	-1.7	3.3	12.9	Sagittal	Step
Low Kick	5.5	0.5	1.0	4.2	28.8	Sagittal	Kick
Side Hop (Full)	5.6	1.7	4.6	4.6	44.7	Frontal	Hop
Lunge (full)	5.7	3.8	7.7	6.7	39.4	Sagittal	Lunge
March with No Arms (Mid)	6.1	2.1	6.0	5.6	62.6	Sagittal	March
Squat Jump (No Arms) (Full)	6.3	-0.6	-1.7	6.1	45.1	Sagittal	Squat
Seated Knee Strike	6.3	11.6	8.7	16.3	45.9	Sagittal	Knee Strike
Lunge with Wood Chop	6.7	3.1	4.5	6.9	59.1	Sagittal	Lunge
Knee Strike	6.9	2.3	8.8	8.3	79.8	Sagittal	Knee Strike
March with No Arms (Full)	7.1	2.2	8.3	7.7	92.2	Sagittal	March
Wood Chop with Squat	7.2	1.9	-3.5	5.4	36.5	Sagittal	Squat
Seated Low Kick	7.6	11.8	6.0	12.4	16.8	Sagittal	Kick
Dodge Cross with Squat	7.7	0.7	1.0	6.0	43.8	Sagittal	Squat
Knee Strike with Overhead Arms	8.5	4.6	3.4	9.4	96.7	Sagittal	Knee Strike
Squat (Full)	9.0	1.1	-5.1	6.1	54.1	Sagittal	Squat
Knee Strike with Row	9.6	1.1	9.8	10.1	93.5	Sagittal	Knee Strike
Sit to Stand (Raised Seat) (Mid)	10.7	-4.5	4.2	6.7	60.3	Sagittal	Sit to Stand
Sit to Stand (Full)	11.5	-9.4	1.0	8.9	72.9	Sagittal	Sit to Stand

A couple of observations can be made from Table 5. First, the exercises that are contained in the frontal plane (seen in the purple boxes) are higher on the table (indicating that they have lower error) than the exercises in the sagittal plane; all the unmarked motions in the "Plane" column are in the sagittal plane. This seems to indicate that there is less error when tracking motions in the frontal plane than in the sagittal plane. Second, the range of motion seems to increase as the ROM Error increases. For example, for the March exercises, which are performed in the sagittal plane (seen in the green boxes on Table 5) the exercises which have lower ROM (partial motion) are near the top of the table, indicating low error; and the exercises which have high ROM (full motion) are near the bottom of the table, indicating high error. This could indicate that for some exercises, a positive correlation exists between the range of motion of an exercise and the ability of the Vitalize system to track the motion; in other words as the ROM of the exercise increases, the tracking error of the Vitalize system also increases.

Table 6 below, is the same as Table 5 but for all the motions that involve the shoulder. All the values are for shoulder angles. The values in Table 6 are also sorted by ROM Error (indicated by the red box), with the exercises higher on the table having lower error.

Table 6. Reference Table of Errors for the Shoulder

Exercise Name	ROM Error	Error at Start	Error at Peak	RMSE	ROM	Plane	Category
Arm Raise (full)	4.1	-0.4	-1.3	9.0	134.0	Frontal	Arm Raise
Cross Body Reach in (Partial)	4.2	-1.4	-1.3	5.3	29.2	both	Reach
Arm Raise (mid)	4.4	-1.0	-2.4	8.7	98.2	Frontal	Arm Raise
Jumping Jack (Full)	5.0	0.4	-6.8	9.3	132.1	Frontal	Jumping Jack
Arm Raise (partial)	5.7	-0.2	-5.8	6.4	36.9	Frontal	Arm Raise
Overhead Arms	6.6	3.3	1.0	8.9	112.5	Sagittal	Overhead Arms
Jumping Jack (Mid)	6.8	0.4	-6.1	8.6	93.3	Frontal	Jumping Jack
Cross Body Reach in (Mid)	9.1	-1.5	-2.2	8.8	50.6	both	Reach
Cross Body Reach Out (Full)	9.1	6.7	-2.3	7.8	45.8	both	Reach
Cross Body Reach Out (Mid)	10.4	1.6	-2.3	5.8	30.5	both	Reach
Row	11.1	-1.1	-1.6	10.8	58.8	Sagittal	Row
Jab	11.7	-4.2	-13.0	13.7	46.8	Sagittal	Jab
Cross Body Reach In (full)	11.9	-2.2	-12.3	12.6	81.3	both	Reach
Dodge Cross w/ Squat	12.4	-3.7	-16.3	21.8	53.0	both	Dodge Cross
Dodge Cross	13.9	-4.3	-17.4	18.6	55.0	both	Dodge Cross
Wood Chop w/Squat	16.5	10.7	-3.1	13.3	72.5	both	Wood Chop
Wood Chop w/ Lunge	16.9	12.9	-2.4	14.1	34.7	both	Wood Chop
Wood Chop	17.2	7.7	-4.9	9.9	62.9	both	Wood Chop

Again it is observed that exercises in the frontal plane (indicated by the purple boxes in Table 6) are higher on the table than motions in the sagittal plane; exercises that involve both planes are also included and seem to perform worse than either individual plane. The range of motion within a category of exercise decreases as ROM Error increases (descending the table). For example, Arm Raise exercises (seen in the green boxes in Table 6), which are performed in the frontal plane, have high ROM (full motion) near the top of the table, indicating low error; with low ROM (partial motion) lower on the table, indicating higher error. This could indicate that for some exercises, a negative correlation exists between the range of motion of an exercise and the ability of the Vitalize system to track the motion; i.e. as ROM increases, the error decreases. Which is opposite of what was observed for the March exercise at the hip in Table 5. This seems to imply that a complicated relationship exists between ROM and error.

The analyses performed directly follow from the observations made from these tables. The first analysis seeks to discover the relationship between the plane of motion and the tracking ability of the Vitalize system. It is hypothesized that the Vitalize system will perform better in the frontal plane than in the sagittal plane because there is no depth measurement required for frontal plane motions. The second analysis attempts to find the relationship between the range of motion and the error of the Vitalize system. It is hypothesized that the range of motion will not have an effect on the error of the system; this has been reported in previous research [32], [36], [38]. However, the initial observations from the exercise tables created in this study may indicate that a relationship exists between ROM and error. The third analysis directly compares the performance of the Vitalize system at the hip to the shoulder and to the knee. It is hypothesized that there will be minimal difference between the tracking accuracy of different joints. The fourth analysis examines multiple variations of a single exercise to see if there is a difference in the tracking ability of the Vitalize system as the complexity of the motion increases. It is hypothesized that adding complexity will not have an effect on the error of the primary joint involved in the exercise. The final analysis is comprised of a series of observations about the decisions made by the Vitalize software, whether an exercise was performed correctly or not.

For all statistical analysis, the ROM error, error at the peak and RMS error were used to analyze the accuracy of the Vitalize system. The Vicon system is held as the gold standard, so any deviation of the Vitalize system from the Vicon system is considered error of the Vitalize system. The repetitions were averaged for each exercise performed by each subject. For errors of the hip joint, the Lthigh_G and Rthigh_G angles, the global orientation angles of both thighs, were used. For errors of the shoulder joint, the LUArm_G and RUArm_G angles, the global orientation angles of both upper arms, were used. For errors of the knee joint, the LShank_G and RShank_G angles, the global orientation angles of both shanks, were used.

Aim 1: Plane of Motion

Aim 1 seeks to answer the first question posed from observations of Tables 5 and 6. Does the plane involved in a motion affect the ability of the Vitalize system to accurately track the motion? To address this question, two analyses were performed:

- Analysis 1: Frontal vs. Sagittal Plane motions of the hip
- Analysis 2: Frontal vs. Sagittal vs. Bi-planar motions of the shoulder

The knee was not used in this analysis because of the anatomical lack of frontal plane motions involving the knee.

Analysis 1: Hip

The exercises at the hip can be characterized as either frontal plane or sagittal plane motions. The following lists indicate the exercises that were included for the frontal plane group and the sagittal plane group. This analysis compares all the hip motions completed in the frontal plane to all the hip motions completed in the sagittal plane.

Frontal Plane

- Side Step
- Jumping Jack (full)
- Side Jump
- Jumping Jack (Mid)
- Jumping Jack (no arms)
- Side Hop

Sagittal Plane

- March with No Arms (Partial)
- March with No Arms (Mid)
- March with No Arms (Full)
- Squat (Partial)
- Squat (Mid)
- Squat (Full)
- Lunge (mid)
- Step Forward and Back
- Low Kick
- Lunge (full)
- Squat Jump (No Arms) (Full)
- Seated Knee Strike
- Lunge with Wood Chop
- Knee Strike
- Wood Chop with Squat
- Seated Low Kick
- Dodge Cross with Squat
- Knee Strike with Overhead Arms
- Knee Strike with Row
- Sit to Stand (Raised Seat) (Mid)
- Sit to Stand (Full)

The data from all frontal plane motions was compared to the data in all sagittal plane motions; this comparison is pictured in the below boxplot (Figure 17).

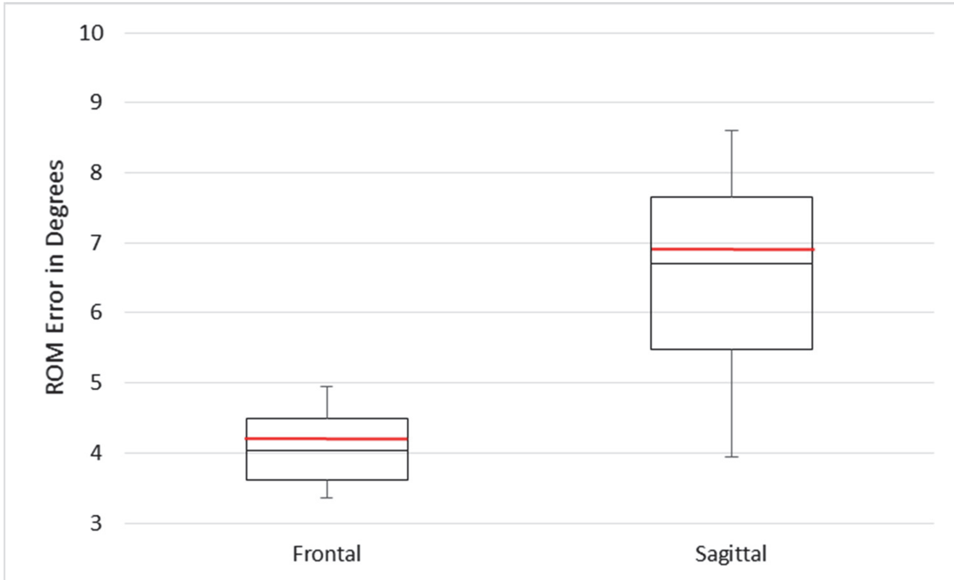


Figure 17. Boxplot comparing Frontal vs. Sagittal Error for all Hip Motions. The middle black bar indicated median values and the red bar indicates mean values.

It can quickly be seen that on average, the frontal plane motions (mean 4.2°) have less error than the sagittal plane motions (mean 6.9°). A two-tailed t-test assuming unequal variance was performed between the frontal and sagittal planes and it was found that the sagittal plane motions have significantly more error than the frontal plane motions at the $p=0.05$ significance level [$t(21)=-4.81$, $p<0.001$]. It can also be observed from the boxplot in Figure 17, that the sagittal plane motions seem to have higher variance than the frontal plane motions. However, the sagittal hip motions also have much higher ranges of motion than the frontal motions, which may contribute to the higher tracking error. So in the following statistical, exercises with similar ranges of motion were selected for comparison. The frontal plane exercises included in this analysis were

- Jumping Jack (full)
- Jumping Jack (no arms)
- Side Step
- Side Jump

Exercises included in the sagittal plane were

- Step forward and back
- Squat (partial)
- March (partial)
- Seated Low kick

The exercises were combined into groups of frontal (mean=3.4°) and sagittal (mean=4.8°); a two-tailed t-test assuming unequal variance was used to compare the groups. At the $p<0.05$ level, there was a significant difference between the frontal plane and the sagittal plane for hip motion [$t(214)=-2.38$, $p=0.018$]. There is significantly less error for the Vitalize system in tracking hip motions in the frontal plane than motions in the sagittal plane.

Analysis 2: Shoulder

A similar analysis was completed on the shoulder. At the shoulder, there is a third category of motion: bi-planar motions which involve motion in both the sagittal and frontal planes, not purely in either plane. The motions used in the planar analysis for the shoulder are as follows:

Frontal Plane

- Bilateral Arm Raise (partial)
- Unilateral Arm Raise (partial)
- Unilateral Arm Raise (full)

Sagittal Plane

- Jab
- Row
- Overhead Arms

Bi-Planar

- Cross-Body Reach in (partial)
- Cross-Body Reach out (mid)
- Cross-Body Reach in (mid)

These motions were not controlled for range of motion, they span the whole range available in the data from this study.

Using these groupings, a one-way ANOVA was used for comparison. There was a significant difference between the groups at the $p<0.05$ level [$F(2,291)=14.07$, $p=<0.001$]. Figure 18 gives a visual of the groupings used in the ANOVA.

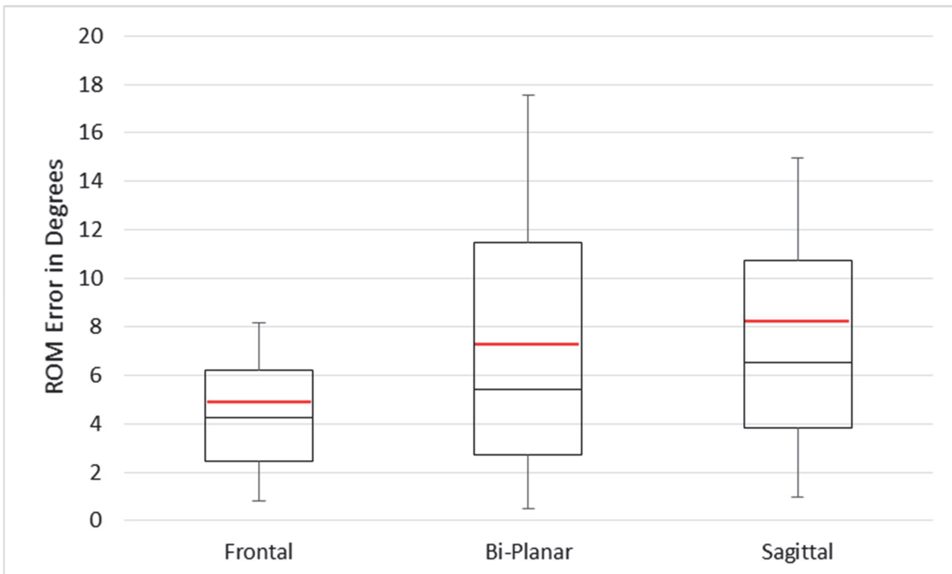


Figure 18. Boxplot Comparing Planar Error for Shoulder Motions (ROM not controlled). The red bar indicates mean values, the black bar indicates median values.

The frontal plane had the least average error, (4.8°); followed by the bi-planar motions (7.5°) and the sagittal plane (8.1°). Post hoc testing was performed with a Bonferroni correction to determine which groups differed significantly. Two-sample, two-tailed t-test assuming unequal variance with a significance level of $\alpha/3$ (where $\alpha=0.05$; for the Bonferroni correction) were used to compare

- Frontal Plane group to Both-plane group
- Both-Plane group to Sagittal plane group
- Frontal Plane group to Sagittal plane group

There was a significant difference for exercises in the frontal plane as compared to the bi-planar motions [$t(96)=-3.67$, $p<0.001$]; and as compared to the sagittal plane [$t(180)=-5.62$, $p<0.001$]. There was not a significant difference between the bi-planar and sagittal plane groups [$t(145)=-0.674$, $p=0.50$]. The bi-planar motions had more variance than the sagittal plane motions which had more variance than the frontal plane motions, this can be seen by the extended box and error bars of the bi-planar and sagittal plane motions in the boxplot (Figure 18) as compared to the frontal plane motions. When looking at the average error values, the average error of the bi-planar motions falls between the average errors of the frontal and sagittal groups, which supports the hypothesized relationship between plane and error that was observed at the hip: that the frontal plane is tracked with more accuracy than the sagittal plane.

This is the result that was expected because of the relationship between plane of motion and error that was observed at the hip. However, these results were not controlled for range of motion, and it is suspected that range of motion has an effect on the error. So the previous analysis was repeated, but with a smaller number of motions with similar ranges to control for tracking error due to the different ranges of motion. The exercises that were used in the following analysis are

Frontal Plane
- Bilateral Arm Raise (partial)
- Unilateral Arm Raises (partial)

Bi-Planar
- Reach in (partial, mid)
- Reach out (mid)

Sagittal Plane
- Row
- Jab

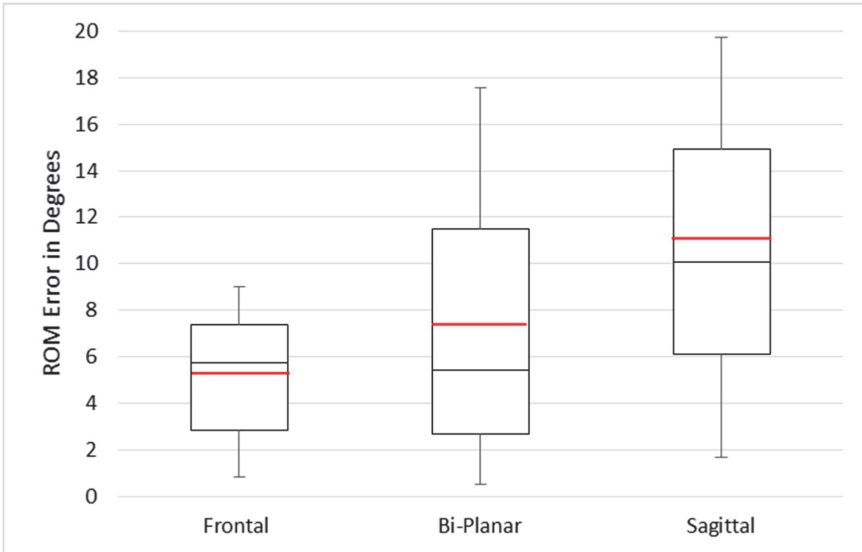


Figure 19. Boxplot Comparing Planar Error for exercises with Controlled ROM at the Shoulder. The red bar indicates mean values, the black bar indicates median values.

The frontal plane had the least average error (5.6°); followed by the bi-planar motions (7.5°) and the sagittal plane (10.7°); these average errors can be seen as the red line in the above box-plots. A one-way ANOVA showed that there was a statistically significant difference between the groups at the $p<0.05$ level [$F(2,174)=12.21$, $p<0.001$].

The results with controlled range of motion mirrored the results obtained with uncontrolled range of motion. Post hoc tests using a Bonferroni correction determined that there was a significant difference for exercises in the frontal plane as compared to the exercises in the sagittal plane [$t(89)=-5.38$, $p<0.001$]; and for bi-planar exercises as compared to the sagittal plane [$t(117)=-2.98$, $p=0.003$]. But there was not a significant difference between the frontal and bi-planar groups [$t(116)=-2.306$, $p=0.023$].

It can be concluded that there is significantly less error in the Vitalize system for shoulder motions in the frontal plane than for shoulder motions that are in the sagittal plane. Motions that involve both planes consistently have more error than purely frontal plane motions but less error than purely sagittal plane motions, which supports the finding that frontal plane motion is more accurately tracked by the exergaming system than sagittal plane motion.

The effect of the plane of motion is supported at both the hip and shoulder; the frontal plane is more accurate than the sagittal plane. At both the hip and shoulder, an analysis was performed that controlled for the range of motion because it is suspected to have an impact on the error. The direct effects of the range of motion of an exercise on the error of the Vitalize system is now addressed in Aim 2.

Aim 2: Range of Motion

To discover the effect range of motion has on the error of the Vitalize system, several analyses were completed. Because a significant effect has been found based on the plane of motion, these analyses werebcontrolled for plane. Three joints were used: the hip, shoulder and knee. The five analyses that were completed are:

- Hip in the sagittal plane
- Knee in the sagittal plane
- Shoulder in the sagittal plane
- Hip in the frontal plane
- Shoulder in the frontal plane

The knee was only analyzed in the sagittal plane because of the anatomical lack of frontal plane knee motion. Range of motion is a continuous variable, as opposed to the discrete variables of “frontal” or “sagittal” plane. To take this into account, correlations were performed with the range of motion data to determine the relationship between range of motion and errors. However, during data collection some of the exercises were split into discrete groups based on the range of motion, for example: full ROM march, mid ROM march, partial ROM march; so some categorical statistical analyses are also performed in this section.

Analysis 1: Sagittal Plane, Knee

The first analysis performed was for sagittal knee motions. All sagittal plane motions collected that involved the knee were used in this analysis; these motions include

- Squat Jump
- Squat (full)
- March (full)
- Lunge (full)
- Low Kick
- Step Forward and Back
- Knee Strike
- Wood Chop with Squat
- Dodge Cross with Squat
- Lunge with Wood Chop
- Knee Strike with Overhead Arms
- Knee Strike with Row
- Squat (mid)
- Lunge (mid)
- March (mid)
- Squat (partial)
- March (partial)

The range of motion (ROM) was plotted against the range of motion error, the results are pictured below in Figure 20.

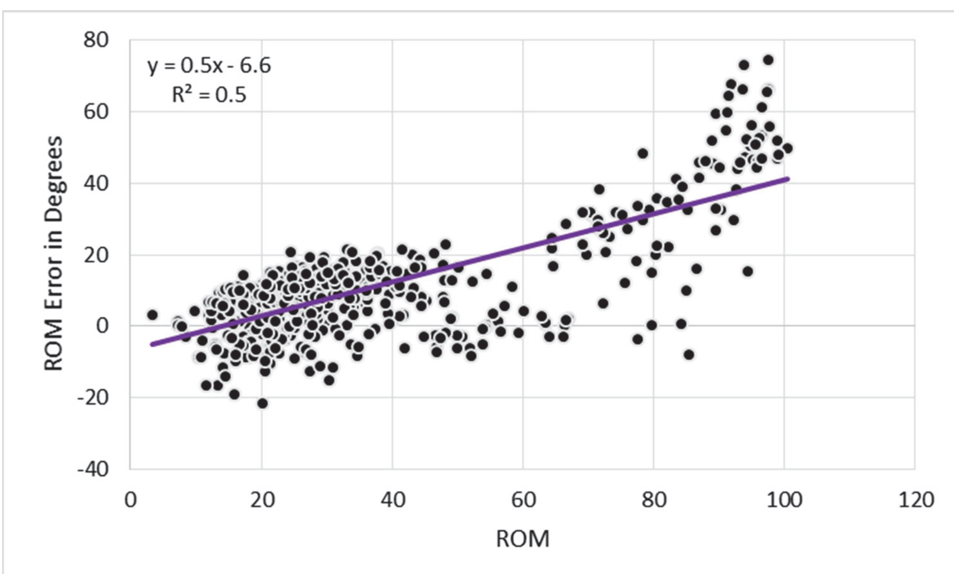


Figure 20. Correlation Plot of ROM vs ROM Error for All Sagittal Knee Motions

There is a strong correlation (r=0.73) between ROM and ROM Error when all sagittal knee motions are considered. Figure 20, above, represents the error involved at the start of the motion and at the peak point of the motion (which combine to make the ROM Error). Start error was not further analyzed in this study, but the error at the peak was. The range of motion of the data was plotted against the error at the peak of the motion, the results (Figure 21) are very similar to the results of the ROM vs ROM Error in Figure 20.

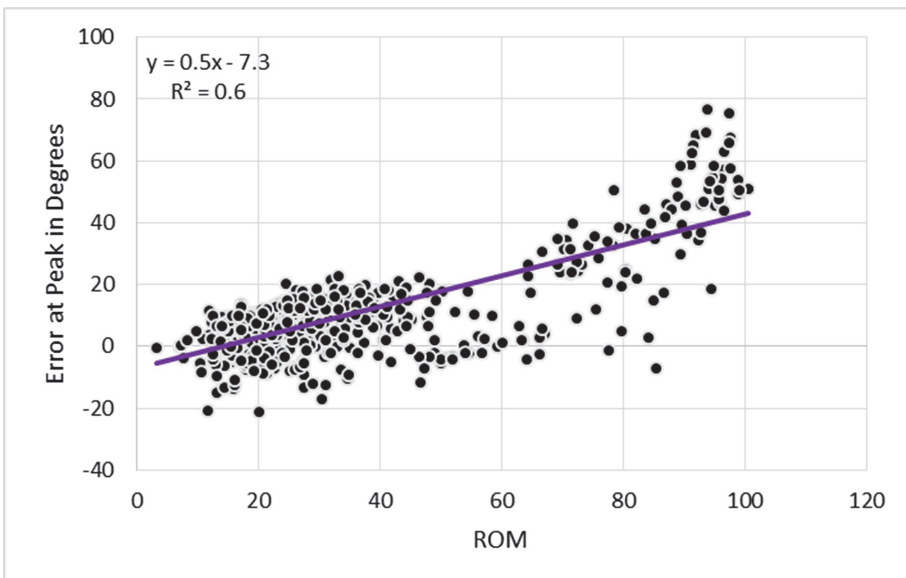


Figure 21. Correlation plot of ROM vs. Error at the Peak of Motion for All Sagittal Knee Motions

Again, there is a very strong correlation (r=0.74) between the ROM and the error at the peak of the motion. In both Figures 20 and 21 it can be seen that as the ROM of an exercise increases, the error associated with that exercise also increases. It can also be seen that the variability increases at the larger ranges of motion. At the low ranges of motion, the data points are tightly clustered, but as the ROM increases, they start to spread out. The data has a natural split at around 60° range of motion. In the following boxplot (Figure 22) the exercises with low ROM (0-60°) were compared to the exercises with high ROM (60-110°).

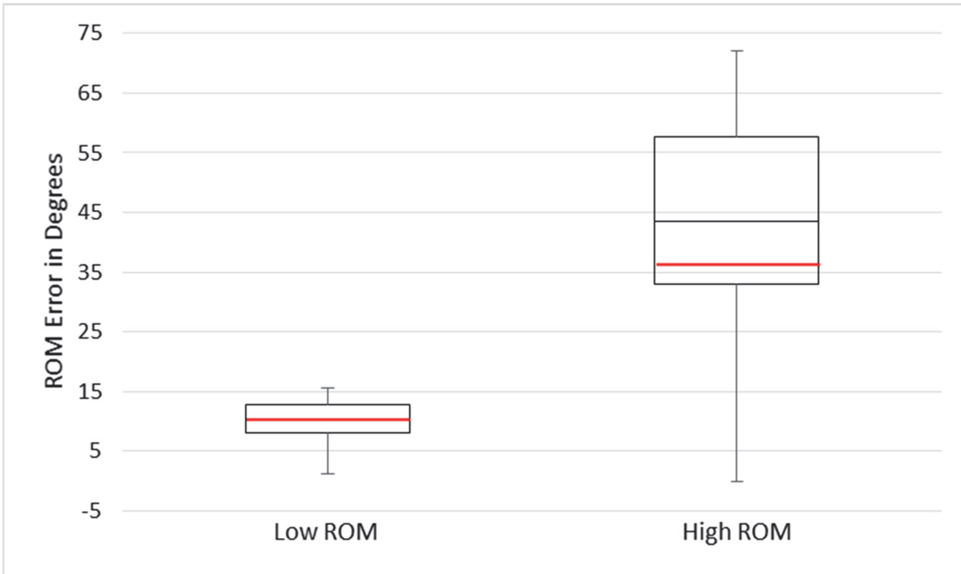


Figure 22. Boxplot Comparing Sagittal Knee Error for Low and High ROM. The red bar indicates mean values, the black bar indicates median values.

This boxplot agrees with the correlation plots that there is a steep increase in the error for motions that have a high ROM (mean=37.0) as compared to those with low ROM (mean=10.2). A two-tailed t-test assuming unequal variance showed that the high ROM motions have significantly more error, on average, than the low ROM motions [$t(88)=-13.7$, $p<0.001$]. It also clearly shows the increase in variability with the high ROM exercises.

The RMS error takes the entire motion into account, whereas the ROM error only looks at the two points that form the ROM. The RMS error emphasizes the magnitude of the errors and removes directional effect. The RMS error was also plotted against the ROM (Figure 23) and appears similar to the ROM error and the error at the peak plots (Figures 20 and 21).

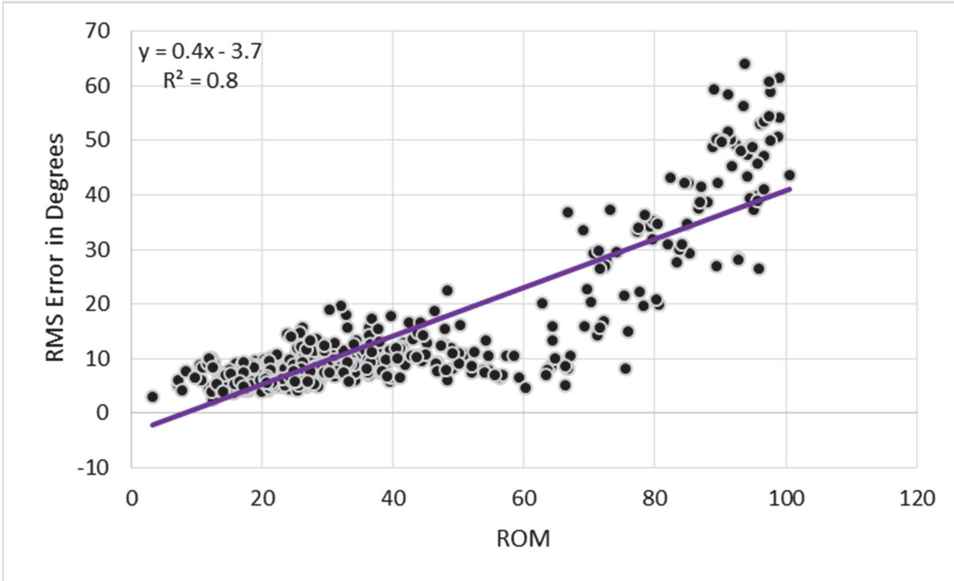


Figure 23. Correlation plot of ROM vs. RMS Error for All Sagittal Knee Motions

There is a very strong correlation (R=0.84) between RMS Error and ROM. The increase in slope past the 60° point may be caused by joint occlusion; at higher ranges of motion in the sagittal plane, the knee and the joints around it become occluded from the Kinect camera. This should cause a sharp increase in error, which can be observed in Figures 20, 21 and 23. This causes a trend that appears to be exponential when analyzing the error; the slope of the trend line greatly increases past the 60° ROM point. It can be seen again that the variance increases at high ranges of motion. For example, at around 90° ROM the errors vary from around 25° to 65°.

To continue analysis on the knee in the sagittal plane, two exercises that were collected at different ROM values were paired and analyzed

- Lunge (full ROM, mid ROM)
- March (full ROM, mid ROM, partial ROM)

The lunge and march data is plotted below (Figure 24) with ROM vs ROM Error. The trend is the same as previously observed when all the exercises were included.

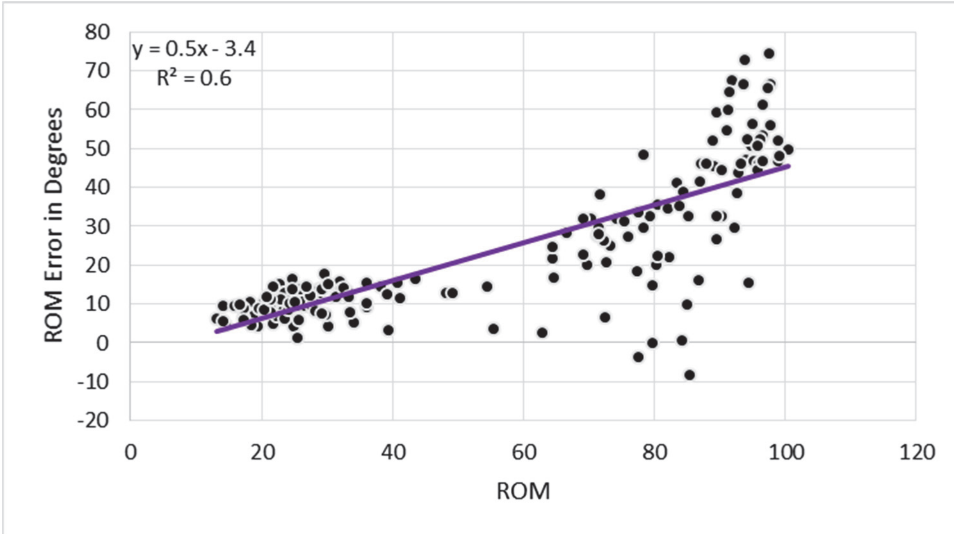


Figure 24. Correlation plot for ROM vs. ROM Error of Knee Angle for March & Lunge exercises grouped by Range of Motion

The categorical groups of Full, Mid and Partial ROM were compared using a one-way ANOVA. The ANOVA showed a statistically significant difference between the groups at the p<0.05 level [F(2,146)=10.09, p=<0.001]. These groups can be seen in the boxplot below (Figure 25).

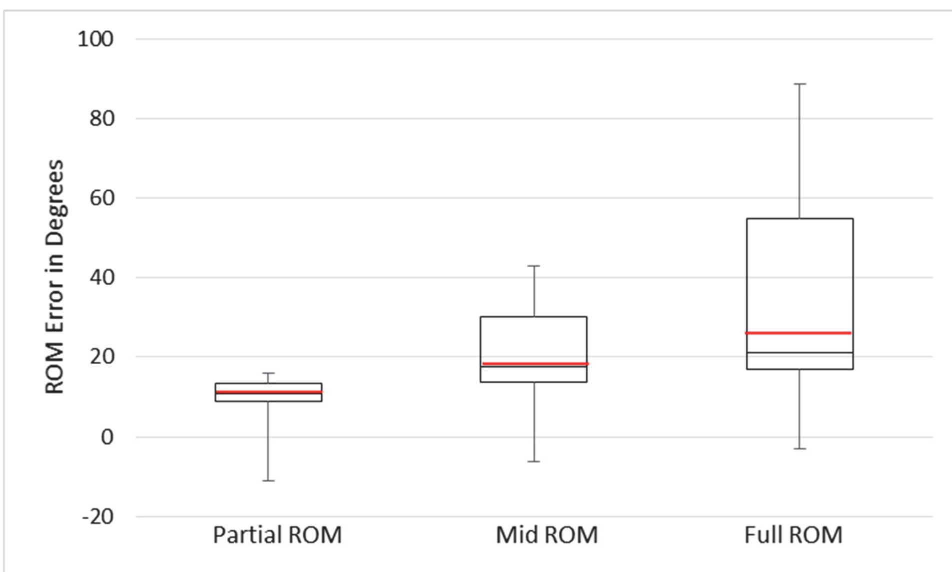


Figure 25. Boxplot comparing the ROM Error for Different ROM in Sagittal Knee Motions. The red bar indicates mean values, the black bar indicates median value.

The partial ROM group had an average error of 11.1°; the mid ROM group had an average error of 17.4°, and the full ROM group had an average error of 26.1°. The trend in variance is also very clear here. The partial ROM motions have small variance, whereas the full ROM motions show considerable variance.

Additional Post Hoc testing was completed with a series of t-tests using a Bonferonni Correction ($\alpha/3$, $\alpha=0.05$). It was found that the error from all three ROM groupings differed significantly from each other. The partial ROM error was significantly lower than the mid ROM error ($p<0.001$) and the full ROM error ($p<0.001$); the mid ROM error was also significantly lower than the full ROM error ($p=0.008$). From this data it can confidently be concluded that for knee motions in the sagittal plane, the error and variability increase as the range of motion increases; with a sharp rise in the rate of error increase once the motions start to go beyond the 60° range. This is likely due to the occlusion that occurs at high knee flexion angles.

Analysis 2: Sagittal Plane, Hip

The second analysis examines hip motions in the sagittal plane. At the hip, findings similar to those at the knee (in Analysis 1) were seen, but not as clearly. The exercises that are included in the first part of this analysis are:

- March (full)
- Lunge (full)
- Low Kick
- Step Forward and Back
- Knee Strike
- Lunge with Wood Chop
- Knee Strike with Overhead Arms
- Knee Strike with Row
- Lunge (mid)
- March (mid)
- March (partial)

All seated exercises were excluded due to the possible effects of the occlusion of the hip joint at the start of the motions. Squat motions were also excluded due to issues with obscurement of pelvis markers in the Vicon dataset.

Figure 26, below, is the plot of all the data from the above exercises; the ROM is plotted against the ROM Error.

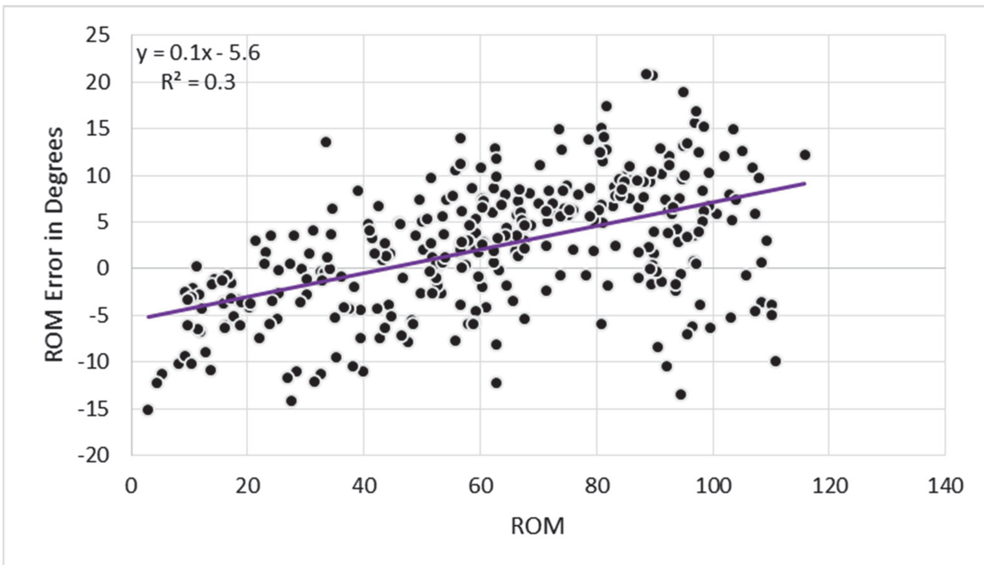


Figure 26. Correlation plot for ROM vs ROM Error of sagittal plane hip motions

There is a moderate correlation between the ROM and the ROM error for the sagittal plane motions of the hip (r=0.52). It can be observed from this data that at smaller ROM, the error values are negative whereas at higher ROM they are positive. This indicates that the Vitalize system is overestimating the hip angle at small ROM and underestimating the hip angle at high ROM. To better understand the error trend, the error at the peak of the motion was plotted against the ROM for all the exercises above, Figure 27 shows the results. It can be seen that the majority of the data is positive now; which indicates that the Vitalize system is consistently underestimating the angle of the hip at the peak of the motions.

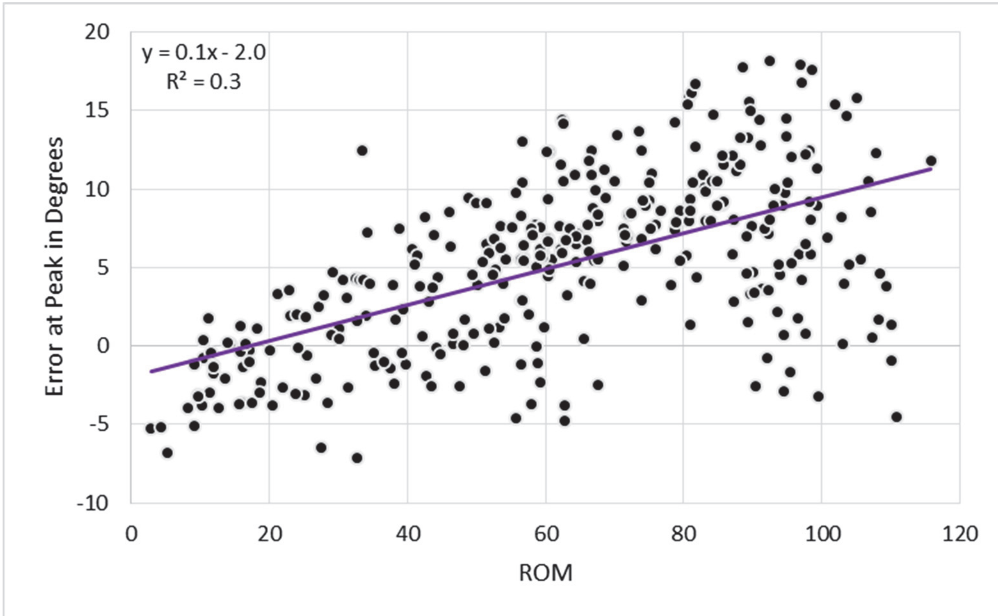


Figure 27. Correlation plot for Error at Peak vs ROM for sagittal hip motions

This plot shows a moderate correlation (r=0.57) with the error increasing as the ROM increases. From Figure 27, it can be seen that not only does the error increase in magnitude as the ROM increases, but the variance of the error also increases. This is seen in the rough trumpet-shape of the data. The data around 20° ROM (on the x-axis) has errors with low variance, with the values varying from around -5° to 2°, but data around 100° ROM (on the x-axis) has high variance with errors that vary from -5° to nearly 20°.

To analyze the magnitudes of the error, the data was grouped by ROM. The 60° ROM point was used as the dividing point because it is the midpoint between the maximum and minimum ROM values observed on Figure 27. The Low ROM group includes all exercises with ROM between 0 and 60°; the High ROM group includes all exercises with ROM between 60 and 120°. A boxplot (Figure 28) was created to visualize the error between the ROM groups using the magnitude of the error at the peak of the motions.

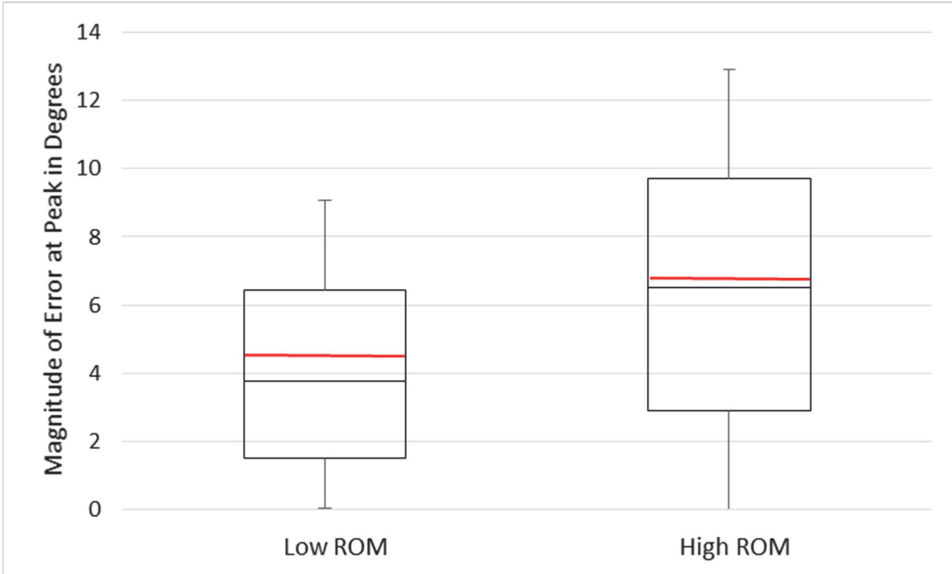


Figure 28. Boxplot comparing Error at the Peak of Low ROM to High ROM Sagittal Hip Motions. The red bar indicates mean values, the black bar indicates median values.

It can be seen that the error at the high ranges of motion is greater than the error at low ranges. However, the difference here is not nearly as stark as the difference observed at the knee (Figure 22). The low ROM group has an average of 4.5° error at the peak and the high ROM group has an average of 6.7° error at the peak. A two-tailed t-test confirmed that the high ROM group had significantly more error than the low ROM group [$t(506)=-6.57$, $p<0.001$]. It can be seen again that the motions with higher ROM also have higher error variance.

The trend toward higher error and increased variance are supported across the entire motion by the RMS error. Figure 29 shows the correlation plot of RMS error vs ROM. This figure shows a strong positive correlation between RMS Error and ROM ($r=0.60$). This demonstrates that as the range of motion increases, the error of the Vitalize system at the peak of the motion also increases. This agrees with the relationship between ROM and error observed for knee motions in the sagittal plane.

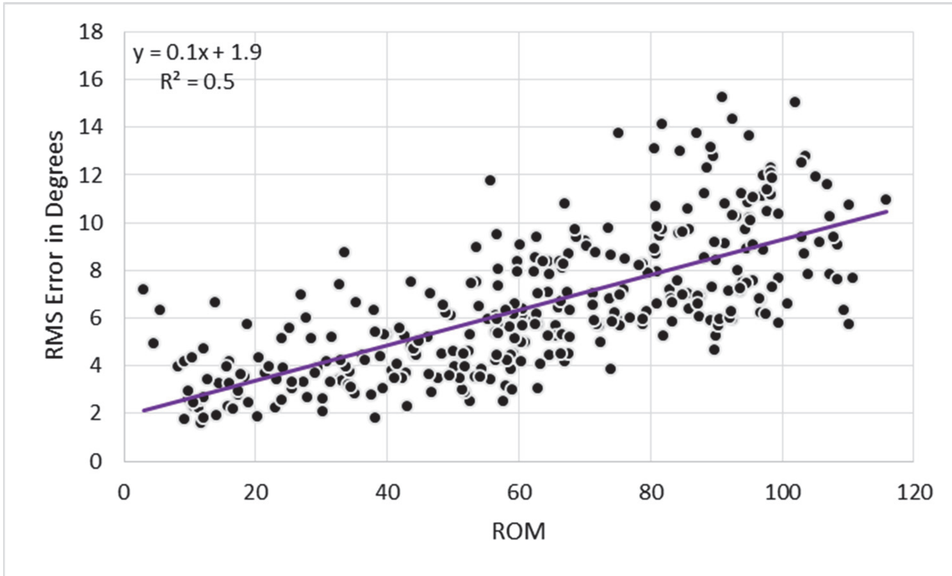


Figure 29. Correlation plot for ROM vs RMS Error for Sagittal Hip Motions

From Figure 29, above 80° of ROM (on the x-axis) there may also be an increase in the rate of RMS error increase; this would agree with the error due to obscurement hypothesis from Analysis 1 at the knee. That the increasing error seen as ROM increases is due to the joint observed being obscured from the Kinect sensor.

To further explore this data, two exercises that were collected multiple times with different ranges of motion categories were selected for analysis:

- Lunge (full ROM)
- Lunge (mid ROM)
- March (full ROM)
- March (mid ROM)
- March (partial ROM)

The ROM of these exercises is plotted against the ROM Error in Figure 30. There is a moderate positive correlation between ROM and ROM Error (r=0.577) when only considering the ROM variations of the March and Lunge exercises. This again indicates that there is a relationship between the ROM of the exercise and the tracking accuracy of the Vitalize system: when the ROM increases, the tracking error also increases.

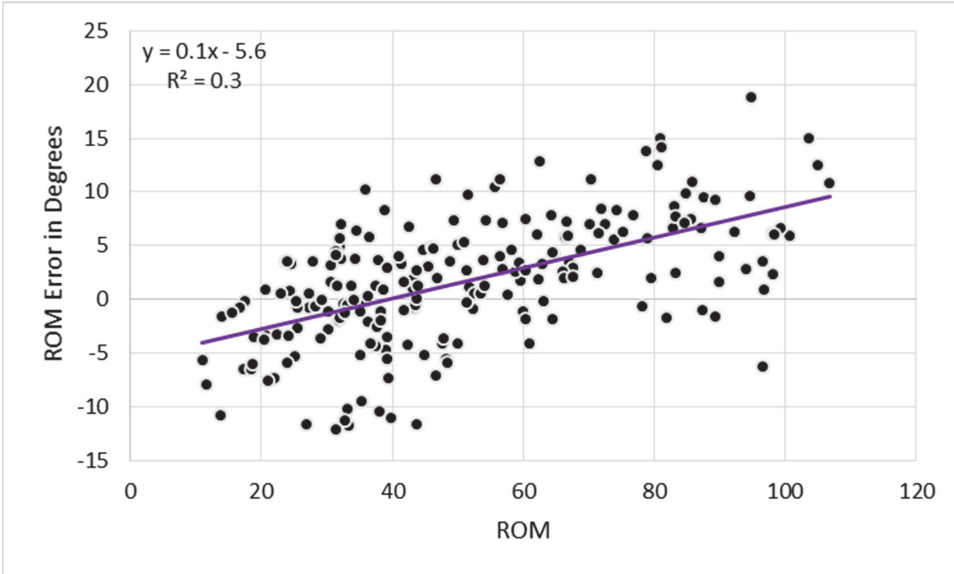


Figure 30. Correlation plot for ROM vs ROM Error for Select Sagittal Plane Hip Motions based on ROM groupings

If just the magnitude of the tracking error that occurs at the peak of the motion is considered (seen in Figure 31) the positive trend between ROM and the tracking error of the Vitalize system becomes stronger.

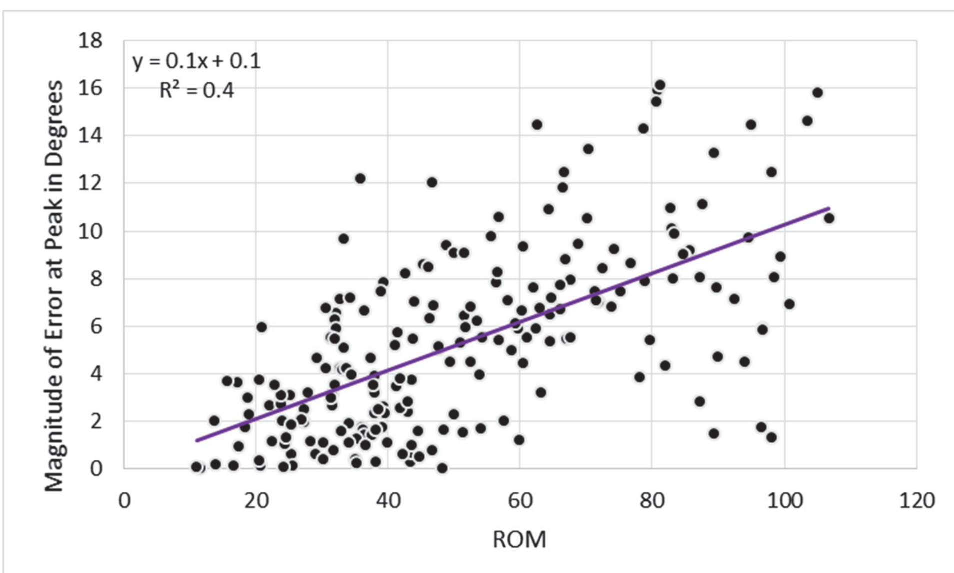


Figure 31. Correlation plot for ROM vs. Error at the Peak (magnitude) for Select Sagittal Hip Motions based on ROM groupings

There is a strong correlation between the magnitude of error at peak vs. ROM (r=0.63). This indicates that more error is occurring at the peak of motions that have a large ROM than at the peak of motions that have smaller ROM. This is supported by the RMS Error data, pictured below in Figure 32.

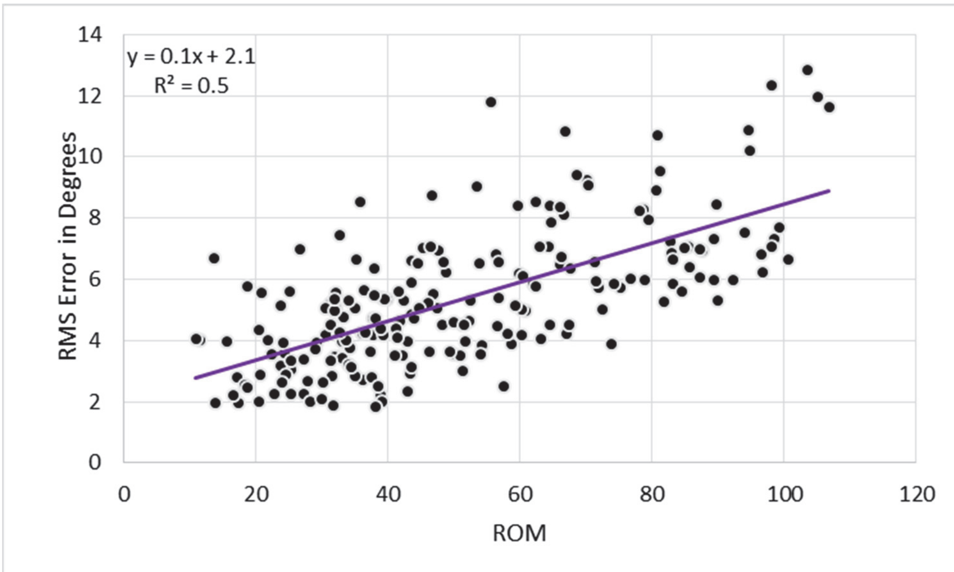


Figure 32. Correlation plot for ROM vs RMS Error for Select Sagittal Hip Motions based on ROM groupings

There is a strong correlation between RMS error and the ROM of the exercises (r=0.67). The RMS error takes into account the error along the whole waveform of the motion, which provides additional support toward the conclusion that the error is increasing as the range of motion increases.

These motions were combined into three categories: Full, Mid and Partial ROM. A one-way ANOVA was performed to determine the effect of range of motion on sagittal-plane hip motions. In agreement with the correlation data, the statistical analysis showed that the error increased as the range of motion increased. The ANOVA showed that the range of motion of an exercise has a significant effect on the error of the Vitalize system for sagittal plane hip motions [$F(2,144)=5.23$, $p=0.006$]. Figure 33, below, is a boxplot of the categories used in the ANOVA.

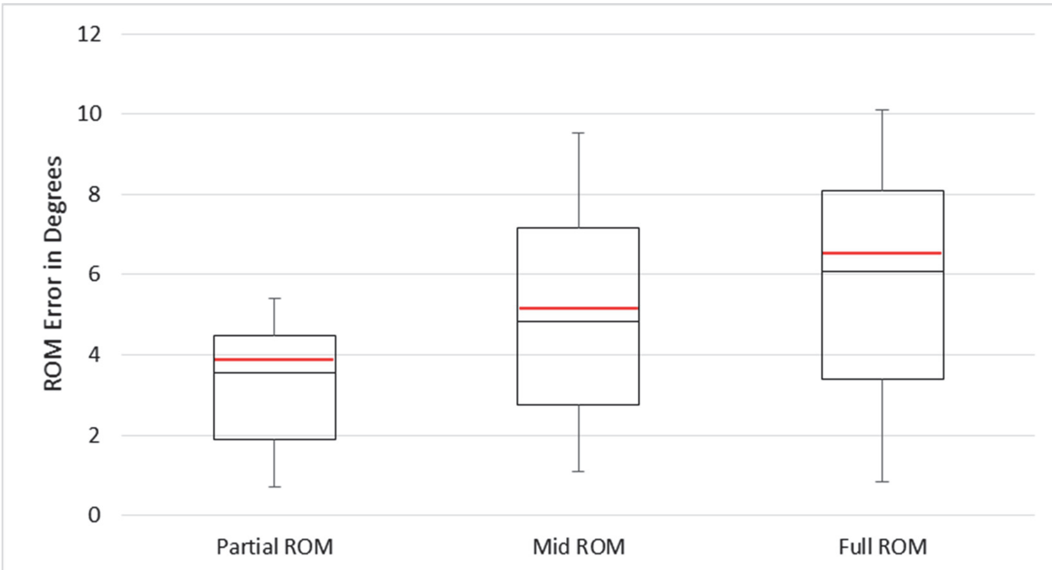


Figure 33. Boxplot comparing ROM Error of Different ROM for Select Sagittal Hip Motions. The red bar indicates mean values, the black bar indicates median values.

The partial ROM category has a mean error of 3.9°; the mid ROM category has a mean error of 5.3° and the full ROM category has a mean error of 6.4°. Post hoc testing was performed with two-tailed t-tests assuming unequal variances using a Bonferroni correction ($p=\alpha/3$, where $\alpha=0.05$) to discover where the significant differences exist. Three t-tests were performed:

- Full ROM vs. Mid ROM
- Full ROM vs. Partial ROM
- Mid ROM vs. Partial ROM

The tests showed that the mid ROM motions did not have significantly more error than the partial ROM motions [$t(69)=2.03$, $p=0.046$] or the full ROM motions [$t(115)=-1.70$, $p=0.093$]. But the full ROM motions had significantly more error than the partial ROM [$t(78)=3.46$, $p<0.001$]. The boxplots also show that there is more variance for the mid- and full ROM motions than for the partial ROM motions. This supports both the initial observations of Table 6 and the results from Analysis 1 at the knee: in the sagittal plane error and variance increase as range of motion increases.

Analysis 3: Sagittal Plane, Shoulder

A complete analysis could not be completed for sagittal plane motions of the shoulder. Because the exercises used in this study were chosen for maximal clinical relevance, the majority of the shoulder motions selected are performed in both the sagittal and frontal planes, not purely in either. There are three motions that are primarily in the sagittal plane; however, the starting positions and ranges of motion vary widely and therefore these motions are not well-matched for direct comparison. This combination of planes, differing start positions and wide ranges of motion are commonly seen in the shoulder motions used in daily activities, but it is not conducive to a controlled analysis.

However a case study can be completed to see if the hypothesis about occlusion in the sagittal plane is supported. The peak of the overhead arms exercise occurs when the arms are straight down by the sides of the body; the peak of the jab exercise occurs when the arm is straight out in front of the shoulder. If occlusion is an issue, the error at the peak of the overhead arms exercise, in which the shoulder is not occluded, should be higher than the error at the peak of the jab, where the shoulder is occluded from the camera. These errors were compared in the boxplot on the next page (Figure 34).

The error at the peak of the jab (mean error=13.2°) which is the occluded motion, is greater than the error at the peak of the overhead arms motion (mean error=4.6°) which is not occluded. The variance of the error is observed to be much greater in the jab than in the overhead arms motion as well.

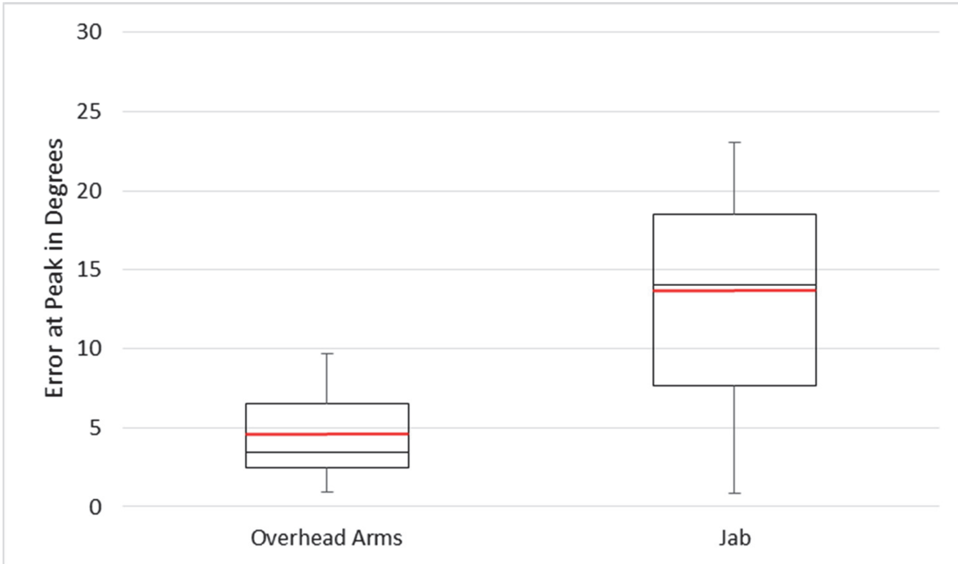


Figure 34. Boxplot comparing Error at the Peak for a Case Study of two Sagittal Shoulder Motions. The red bar indicates mean values, the black bar indicates median values.

The observations on mean error support the hypothesis that occlusion from the camera causes more tracking error for motions in the sagittal plane. The observations about the trends in variance of error also support the hypothesis. These findings intuitively make sense. If a joint is obscured from the sensor, the system will have more difficultly tracking the joint, which will result in higher average tracking error and more variance in the observed tracking errors.

Analysis 4: Frontal Plane, Hip

Analysis 4 marks the change from sagittal plane motions to frontal plane motions. A correlation was performed to determine the relationship of range of motion (ROM) vs ROM error for fontal plane hip motions, Figure 35. The following exercises were used:

- Side Step (Full)
- Jumping Jack (Full)
- Side Jump (Full)
- Jumping Jack (Mid)
- Jumping Jack (No Arms) (Full)

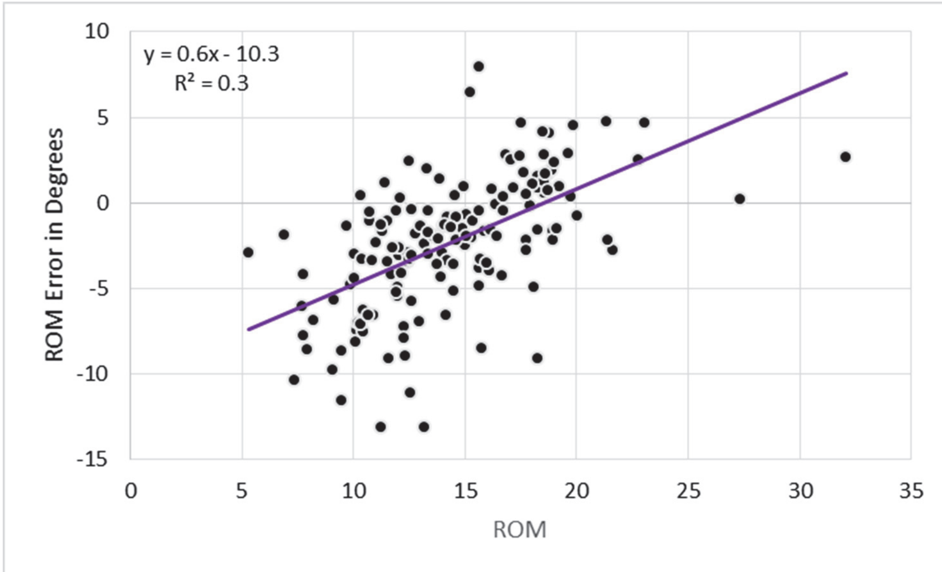


Figure 35. Correlation plot for ROM vs. ROM Error for All Frontal Hip Motions

There is a moderate correlation here between ROM and ROM error (r=0.57). The data was then further controlled to contain only jumping jack data, seen in Figure 36.

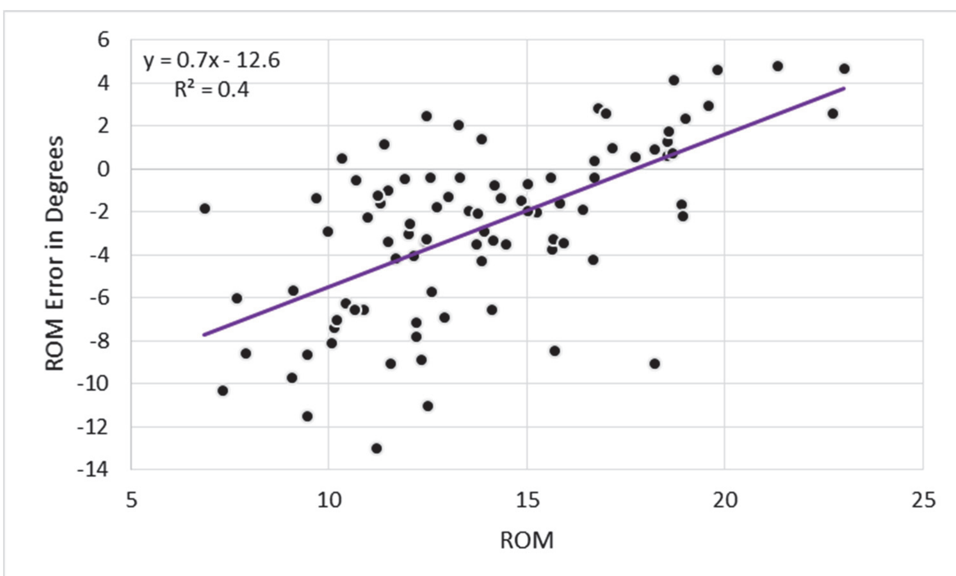


Figure 36. Correlation plot for ROM vs ROM Error for Select Frontal Hip Motions (Jumping Jacks)

Now a strong correlation exists for just the jumping jacks (r=0.62). Similar to what was observed at the hip with the sagittal plane motions, the data is split above and below the y-axis; at lower ROM values the error is negative, and at higher ROM values the error is positive. This indicates that at lower ROM values, the Kinect overestimates the hip angle and at higher ROM values the Kinect underestimates the hip angle. However, unlike the hip sagittal data, when looking at the magnitude of error in the frontal plane, there is no longer a correlation between ROM and error. This is seen vividly in Figures 37 and 38 which show the ROM vs. the magnitude of the error at the peak for all frontal plane hip motions and for the jumping jack motions, respectively.

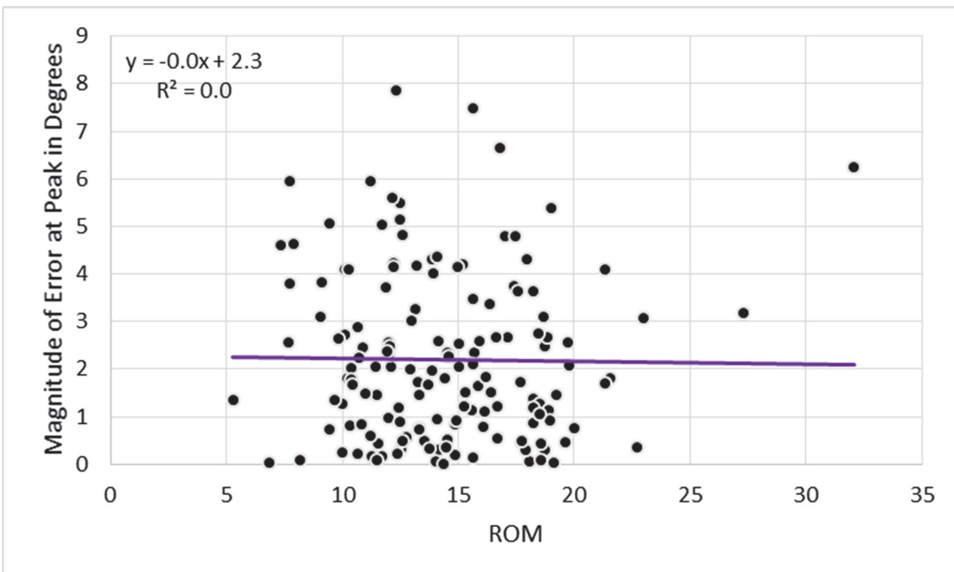


Figure 37. Correlation plot for ROM vs ROM Error (magnitude) for All Frontal Plane Hip Motions

The directional effect was removed by taking the absolute value of the error. The magnitude of the ROM Error has a very weak correlation to the ROM when all the data is considered (r=-0.01).

In Figure 38, on the next page, the magnitude of the error at the peak of the motion was plotted against the ROM for the hip angle of the more controlled frontal plane hip motion group, the jumping jacks.

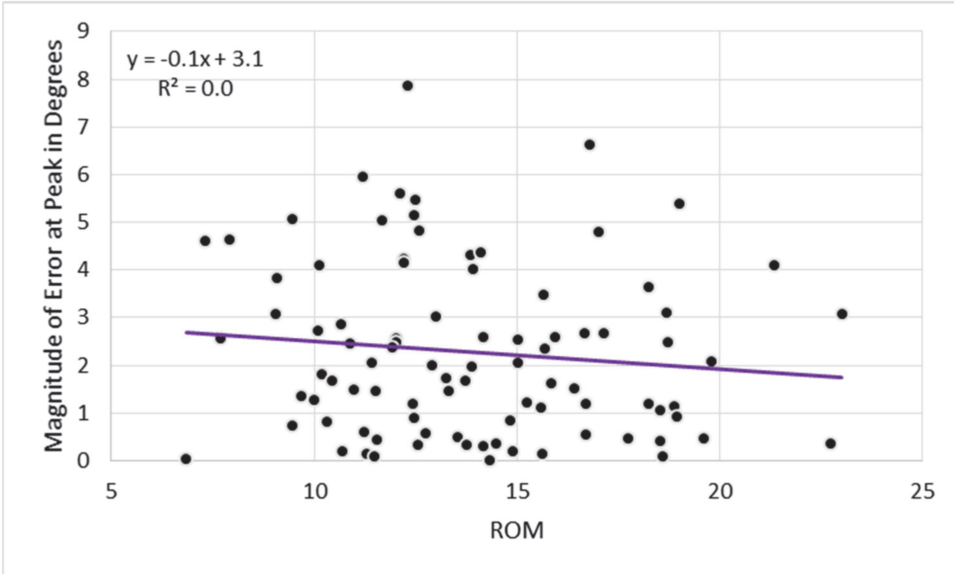


Figure 38. Correlation Plot for ROM vs. Error at Peak (magnitude) for Select Frontal Hip Motions (Jumping Jacks)

For the more controlled data, using only jumping jack motions, there is also a very weak correlation between the magnitude of the error at the peak of the motion and the range of motion (r=-0.11). This is in direct contrast with the controlled sagittal hip data using the march and lunge (Figure 31), where a strong correlation (r=0.63) existed between the magnitude of the error at the peak of the motions and the ROM. This indicates that the error trend observed in the frontal plane for hip motions (See Figures 35 and 36) is due the overestimation and underestimation of the hip angle by the Vitalize system as ROM increases, not due to the magnitude of the error.

The data from all frontal hip motions was divided into low and high ranges of motion at 15 degrees, which is roughly half the largest range of motion observed. The boxplots below (Figure 39) demonstrate how the magnitude of the tracking error is related to the range of motion. The error at the low ranges of motion (mean=2.5°) is similar to the error at the high ranges of motion (mean=2.1°).

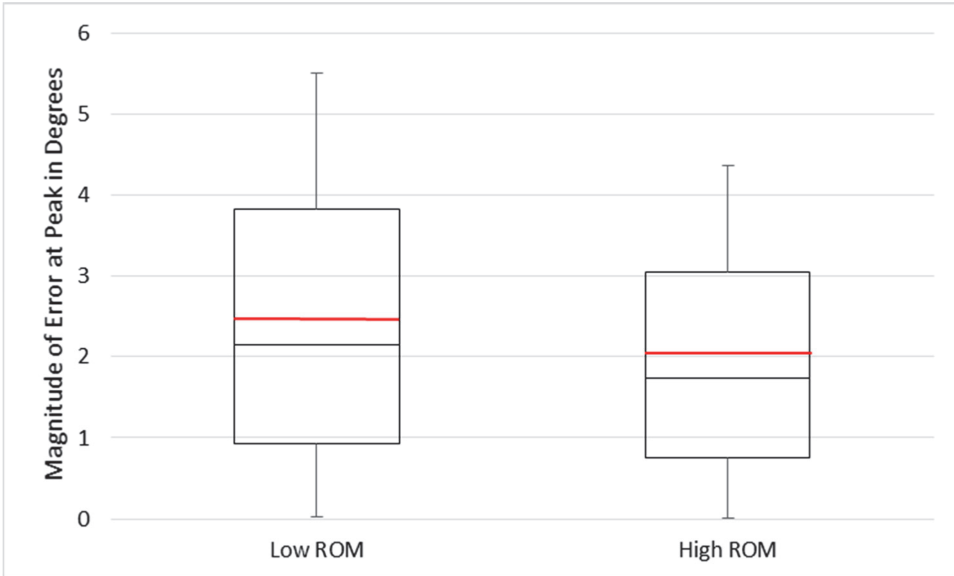


Figure 39. Boxplots comparing ROM Error of Low ROM and High ROM Frontal Hip Motions. The red bar indicates mean values, the black bar indicates median values.

A t-test confirmed that there is no significant difference between the errors of these groups [t(93)=1.33, p=0.18]. The variance between groups is also very similar, with slightly more variance in the low ROM group. This lack of correlation between range of motion and error is supported by the RMS error, pictured below (Figure 40).

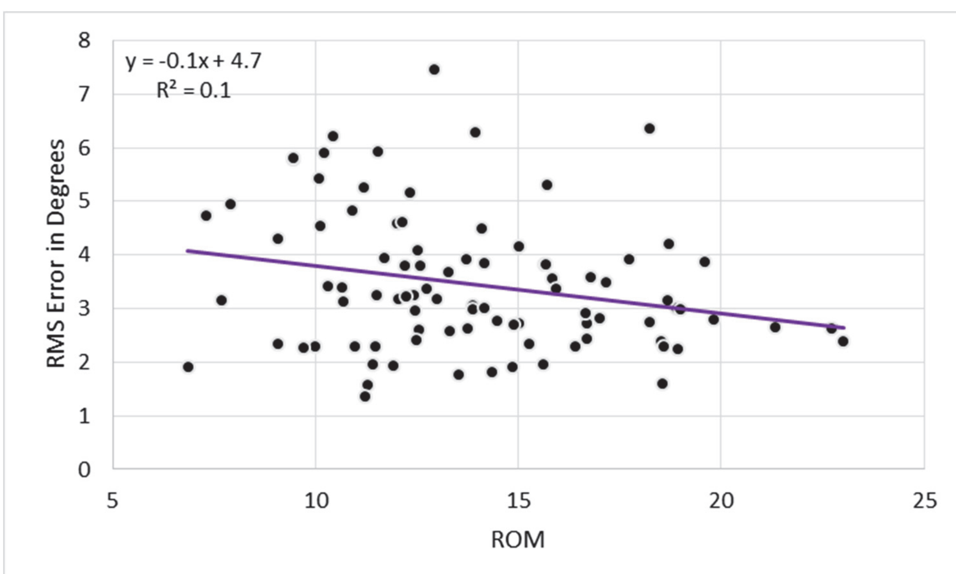


Figure 40. Correlation Plots for ROM vs. RMS Error for Select Frontal Hip Motions (Jumping Jacks)

The RMS error removes the directionality effect. There exists only a weak correlation between the RMS error and the ROM (r=-0.24) for error at the hip during the jumping jacks. Again, it can be seen that there is slightly higher variance at lower ranges of motion; which is opposite what was observed at the hip in the sagittal plane, where the high range of motion activities had both higher error and variance. The lack of correlation seen here supports the conclusion that the observed trend for all frontal hip motions in Figure 35 (at the beginning of this analysis) is due to the directionality of the angle not a relationship between the magnitude of error and the range of motion. Contrary to the findings in the sagittal plane, the variance in the frontal hip motions was slightly larger at smaller ranges of motion.

For hip motions in the frontal plane, a trend toward more error as ROM increases was found; but it is due to the Vitalize system overestimating the hip angle at small ranges and underestimating the angle at large ranges; it was found that no relationship between the magnitude of error and ROM exists for frontal hip motions. This consistent overestimation at small ROM and underestimation at large ROM was a unexpected finding of this study.

Analysis 5: Frontal Plane, Shoulder

The final analysis of Aim 2 examines shoulder motions in the frontal plane. The plot of ROM vs ROM Error for all the shoulder motions that occur in the frontal plane is included below, Figure 41.

- Arm Raise (full)
- Arm Raise (mid)
- Jumping Jack (Full)
- Arm Raise (partial)
- Jumping Jack (Mid)

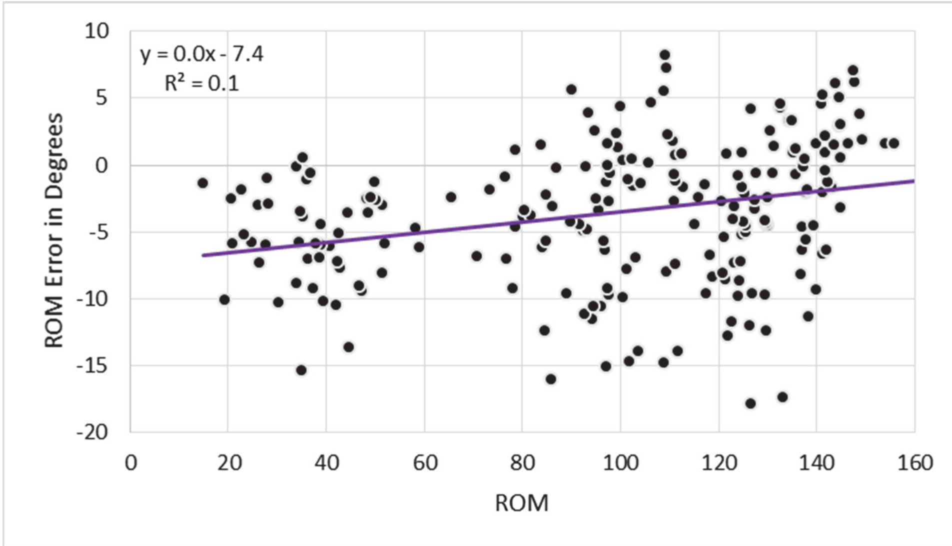


Figure 41. Correlation Plot for ROM vs ROM Error of all Frontal Plane motions that involve the Shoulder

The correlation between the ROM error and ROM is weak (r=0.28). This indicates that there is not a relationship between ROM error and ROM for frontal plane shoulder motions. Similar results are seen when viewing the error at the peak of these shoulder motions compared to the ROM, which is pictured in the correlation plot in Figure 42.

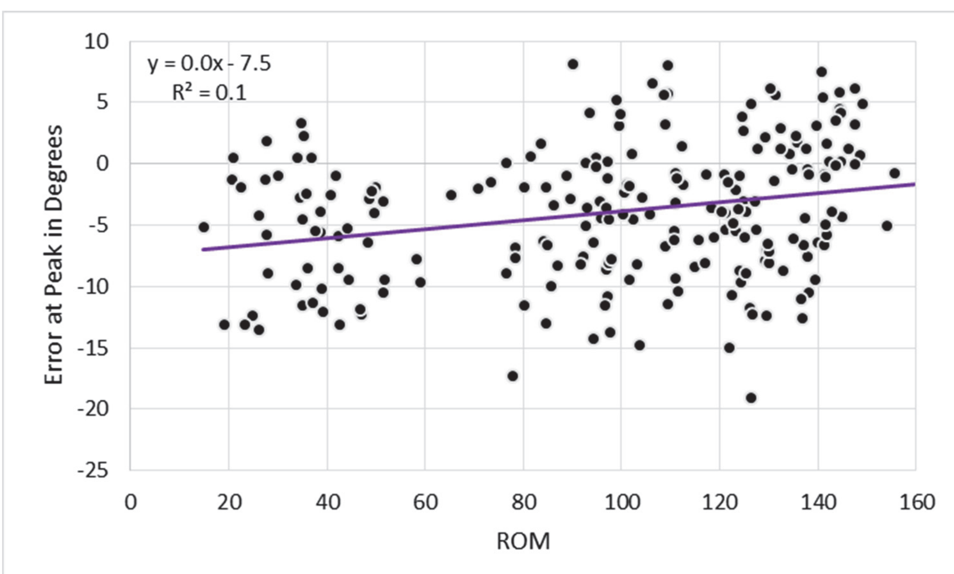


Figure 42. Correlation Plot for ROM vs. Error at Peak for all Frontal Shoulder Motions

Again, the correlation is weak (r=0.26). It can be seen in both Figure 41 and 42 that the majority of the data is negative; this shows that the Vitalize system is consistently overestimating the shoulder angle. The lack of correlation between the error and ROM along with the lack of variation between over and underestimations supports the idea from the hip motions in the frontal plane that any observed trends in the relationship between error and ROM are due to an overestimation/underestimation of error by the Vitalize system. A slight increase in the variance is seen as the ROM increases when all frontal shoulder motions are considered.

The error was then split into two groups based on the ranges: low ROM and high ROM. A visualization of the data is provided in the boxplot below (Figure 43).

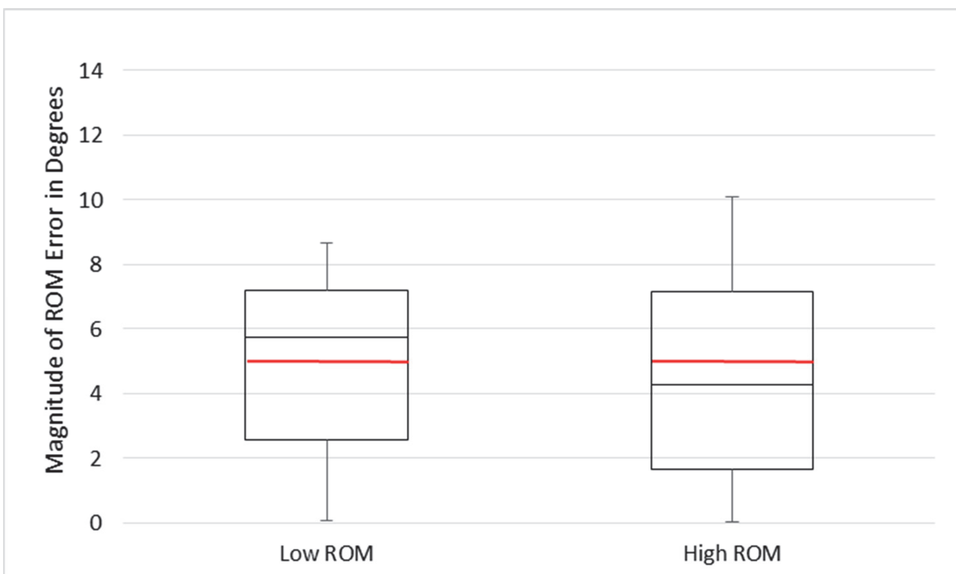


Figure 43. Boxplot comparing ROM Error of Low to High ROM for Frontal Shoulder Motions. The red bar indicates mean values, the black bar indicates median values.

The error at low ROM (5.5°) and high ROM (5.0°) is very similar, as is the variance. A t-test confirmed that there is no significant difference between the error for low ROM motions and the error for high ROM motions [t(99)=0.90, p=0.37].

The correlation plot from the beginning of this analysis (Figure 41) seems to indicate that there is no relationship between range of motion and error for frontal plane motions that involve the shoulder. To look closer at this data, a single exercise collected at multiple ranges of motion, the Arm Raise, was analyzed. Figure 44, below, is the plot for the arm raise motions examining the magnitude of the ROM error and the ROM.

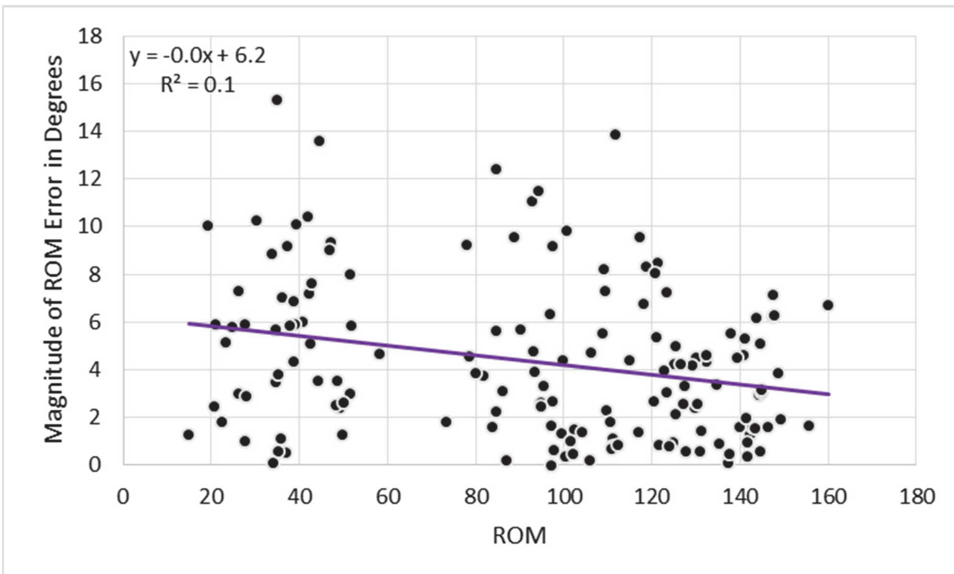


Figure 44. Correlation Plot for ROM vs ROM Error for select Frontal Shoulder Motions (Arm Raises) grouped by ROM

The correlation between the magnitude of the ROM error and ROM for controlled frontal plane motions of the shoulder is weak (r=-0.24). This agrees with the data seen above when all shoulder motions were considered, that there is not a meaningful relationship between ROM and error for frontal plane shoulder motions.

A one-way ANOVA, with the groupings pictured in the boxplot in Figure 45, was conducted on the arm raise data split into the groups of

- Full ROM Arm Raise
- Mid ROM Arm Raise
- Partial ROM Arm Raise

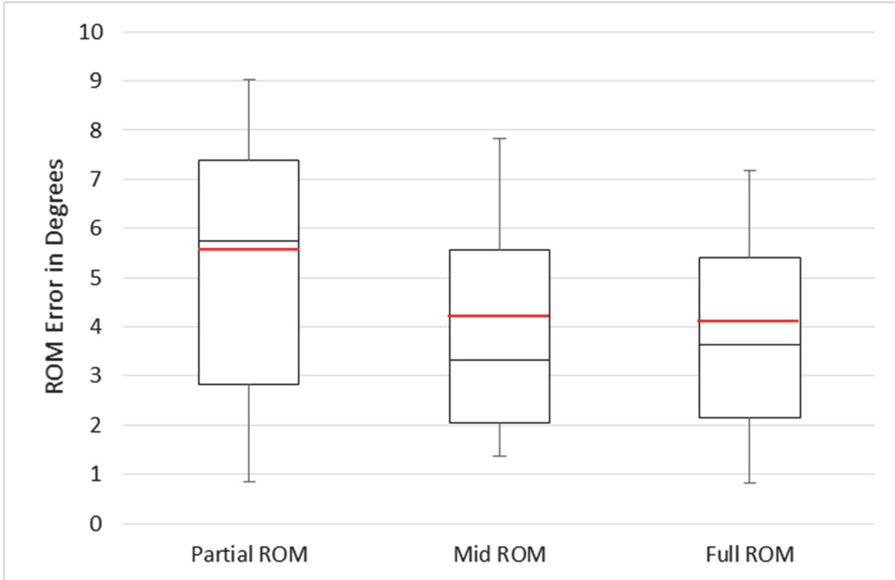


Figure 45. Boxplot comparing ROM Error to ROM of select Frontal Shoulder Motions (Arm Raises) grouped by ROM. The red bar indicates mean values, the black bar indicates median values.

At the $p<0.05$ significance level, there is not a significant relationship between the range of motion and the ROM error for frontal plane exercises that involve the shoulder [$F(2,141)=3.05$, $p=0.050$]. Despite there not being a significant relationship, an interesting observation can be made from the data here. For the controlled analysis using just arm raise data, there is a slight decrease in error and variance as ROM increases. Higher variance for lower ROM was also observed in the frontal plane hip motions and contrasted with lower variance for lower ROM in the sagittal plane motions.

The lack of a relationship between ROM and error is further supported by the RMS error vs ROM correlation plot that is pictured in Figure 46 for all shoulder motions in the frontal plane. Recall that this measurement of error removes any directionality effect and considers the entire waveform of motion. The correlation between RMS error and ROM is also weak ($r=0.29$). But now it is a positive correlation, as opposed to the negative correlation seen in Figure 44 for the ROM error plot.

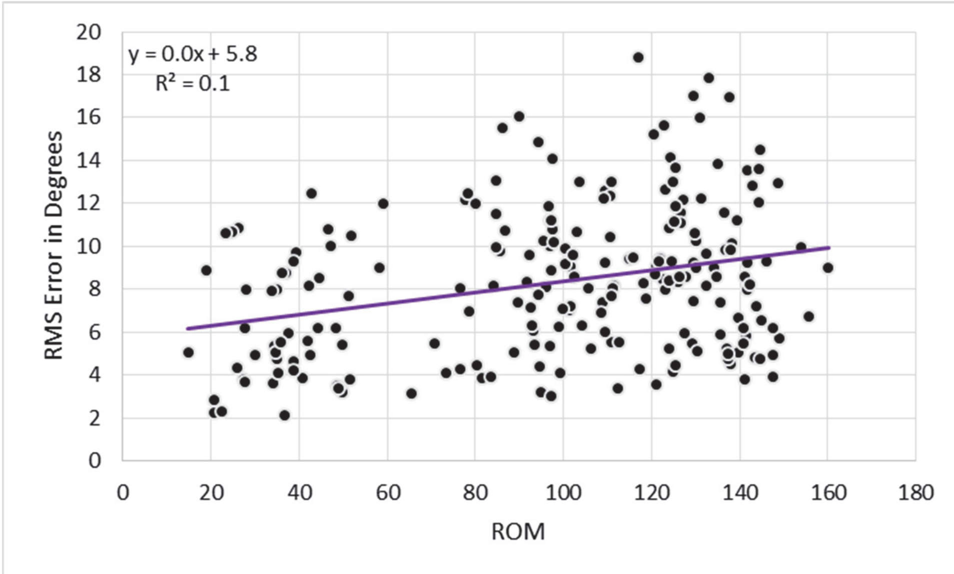


Figure 46. Correlation Plots for ROM vs. RMS Error for All Frontal Shoulder Motions

The weak correlations between error and ROM along with the trend changing from increasing error when considering ROM error to decreasing error when considering RMS error support the conclusion that there is not a relationship between ROM and error in the frontal plane for shoulder motions.

This concludes the second aim of the study. The findings of Aim 2, investigating the relationship between error and ROM are summarized below, split into the different analyses performed.

- Analysis 1: For sagittal plane knee motions, a strong relationship exists between tracking error and ROM, with error increasing as ROM increases. A sharp rise in the rate of error increase is observed past 60° when joint occlusion may become an issue. Variance was also observed to increases as ROM increases.
- Analysis 2: For sagittal plane hip motions, there is a strong relationship with error increasing as ROM increases but not as blatantly as observed at the knee. Again, variance increases as ROM increases.
- Analysis 3: For sagittal plane shoulder motions, a small case study showed support for the occlusion argument for motions in the sagittal plane.

- Analysis 4: For frontal plane hip motions, there was a relationship with error increasing as ROM increases. However, this relationship is due to the Vitalize system overestimating the hip angle at small ROM and underestimating it at large ROM. No trend was observed when comparing the magnitude of the error to the ROM.
- Analysis 5: For frontal plane shoulder motions, no relationship was observed between ROM and error.

Aim 3: Joint Involved

Up until this point, the joint involved has been kept constant in all the analyses. This is based on the assumption that there is a difference in the tracking ability of the Vitalize system that is dependent on the joint being tracked. In this aim, that assumption is tested. All the sagittal plane motions at the hip, shoulder and knee were compared to each other in the boxplot in Figure 47.

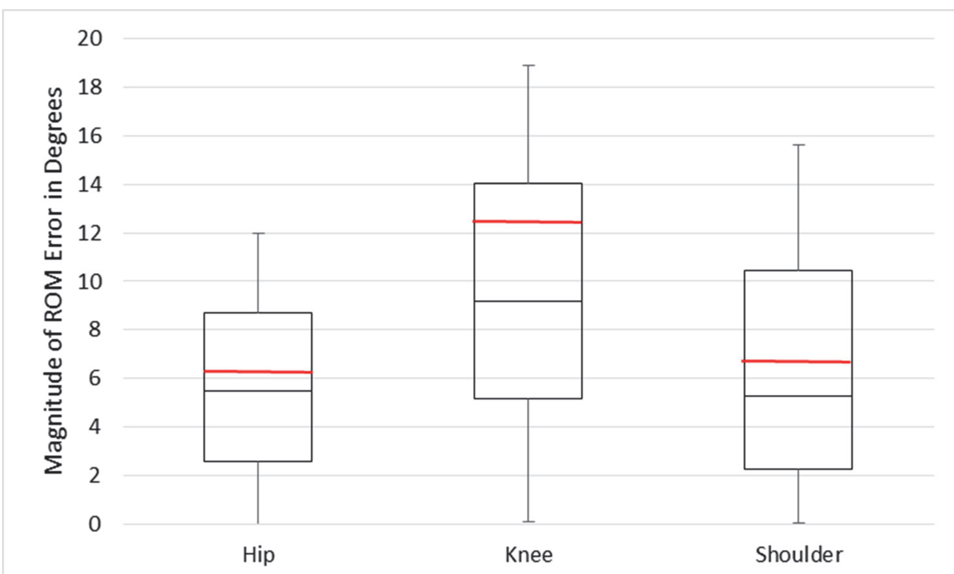


Figure 47. Boxplot Comparing ROM Error of All Hip, Knee and Shoulder in the Sagittal Plane. The red bar indicates mean values, black bar indicates median values.

From the boxplots, it can be seen that when using all sagittal plane motions without controlling for range of motion, the knee (mean=12.4°) has more error than the shoulder (mean=6.7°) and hip (mean=6.3°). An ANOVA confirmed that there exists a significant difference in the error between these groups [$F(1433)=76.6$, $p<0.001$]. Post Hoc testing was completed with a series of two-tailed t-tests with a Bonferroni correction ($\alpha/3$, where $\alpha=0.05$). It was found that the knee has significantly more error than the hip [$t(813)=-11.5$, $p<0.001$] and the shoulder [$t(526)=8.2$, $p<0.001$]; but the error of the hip and shoulder do not differ significantly [$t(196)=-1.2$, $p=0.23$].

The same thing was completed for the frontal plane. All frontal plane motions that involve the hip or shoulder were used to create the following boxplots (Figure 48).

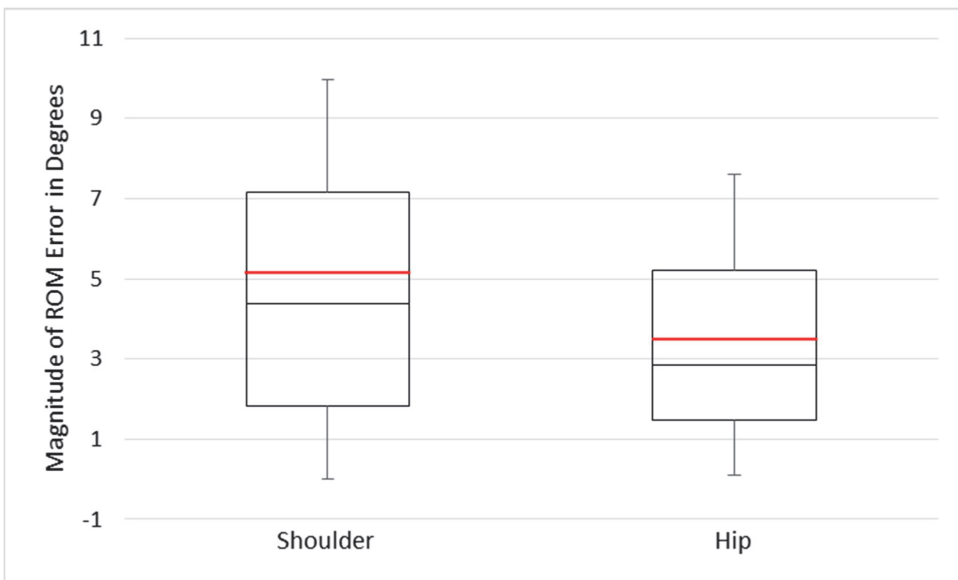


Figure 48. Boxplot comparing ROM Error of All Hip and Shoulder Frontal Motions. The red bar indicates mean values, the black bar indicates median values.

For all the frontal plane motions of the shoulder compared to all the frontal plane motions of the hip, the shoulder appears to have more error (mean=5.1°) than the hip (3.7°). A t-test confirmed that the shoulder has significantly more error than the hip [$t(387)=3.88$, $p<0.001$].

Rough observations can be drawn from the boxplots in Figures 47 and 48, but controlled analyses should be completed for more accurate results. Two methods were used to analyze the error based on the joint involved. In the first two analyses, exercises were grouped to control for the effect that plane and range of motion have on the error of the Vitalize system, as found in Aim 1 and 2, respectively. In the third analysis, motions that involve multiple joints within the same exercise were analyzed.

Analysis 1: Sagittal Plane

In this analysis, exercises at the hip were paired with exercises at the knee and shoulder in the sagittal plane with similar range of motion. This was done to attempt to control for the error associated with the plane of motion and the range of motion that were found in aims 1 and 2 of this study.

Hip:

- Squat (mid)
- Lunge (mid)
- March (mid)

Knee:

- Squat (partial)
- Lunge (mid)
- March (partial)

Shoulder:

- Jab
- Row

The magnitude of the ROM error for these groupings was compared in a one-way ANOVA. The boxplots in Figure 49, below, give a visualization of the data. The hip has an average error of 4.8°, the shoulder has average error of 7.5°, and the knee has average error of 16.1°. The ANOVA indicated that there exists a significant difference between at least one pair of the groupings at the $\alpha=0.05$ level [$F(2,263)=64.07$, $p<0.001$].

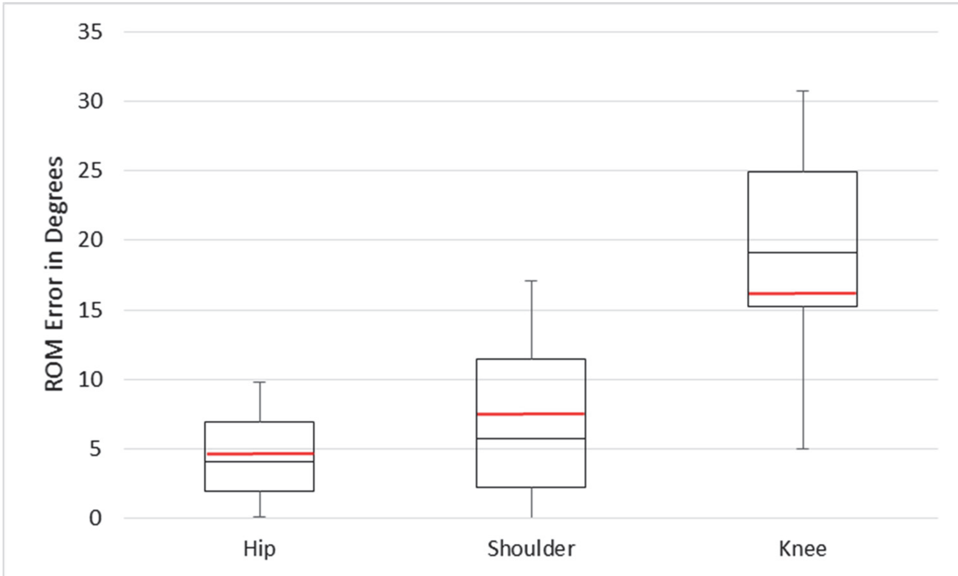


Figure 49. Boxplot comparing ROM Error for ROM Controlled Hip, Shoulder and Knee Motions in the Sagittal Plane. The red bar indicates mean values, the black bar indicates median values.

Post hoc testing was performed with a Bonferroni correction to determine which groups differed significantly. Two-sample, two-tailed t-test assuming unequal variance ($\alpha/3$, where $\alpha=0.05$; for the Bonferroni correction) were used to compare

- Hip Error to Shoulder Error
- Hip Error to Knee Error
- Shoulder Error to Knee Error

It was found that the hip had significantly less error than the shoulder [$t(137)=-3.48$, $p<0.001$] and the knee [$t(112)=-10.33$, $p<0.001$]; the shoulder also had significantly less error than the knee [$t(151)=-7.03$, $p<0.001$]. So the accuracy is ranked as follows: the hip has significantly less error than the shoulder which has significantly less error than the knee.

Analysis 2: Frontal Plane

In the frontal plane, the hip joint was compared to the shoulder joint. The following exercises were chosen because they have similar ranges of motion:

Hip:

- Jumping Jack (no arms)
- Side Step

Shoulder:

- Bilateral Arm Raise (partial)
- Unilateral Arm Raise (partial)

A two-tailed t-test assuming unequal variance was used to compare the ROM error for the hip exercises to the ROM error for the shoulder exercises. The comparison is visualized in the following boxplot (Figure 50).

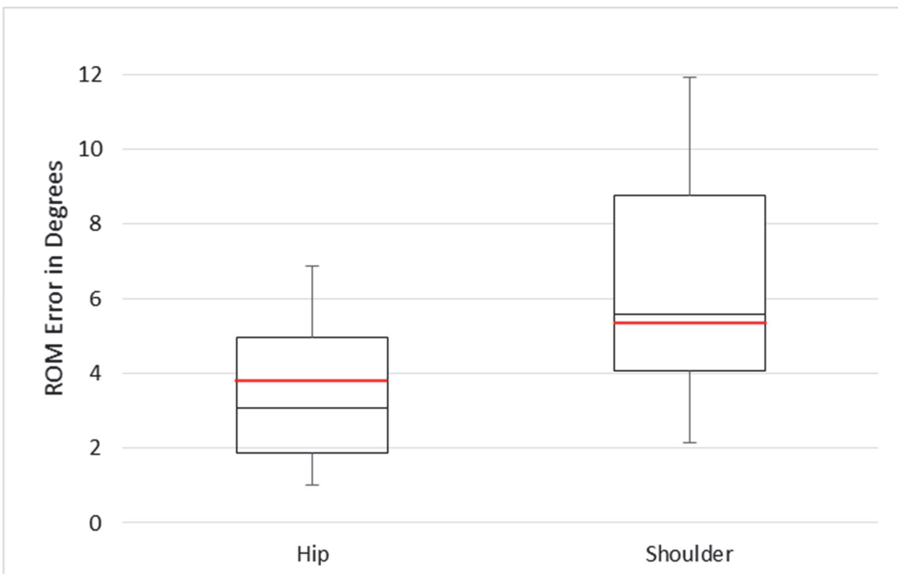


Figure 50. Boxplot comparing ROM Error of ROM Controlled Hip and Shoulder Motions in the Frontal Plane. The red bar indicates mean values, the black bar indicates median values.

A t-test showed that there was significantly more error associated with the shoulder motions (mean=5.6°) than the hip motions (mean=4.0°) in the frontal plane [t(98)=-2.60, p=0.011]. This agrees with the results from the sagittal plane that the hip is more accurate than the shoulder.

These results indicate that the Vitalize system tracks the hip joint with more accuracy than the shoulder; and tracks both joints with more accuracy than the knee.

However, in physical therapy many motions are used that simultaneously involve the hip, shoulder and knee. In analysis 3, three of these motions were analyzed to determine how well the Vitalize system performed on different joints within the same exercise.

Analysis 3: Multiple Joints within an Exercise

Three tests were run using single exercises. The shoulder angle and the hip angle were extracted and compared for the jumping jack; the knee angle was added for the knee strike motions. These exercises were selected because the motion of both the arms and legs is contained in the same, single plane; this controls for the effects of plane on error. However, widely different ranges of motion are involved between the shoulder and the hip and knee, which introduces additional error into these tests.

Jumping Jack. The first test used the jumping jack, which involves only the frontal plane. A two-tailed t-test assuming unequal variances was used to analyze the relationship between the magnitude of the ROM error at the hip and at the shoulder during a jumping jack. The boxplot pictured in Figure 51 gives a visualization of the data that was used in the t-test analysis.

This test found that in a jumping jack, there was significantly more error at the shoulder than at the hip [$t(87)=-5.23$, $p<0.001$]. This boxplot is nearly identical to the boxplot in Figure 50, which controlled for range of motion in the frontal plane. The hip joint here had a mean error of 3.8° and the shoulder joint had a mean error of 7.5°. It can also be observed in Figure 51 that the shoulder joint has higher variance than the hip joint, which is also observed for the controlled ROM, frontal plane joint comparison seen in Figure 50.

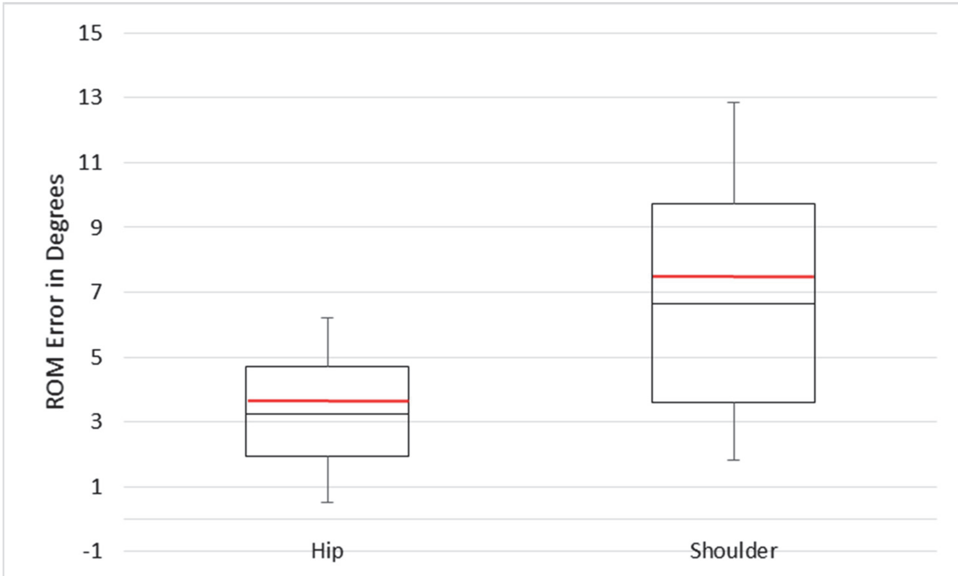


Figure 51. Boxplot comparing ROM Error at the Hip and Shoulder during a Jumping Jack. The red bar indicates mean values, the black bar indicates median values.

Knee Strike with Row. The second test used the Knee Strike with Overhead Arms exercise. This involves a single knee strike with a row/pull back motion of the arms; the motion of the hip, knee and shoulder are all contained in the sagittal plane. A one-way ANOVA was used to analyze the magnitude of the ROM error at the hip, shoulder and knee. The boxplots in Figure 52 give a visual of the data used in the statistical analysis for the tracking error associated with the three different joints.

The ANOVA indicated a significant difference between at least two of the joints. The average error of the hip was 9.0°, of the shoulder 6.0° and of the knee 9.2°; recall that these average errors are indicated in the figure by the red bar in the boxplots. Both the hip and shoulder had high variance whereas the knee joint had lower variance, which makes the results of the ANOVA less obvious from just viewing the boxplots (Figure 52). Post hoc testing was performed with a Bonferroni correction to determine which groups differed significantly.

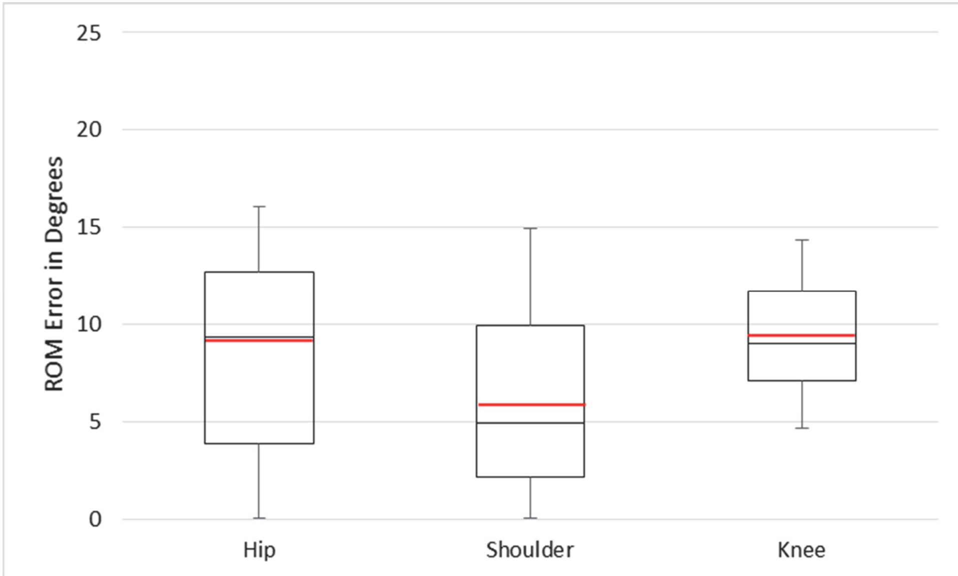


Figure 52. Boxplot comparing ROM Error of Hip, Shoulder and Knee during Knee Strike with Row. The red bar indicates mean values, the black bar indicates median values.

Two-sample, two-tailed t-test assuming unequal variance with a significance level of α/3, (where α=0.05; for the Bonferroni correction) were used to compare

- Hip Error to Shoulder Error
- Hip Error to Knee Error
- Shoulder Error to Knee Error

The results showed that the hip had greater error than the shoulder, but not significantly more [t(50)=2.40, p=0.02]. The hip had slightly less error than the knee, but no significant difference between the error at the hip and knee existed [t(41)=-0.23, p=0.82]. The significant difference exists between the error of the shoulder and the knee; the shoulder has significantly less error than the knee [t(87)=-4.03, p<0.001]. This does not agree with the results from Analysis 1. The shoulder is the most accurate joint for this exercise, as opposed to the hip being most accurate for a more controlled analysis.

Knee Strike with Overhead Arms. The third test used the Knee Strike with Overhead Arms exercise. This involves the same single knee strike with simultaneous bilateral arm-lowering and raising; all of which is again in the sagittal plane. The magnitude of the ROM error at the hip, knee and shoulder was compared using a one-way ANOVA. The groups are shown as boxplots in Figure 53.

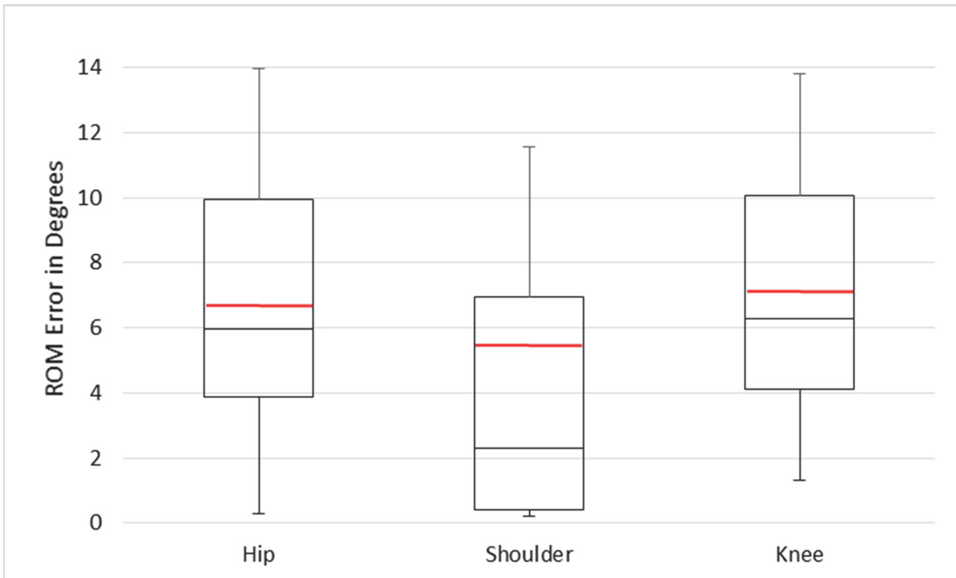


Figure 53. Boxplot comparing ROM Error at Hip, Shoulder and Knee during Knee Strike with Overhead Arms Exercise. The red bar indicates mean values, the black bar indicates median values.

The results of the ANOVA show that there is not a significant difference between the error of the hip, shoulder or knee [$F(2,116)=1.15$, $p=0.320$]. The average error of the hip was 6.6°, of the shoulder 5.8° and of the knee 7.2°.

Analysis 3, looking at the error of multiple joints that are used within the same exercise, provides interesting results. Neither the hip, shoulder nor knee is consistently more accurate than the others. When controlling for the known effects of plane and range of motion, it was shown that the tracking of the knee joint has more error than that of the shoulder or hip; and the shoulder joint has more error than that of the hip joint. However, this was not always the case when analyzing a single motion that used multiple joints. Because there are many factors that influence the tracking ability of the Vitalize system, it is possible to pair the most accurate shoulder motion (overhead arms motion) with a less accurate hip motion (knee strike); and obtain results that refute the broad trend finding that the hip has less error than the shoulder. This finding shows that every exercise has its own unique error profile for different joints. It is not true that the hip has 3° less error than the shoulder for every exercise, though that was found to be the overarching trend. Physical therapy does not control for the plane and range of motion of an exercise; clinically, there will be a mix of planes and ROM between different joints. This is why it is important to reference the errors associated with each joint for the exercise being selected; which can be done using the exercise tables created in this study (see the tables in Appendix F).

Aim 4: Adding Complexity to a Motion

It has been found that plane of motion, range of motion and the joint involved have an effect on the ability of the Vitalize system to accurately track motion. Most of the exercises used so far have been relatively simple; this raises the question of complexity. What happens to the error at a specific joint when additions are made to the complexity of the motion? In the set of exercises collected, a few motions have several variations associated with them. A case study was completed using the "Knee Strike" variations to determine if the complexity has an effect of the error. The variations used were:

- Full Knee Strike
- Seated Knee Strike
- Knee Strike with Overhead Arms
- Knee Strike with Row

A one-way ANOVA was completed on the magnitude of the ROM error of the hip angle for these four variations.

The results of the ANOVA can be viewed as a boxplot in Figure 54. The simple knee strike had an average error of 6.9°, the seated knee strike had an average error of 6.3°, the knee strike with overhead arms had an average error of 8.6° and the knee strike with row had an average error of 9.6°.

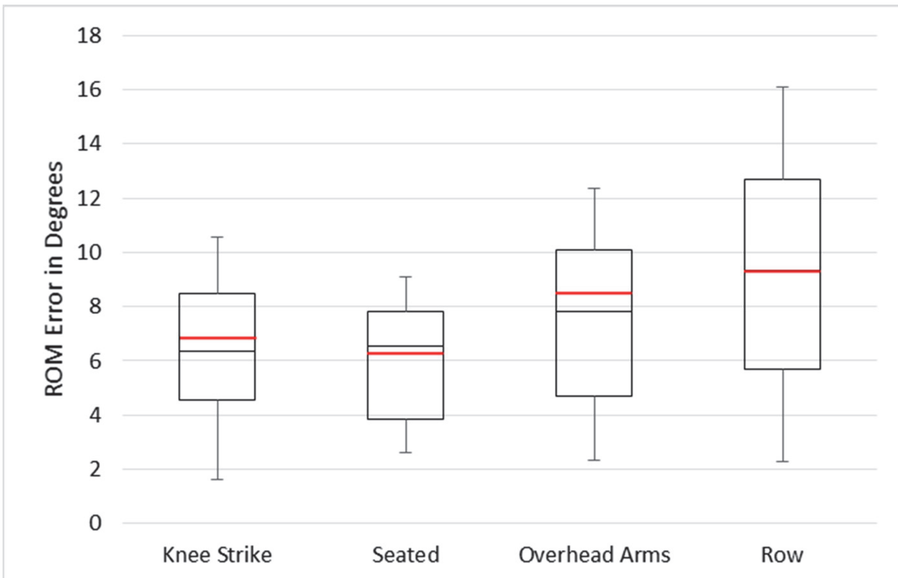


Figure 54. Boxplot comparing ROM Error of Variations of the Knee Strike. The red bar indicates mean values, the black bar indicates median values.

There is not a statistically significant effect of complexity on the error associated with the knee strike [$F(3,109)=2.53$, $p=0.06$]. But there seems to be a trend toward more error as motion of the arms is added. These arm motions require the arms to be near the hips, which could cause some occlusion from or confusion to the Kinect sensor as the arms and hands are close to the hips.

From this quick analysis, the claim can be made that adding additional elements to a specific exercise does not seem to have an effect on the tracking ability of the Vitalize system. However, the error does differ by exercises; so each exercise should be considered separately ahead of the development of physical therapy protocols. This again highlights the need for the error tables developed in this study.

Aim 5: Vitalize Decision-Making

An aspect of this study which makes it unique as compared to similar studies [15], [32], [34]–[36], [38]–[42], [52] is the highly advanced software component. In this study, the exergame (Vitalize, Figure 55) both directed when and how to perform the exercise and decided if the exercise was performed correctly.

Figure 55. Screenshot of Vitalize during gameplay

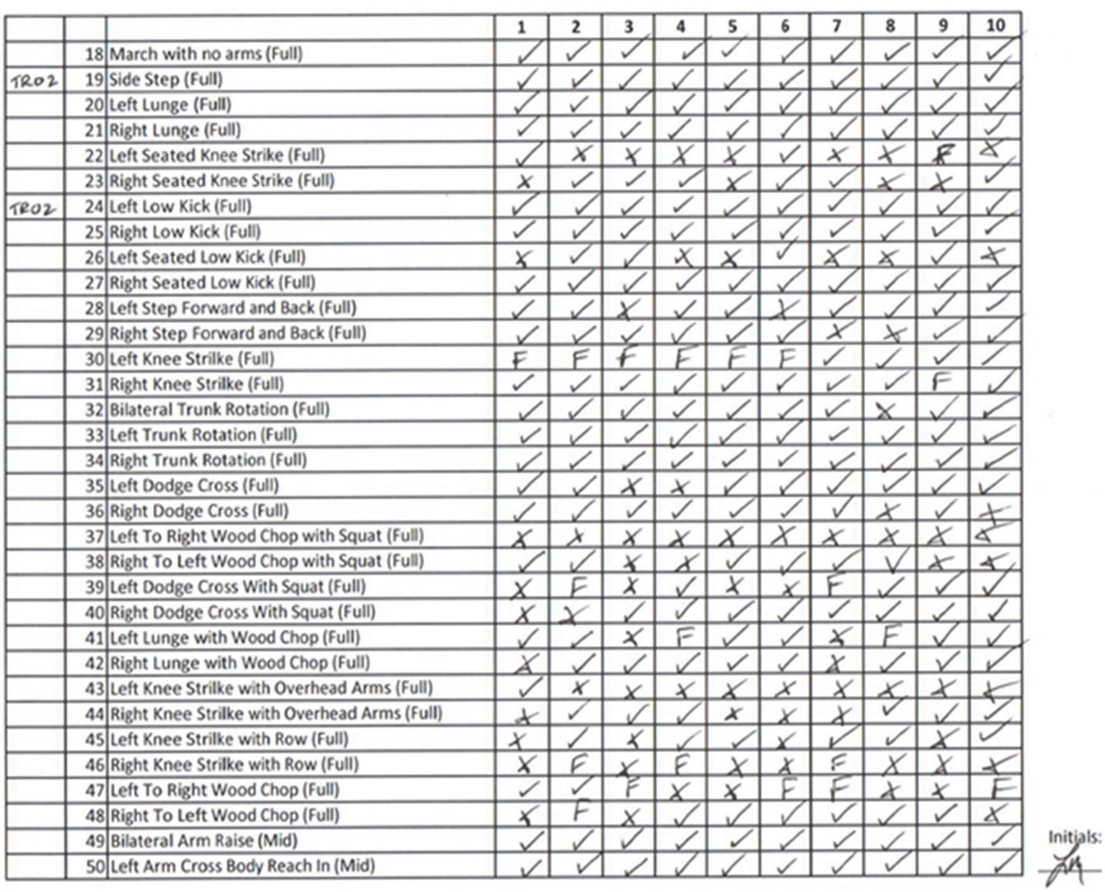
Recall that for an exergaming system to be clinically usable, it needs to accurately track the motion and properly decide if a motion was performed correctly or incorrectly. Both components are crucial and interdependent: in order for the correct decision to be made, the software developer must have some knowledge about the tracking abilities of the system during the development of “rules” to guide the software in making decisions.

For example, if the system has been shown to have 5° of error relative to the actual value, the software must either correct for the error or allow for at least that much tolerance in the "rules" that govern the decisions being made. The previous four aims have focused on the tracking accuracy of this exergaming system; this aim focuses on the decisions made by the software.

There are three possible outcomes when an exercise is completed in Vitalize:

- The motion is accepted as correct, which will either load or fire the weapon
- The motion is rejected as incorrect
- The motion is not acknowledged by the system

During data collections, the decisions made by Vitalize were recorded for each repetition performed; a sample of a collection sheet is included below as Figure 56.



			1	2	3	4	5	6	7	8	9	10
	18	March with no arms (Full)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
TR02	19	Side Step (Full)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	20	Left Lunge (Full)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	21	Right Lunge (Full)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	22	Left Seated Knee Strike (Full)	✓	X	X	X	X	✓	X	X	F	X
	23	Right Seated Knee Strike (Full)	X	✓	✓	✓	X	✓	✓	X	X	✓
TR02	24	Left Low Kick (Full)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	25	Right Low Kick (Full)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	26	Left Seated Low Kick (Full)	X	✓	✓	X	X	✓	X	X	✓	X
	27	Right Seated Low Kick (Full)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	28	Left Step Forward and Back (Full)	✓	✓	X	✓	✓	X	✓	✓	✓	✓
	29	Right Step Forward and Back (Full)	✓	✓	✓	✓	✓	✓	X	X	✓	✓
	30	Left Knee Strilke (Full)	F	F	F	F	F	F	✓	✓	✓	✓
	31	Right Knee Strilke (Full)	✓	✓	✓	✓	✓	✓	✓	✓	F	✓
	32	Bilateral Trunk Rotation (Full)	✓	✓	✓	✓	✓	✓	✓	X	✓	✓
	33	Left Trunk Rotation (Full)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	34	Right Trunk Rotation (Full)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	35	Left Dodge Cross (Full)	✓	✓	X	X	✓	✓	✓	✓	✓	✓
	36	Right Dodge Cross (Full)	✓	✓	✓	✓	✓	✓	✓	X	✓	X
	37	Left To Right Wood Chop with Squat (Full)	X	X	X	X	X	X	X	X	X	X
	38	Right To Left Wood Chop with Squat (Full)	✓	✓	X	X	✓	✓	✓	✓	X	X
	39	Left Dodge Cross With Squat (Full)	X	F	X	✓	X	X	F	✓	✓	✓
	40	Right Dodge Cross With Squat (Full)	X	X	✓	✓	✓	✓	✓	✓	✓	✓
	41	Left Lunge with Wood Chop (Full)	✓	✓	X	F	✓	✓	X	F	✓	✓
	42	Right Lunge with Wood Chop (Full)	X	✓	✓	✓	✓	✓	X	✓	✓	✓
	43	Left Knee Strilke with Overhead Arms (Full)	✓	X	X	X	X	X	X	X	X	X
	44	Right Knee Strilke with Overhead Arms (Full)	X	✓	✓	✓	X	X	X	✓	✓	✓
	45	Left Knee Strilke with Row (Full)	X	✓	X	✓	✓	X	✓	✓	X	✓
	46	Right Knee Strilke with Row (Full)	X	F	X	F	X	X	F	X	X	X
	47	Left To Right Wood Chop (Full)	✓	✓	F	X	X	F	F	X	X	F
	48	Right To Left Wood Chop (Full)	X	F	X	✓	✓	✓	✓	✓	✓	X
	49	Bilateral Arm Raise (Mid)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	50	Left Arm Cross Body Reach In (Mid)	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Initials:

Figure 56. Sample of a Data Collection Sheet after a collection

On the sheet shown in Figure 56,

√=Motion Accepted as Correct by Vitalize
F= Motion Rejected as Incorrect by Vitalize
X=Motion not Acknowledged by Vitalize

The goal of this case study was to try to determine why a √, F or X was given by Vitalize and if that decision was right in deciding if the subject performed the exercise correctly. These decisions from the software were analyzed against the Vicon data, the Vitalize data and the subject's general body position during the repetition to search for reasons behind the different decisions being made. Several exercises performed by Subject 13 that had repetitions accepted, rejected and not acknowledged were analyzed in this case study.

In the "Left Lunge with Wood Chop" exercise a trend was discovered between the ROM and the acceptance. Repetitions 3 and 8 were rejected as incorrect; the ROM of these two repetitions was lower than the rest of the repetitions that were accepted, as indicated by the red arrows in Figure 57.

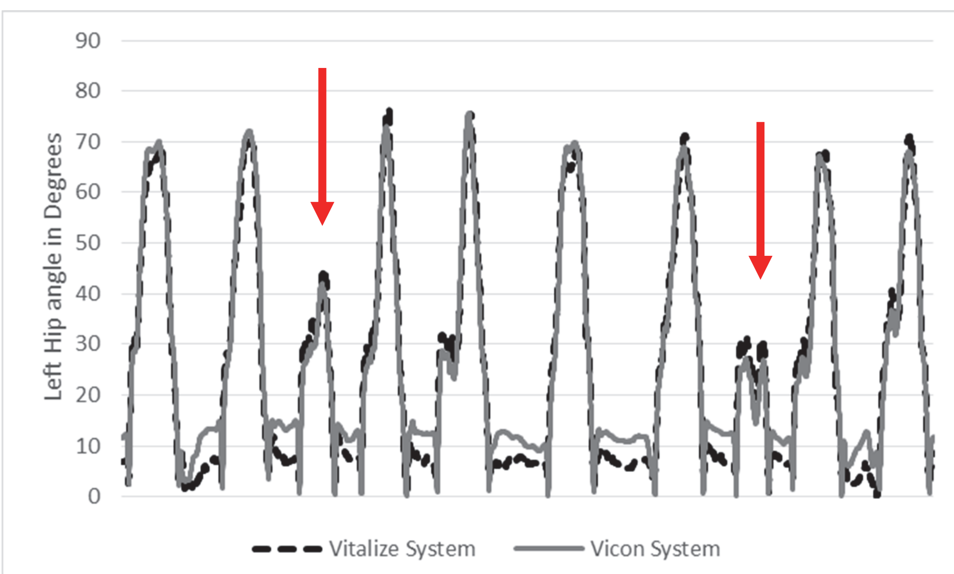


Figure 57. Exemplar Data showing ROM effect on "Incorrect" Decisions made by Vitalize

On the repetitions that were not acknowledged by the system, either the subject's left hip and knee were not in line with each other or the subject's trunk was at an angle. This seems to indicate that incorrect ROM leads to Vitalize rejecting the motion; but that Vitalize doesn't acknowledge motions that contain an incorrect body position.

In the "Left Knee Strike" exercise, the repetitions that were accepted had a left thigh angle between 70-75°, rejected repetitions had a left thigh angle greater than 80° or lower than 70°. This supports the observation from the previous exercise that motions are rejected if they have incorrect ROM. There were no repetitions that were not acknowledged, and it was observed that the knee was kept straight in front of the body, not veering toward either the left or the right. This also agrees with the observation from the previous exercise that the system doesn't acknowledge repetitions where the primary body segments are not positioned correctly.

In the "Right Jab" exercise, the repetitions that were rejected as incorrect had an upper arm angle ROM of less than 75 whereas all accepted motions had a ROM of greater than 75. For repetitions that were not acknowledged, the subject did not bring their jab far enough across the body and did not fully extend their arm. Again, this supports the observations that rejected motions have incorrect ROM and motions with incorrect body position are not acknowledged.

In the "March (mid)" exercise, it was again seen that if the range of motion was too high or too low, the motion was rejected as incorrect; which agrees with all previous observations. No repetitions were unacknowledged, and for all repetitions the knees were moving straight up and down; this also agrees with the previous observations that when incorrect body positions are present, Vitalize does not acknowledge the motion.

In addition to these findings, during data collections another element was observed. For the exercises that used a lunge, the knee and foot of the front leg had to be in view of the Kinect camera for the exercise to be acknowledged by the Vitalize system. This is understandable because the software likely has to ensure that the leg is correctly positioned. However, this became an issue because the subject had to take a step backward from their position for all other exercises before performing a lunge in order to keep the front leg of the lunge within the view of the Kinect camera. This could be a problem for at-home therapy if the software is consistently rejecting the exercise without a given reason. The patient may think they are doing the motion incorrectly when in actuality, a body segment is just out of range of the camera.

A few trends are seen with the cases that were examined. Accepted repetitions seem to occur when the motion is completed correctly and the ROM falls within a certain range. Repetitions were rejected as incorrect when the ROM fell above or below a certain range for each joint involved. Repetitions were unacknowledged by Vitalize when the body positioning was not done correctly; for example, the knee crossing the centerline of the body during a knee strike instead of going straight up and down.

The two key parts of a successful exergaming system for physical therapy are accurate tracking of the motion and a good decision on the correctness of the motion. Both of these elements have been analyzed in this study for a custom exergaming system that consisted of the Microsoft Kinect and the exergame Vitalize. Discussion about these findings is contained in the next chapter.

CHAPTER FOUR

Discussion

Due to the large number of exercises used, two important factors were able to be studied: the broad trends in error that would otherwise be difficult to identify and the error profile individual to exercise and joint. In this discussion section, first the key findings of this study will be presented and discussed. Then the results of the specific aims of this study will be discussed and compared to similar studies.

Key Findings

In the testing of this custom exergaming system, many interesting findings were discovered. However, a few stand out as the most important for the clinical use of an exergaming system in a physical therapy home exercise program.

- Plane of motion has an effect on the error and variance
- Range of motion effect on error and variance is dependent on the plane of motion
- Vitalize system overestimates angles for low ROM motions and underestimates angles for high ROM motions
- Each exercise has a unique error profile for each joint involved

Prior studies have hypothesized about the effects of plane, range of motion and joint on the accuracy of a Kinect-based exergaming system [32], [35], [39]. However, in this study, evidence based on a large number of exercises has demonstrated which of these factors lead to error.

Plane of Motion Effect on Error and Variance

This study indicates that the plane of motion has an impact on the error involved in tracking the exercise. Motions in the frontal plane have been shown to have significantly less error than motions in the sagittal plane. This is in agreement with previous related research on validating the Kinect [36], [39], [42]; these studies showed that motions in the plane perpendicular to the camera direction (most commonly the frontal plane) has less error than motions in the plane parallel to the camera (sagittal plane). Figure 58, below is from Aim 1, Analysis 1 in the results section. It is a boxplot of the ROM Error of all hip frontal motions compared to all hip sagittal motions.

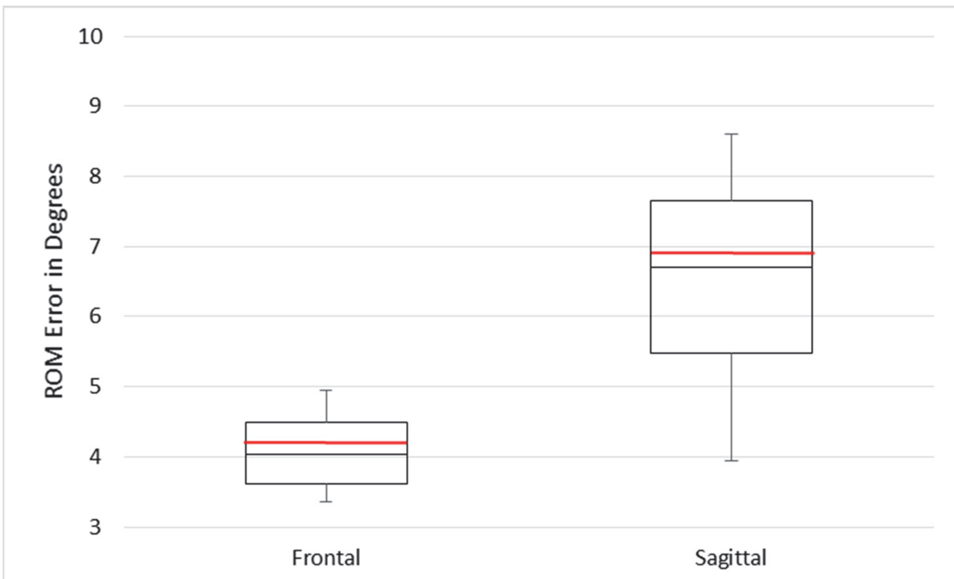


Figure 58. Boxplot comparing ROM Error of All Frontal vs. Sagittal Hip Motions. The red bar indicates mean values, the black bar indicates median values.

The increased error in the sagittal plane intuitively makes sense when considering the Kinect sensor; frontal plane motions are in full view of the camera whereas sagittal plane motions have to deal with joint obscurement and they heavily depend on the accuracy of the depth-sensing technology in the Kinect.

Another interesting observation was found in analyzing the plane data; the error variance is greater in the sagittal plane. Variance was not analyzed quantitatively, but several qualitative observations were made throughout the study. Error variance is an important factor to consider in the development and use of exergaming systems. Software developers must know the range of variance as they are creating the “rules” to determine the correctness of motion. For example, if the exergaming system has been shown to consistently overestimate the angle by 5°; that value can be subtracted across the motion to correct for this tracking inaccuracy. However, variance is much more difficult to handle. For example, if the system has error varying between ±5° of the actual value, the software cannot simply make a correction, it must allow for at least the ±5° of tolerance in the “rules” that govern the decisions being made.

Range of Motion Effect is Dependent on the Plane of Motion

It has also been shown that the range of a motion has an effect on the tracking accuracy in the sagittal plane. As the range of motion increases there is a significant increase in the error of the Vitalize system. This result is contrary to the findings of previous studies that sought to validate the use of the Kinect for clinical settings [32], [35], [36]. However, more than ten times as many exercises were used in this study than in any of these previous studies; and with what we now know about the unique error signature of each exercise and joint, it is very difficult to draw meaningful conclusions about broad trends from a small number of exercises. This study had an additional benefit to an in-depth analysis of the effect of range of motion in that several exercises were collected multiple times at varied ROM; which controls for nearly every compounding factor. For example, the squat was collected three times for each subject: full ROM squat, mid ROM squat and partial ROM squat. This gives a great measure of confidence to the results finding a relationship between ROM and error even though it is contrary to previous literature.

This increased error in the sagittal plane is not surprising when considering that at deeper flexion angles of the hip and knee in the sagittal plane, joints can become almost completely obscured from the view of the camera. For example, during a lunge when the hip and knee angles reach 90 degrees the knee is directly in front of the hip. Recall the error plots from the knee (Aim 2, Analysis 1), one is reproduced below as Figure 59.

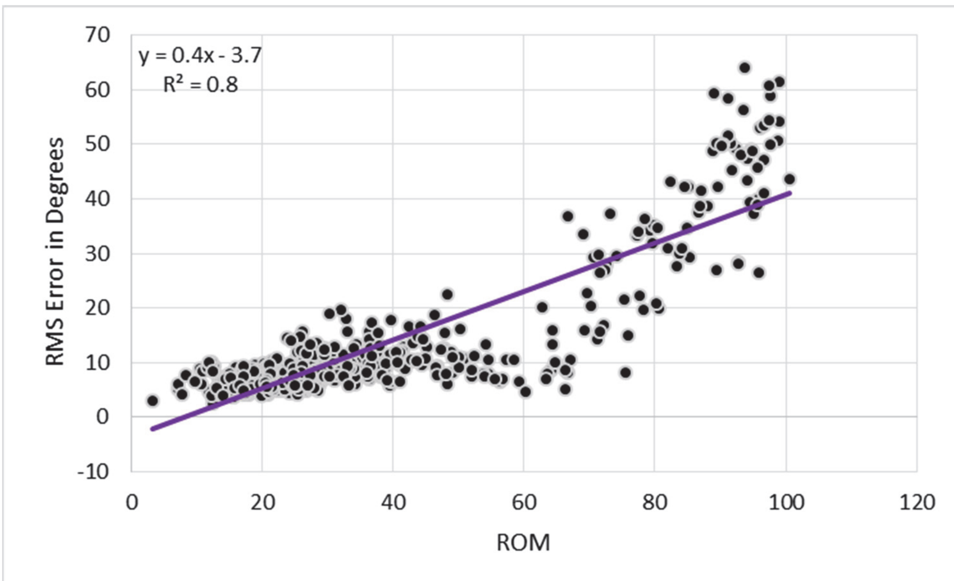


Figure 59. Correlation Plot for ROM vs RMS Error for all Sagittal Knee Motions

The increase in error can clearly be seen past 60 degrees when obscurement might begin to be an issue in the sagittal plane. In addition to the increase in error at high ROM, the variance was also observed to increase at high ROM. The variance is clearly seen in the boxplot below in Figure 60, (reproduced from Aim 2, Analysis 1). This boxplot shows the sharp difference in both error and error variance between the low ROM motions and the high ROM motions for the knee in the sagittal plane. This data from the sagittal plane solidly supports the conclusion that as the ROM increases the error also increases.

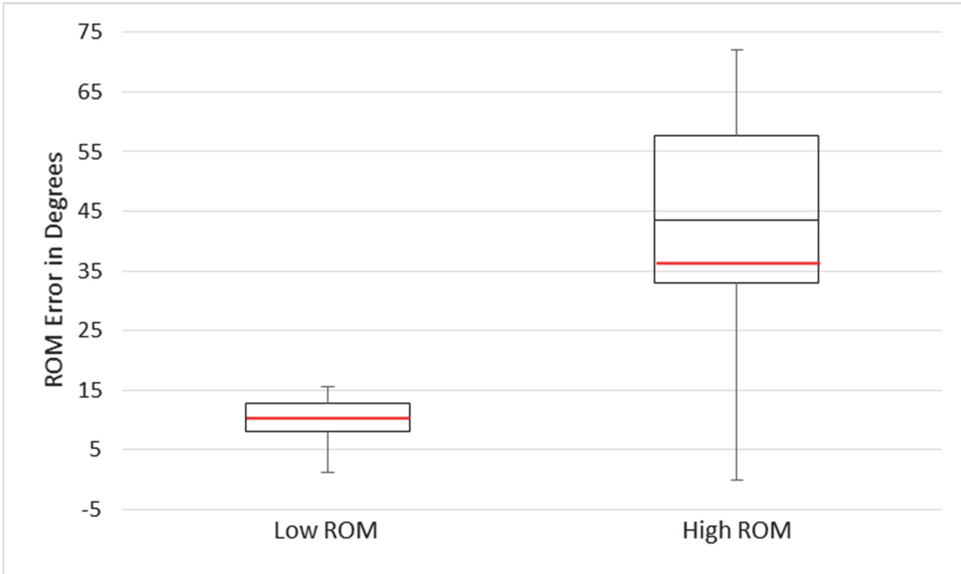


Figure 60. Boxplot comparing Error and Variance at low and high ROM for Sagittal Knee Motions. The red bar indicates mean values, the black bar indicates median values.

The relationship between range of motion and error of the Vitalize system, however, is not simple. This study has shown that the effect of the range of motion on error is also dependent on the plane of motion. No relationship was found to exist between the magnitude of error and the ROM for frontal plane motions.

From the ROM analysis, an interesting and unexpected observation was made about the directionality of the error of the Vitalize system as compared to the Vicon system.

Vitalize System Overestimating and Underestimating Angles

A trend about the directionality of the error was observed when analyzing the possible effects of ROM. The Vitalize system consistently overestimated the angle at low ranges of motion and underestimated the angle at high ranges of motion, in both the frontal plane and sagittal plane. This can be seen in Figure 61, which is a plot of the error of the hip angle at the peak of frontal hip motions compared to the ROM (See Aim 2, Analysis 4) and Figure 62, which is a plot of the error of the hip angle at the peak of sagittal hip motions compared to the ROM (See Aim 2, Analysis 2). Additional red markings have been added to the correlation plots to highlight the areas of overestimation and underestimation.

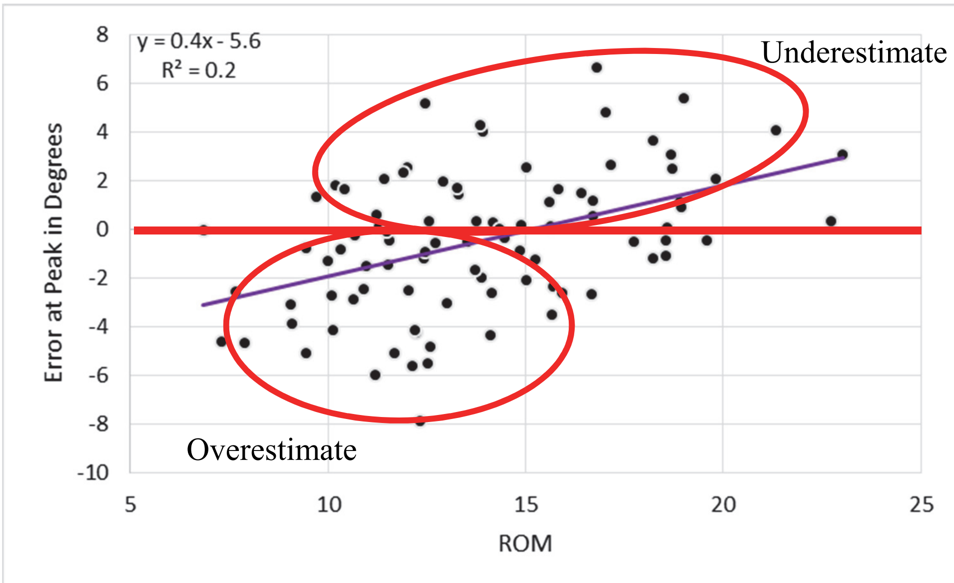


Figure 61. Plot showing Directionality of Error for Frontal Hip Motions

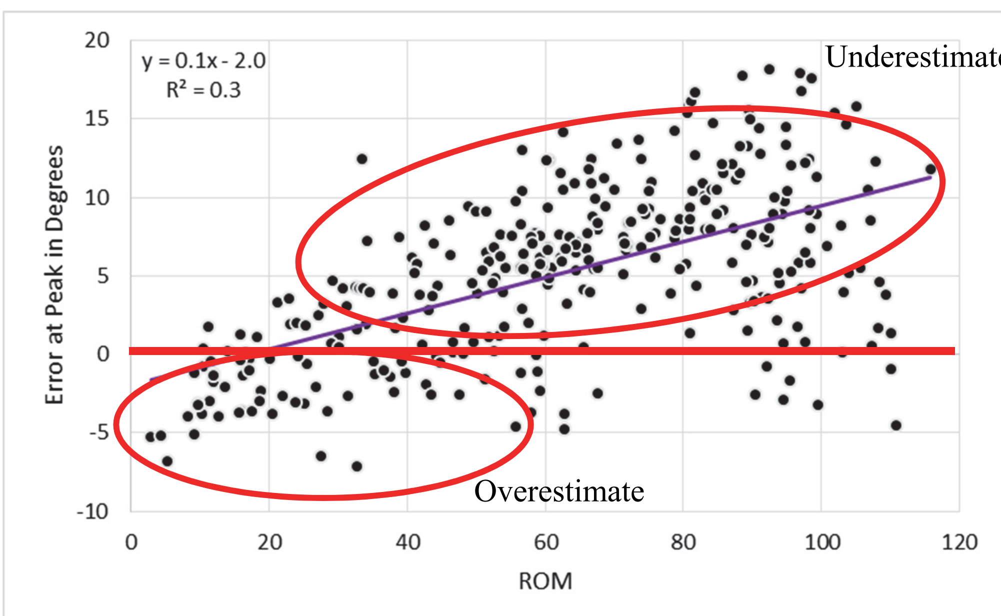


Figure 62. Plot showing Directionality of Error for Sagittal Hip Motions

For both the frontal and sagittal planes, at low ranges of motion, the error tends to be negative because the Vitalize system has overestimated the hip angle; as the ROM increases, the error tends to be positive which is caused by the Vitalize system underestimating the hip angle. This is supported by research performed by Yeung [42]. Yeung studied the ability of the Kinect to track body sway, a low range of motion activity; that study found that the Kinect consistently overestimated the angle of interest as compared to the Vicon system.

However, no previous research has been found that shows a relationship between the direction of error (overestimate or underestimate) and the range of motion as observed in this study. This is an important discovery in analyzing the tracking abilities of the Kinect as part of an exergaming system as it shows an interesting trend in the error. Further research is needed to understand why this trend exists.

Each Exercise has a Unique Error Profile for Each Joint Involved

The most significant result of this study was found in analyzing the error at different joints (Aim 3). When controlling for plane and range of motion, it was found that the knee had the most error, followed by the shoulder, and the hip had the least error. This broad trend is based on all the exercises at each of the three joints. However, in physical therapy, plane and range of motion are not controlled. So three individual exercises were analyzed at each joint. The conclusion of this exercise- and joint-specific analysis was that no joint consistently out-performed the others in terms of tracking accuracy. This indicates that each exercise has a unique error profile for each joint involved. The claim cannot be made that the knee always has more error than the hip; the joint-based error rankings depend on which exercise is being evaluated.

While broad trends about the abilities and limitations of a Kinect-based exergaming system can be drawn from this study, the more important result is the production of unique error profiles for many common exercises at four primary body joints. This information is included in tables of error at the hip, shoulder, knee and elbow (see Appendix F). Both the exergaming software developer and the physical therapist will be able to examine the amount of error in the system's tracking ability for specific exercises and joint before using the exercise in a exergaming therapy regime. Because there are so many interdependent factors that affect the tracking accuracy, it is important to have reference databases like this to find the amount of error associated with a specific joint within a specific exercise.

Specific Aims

Beyond these key elements, there are many observations that can be made from each broad aim completed in this study; this section includes discussion specific to each aim.

Aim 1: Effect of Plane

Aim 1 examined the effect that the plane of motion had on the tracking accuracy of the Vitalize system. At the hip, it was shown that the frontal plane had significantly less error than the sagittal plane ($p=0.018$). At the shoulder, motions in the frontal plane were compared to motions in the sagittal plane and motions that used both planes. The motions in the frontal plane again had significantly less error than the sagittal plane ($p<0.001$). It was also shown that the error of motions that used both planes was greater than the error of purely frontal plane and less than the error of purely sagittal plane motions; this confirms that the error being observed is due to the plane. This agrees with previous work that found the Kinect performs best in the plane perpendicular to the camera, which is almost always the frontal plane of the body [36], [42], [53]. For example, for the hip angle there is more error inherent to the system for a knee strike than for a jumping jack. Additionally, more variance was observed in the sagittal plane than in the frontal plane.

This association between the plane of motion and the tracking ability of the Vitalize system is something that a therapist should keep in mind when assigning exercises to be completed with an exergaming system. Some motions in the sagittal plane, especially for the knee, have so much error inherent to the exergaming system that they should not be included in an exergaming therapy prescription. With such high error and variance, there are two likely outcomes from the exergaming system: either it will reject motions that are actually correct because of error due to the hardware of the system, or it will require such a large tolerance in deciding a “correct” motion that the decision becomes meaningless. For example, if a motion has error of ±30° associated with it and the “rules” that govern the decision about correctness of motion take that into account, the system would be accepting motions that range from 20° to 80°. This may cause a large number of incorrect motions to be accepted and counted as correct by the exergaming system, which makes the decision made practically meaningless.

Aim 2: Effect of Range

The second analysis examined the effect range of motion has on error. Five cases were examined; the knee, hip and shoulder in the sagittal plane and the hip and shoulder in the frontal plane. This discussion is split into the sagittal plane and frontal plane findings.

Sagittal Plane. For motions in the sagittal plane, there was a statistically significant relationship between range of motion and the error of the exercise. This relationship is likely due to joints becoming occluded by other parts of the body during sagittal plane motions at higher ranges of motion. Three previous studies have referenced occlusion as a possible source of error [15], [36], [38]. Nixon [38] explains that if a joint position is occluded from the Kinect sensor, the algorithm makes an inference which leads to an increase in error, and likely variability which was also observed in this study, during the occlusion. Kuster [36] noted a significant impact the error associated with the Kinect (generation 2) during shoulder motions where the elbow and hand were occluding the view of the shoulder. Zhao [15] also noted that the Kinect system failed to track the motion during significant self-occlusions.

This finding is clinically important because it informs the exercises and ranges of motion that can be accurately tracked by the Kinect sensor. A physical therapist should note that there is much more accuracy in the tracking of a shallow lunge with the hip going to a 45 degree angle than a deep lunge with the hip going to a 90 degree angle. This could cause problems in rehabilitation where a patient may be consistently not reaching the range of motion assigned during their at-home therapy with an exergaming system because the hardware is reporting inaccurate information. It was also observed that the Vitalize system was overestimating the angle at low ranges of motion and underestimating the angle at high ranges of motion. The primary message to those using the Kinect in a clinical setting is to avoid deep flexion (high range of motion) movements in the sagittal plane because the system cannot accurately track them, especially at the knee.

Frontal Plane. For the frontal plane, there was no relationship between error and ROM for shoulder motions. However, there was a relationship observed at the hip. Upon closer examination, the trend toward more error as the ROM increased is better explained by the overestimation of the hip angle at low ranges of motion and underestimation of the hip angle at high ranges of motion. This overestimation at low ranges of motion could be due to the Kinect struggling to distinguish between the legs and correctly place the hip joint centers at small hip angles. An overestimated angle at small ranges of motion was also observed in the frontal plane shoulder data.

A possible explanation to the angle underestimation at high ranges of motion is that it may be due to the lower sampling rate of the Kinect (30 Hz as compared to 120 Hz for the Vicon system). At high rates of motion, a lower frame rate becomes a critical consideration. A slower collection rate could account for an increase of error because the system interpolates between collected data points; as the distance between the points increases (as it will as speed of the motion increases) the data must rely more heavily on the interpolation. This causes error. This is especially true at the peak of the motion, where there is a change in direction. Data from a single repetition is shown in Figure 63, as an example of a time when the Vitalize system may be underestimating the angle due to the speed of the motion.

The lower collection rate of the Kinect-based Vitalize system may cause it to miss the true peak of the motion and interpolate between two points lower on the curve to create an underestimated peak; this would be expected to happen more often during fast motions. The red arrow in Figure 63 calls attention to the difference between the peaks recorded by the two systems.

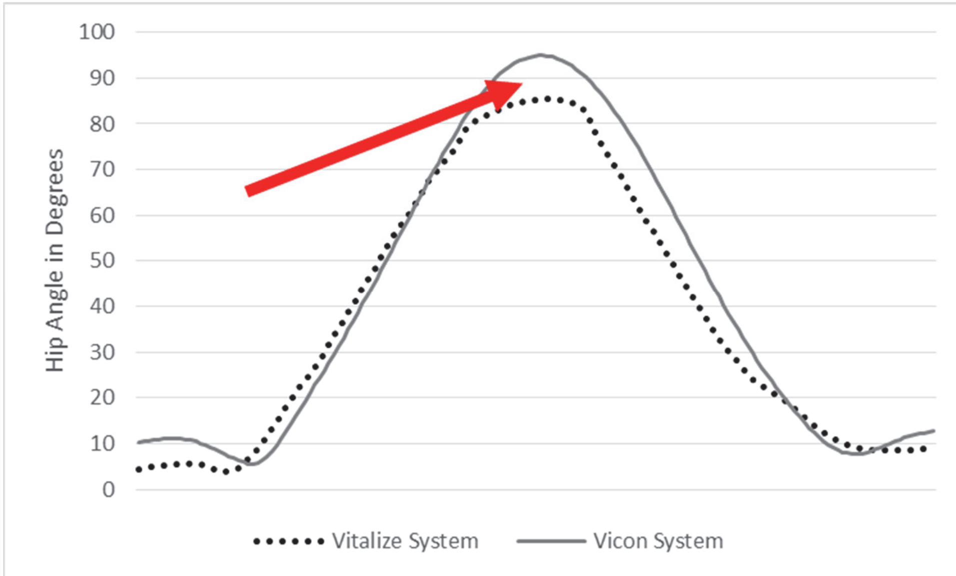


Figure 63. Exemplar Data showing the underestimate of peak angle by the Vitalize System

The correlation between ROM and error that was observed at the frontal hip is due to the overestimation of the angle by the Vitalize system at low ranges of motion and the underestimation of the angle by the Vitalize system at high ranges of motion. This is supported by the RMS Error, seen below in Figure 64.

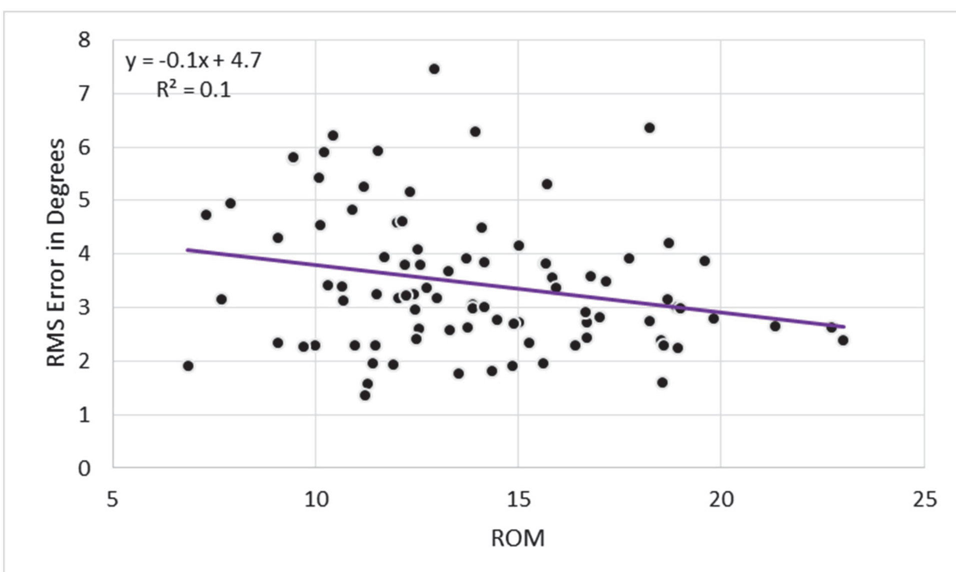


Figure 64. Correlation Plot for ROM vs RMS Error for Frontal Plane Hip Motions

The RMS error removes directional effects and considers the entire waveform of the motion. The correlation between ROM and error here is weak and tending toward less error as the ROM increases, see Figure 64 on the previous page (Reproduced from Aim 2, Analysis 4 of Results). The magnitude of the error and variance seem to decrease slightly with increasing ROM in the frontal plane; this is in direct contrast to the sagittal plane where the error and variance increased when ROM increased.

This decrease in error and variance as ROM increases in the frontal plane is likely due to the way the Kinect sensor tracks motion. Recall that the Kinect tracks the form of the body and infers joint positions to create a skeletal model of the user. When there is no movement or very small movements the Kinect is likely less accurate in placing the position of the joint centers. For example, if the arm is held next to the body without any movement, the Kinect has to infer the location of the shoulder joint by determining where the form of the upper arm stops and the form of the trunk starts. On the other hand, when the arm is raised above the head, a high ROM motion, the Kinect sensor is better able to detect the center of rotation, and thus able to make a more informed and therefore, more accurate inference about the location of the shoulder joint. This helps explain the higher error that was observed at low ranges of motion in the frontal plane.

This decrease in error with increasing ROM is opposite what was seen for the RMS error for sagittal hip motions, see Figure 65 (Reproduced from Aim 2, Analysis 2). A strong positive correlation exists between the RMS error and ROM for motions in the sagittal plane. The use of RMS error removes the directionality effect that could be causing a correlation between tracking error and ROM. In the sagittal plane, a relationship exists between error and ROM regardless of the directionality of the error.

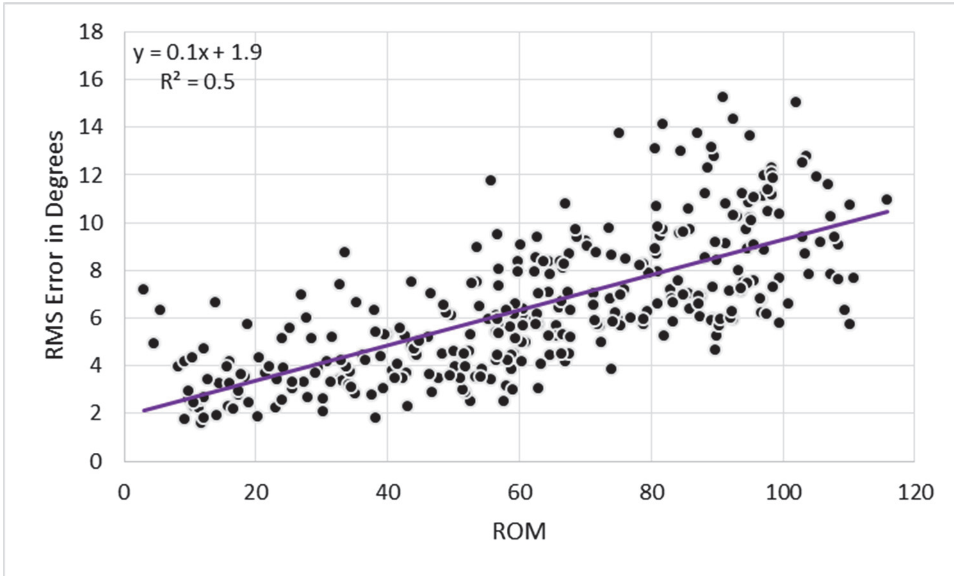


Figure 65. Correlation Plot for RMS Error vs. ROM for Sagittal Plane Hip Motions

In summary, these are the primary findings from the Aim 2, which sought to discover the relationship between ROM and error:

- Error and variance increase as ROM increases in the sagittal plane
- Error and variance are not correlated to ROM in the frontal plane
- The Vitalize system consistently overestimates the supports the angle at low ranges of motion and underestimation of the angle at high ranges of motion

Similar to Aim 1, these results serve to inform both exergaming software developers and physical therapists in choosing which motions to include in an exergaming therapy regimen.

Aim 3: Joint Involved

When accounting for the error associated with the plane and range of motion, it was found that the joint involved is also correlated with the amount of error observed. For similar exercises (controlled for plane and range of motion), the hip consistently demonstrated a significantly lower amount of error than the shoulder, and the knee had the highest error of the three joints considered. Bonnechere [32] also found that hip had less error than the knee; however when the shoulder and hip were compared in the frontal plane, the Bonnechere study found that the shoulder had less error than the hip. The study conducted by Pfister [40] also obtained results contrary to this study; they found that the knee angle was more accurate than the hip angle.

Though there are direct contradictions between these studies, there are several major differences in the underlying factors in the development of the studies that could be affecting the results. These differences could be due to the number of motions considered: Bonnechere [32] used four motions

- Shoulder abduction (frontal plane)
- Hip abduction (frontal plane)
- Elbow flexion (sagittal plane)
- Knee flexion (sagittal plane)

While Pfister [40] looked only at gait. With the information provided in this study about the unique joint- and exercise-specific error profiles, it is difficult to compare this study to previous studies that did not use the same exercises. It is likely this study came to different conclusions than previous works because data from 69 exercises was used.

The angles used in analysis may also cause variation in results. Bonnechere [32] used anatomical angles (knee angle as defined by the vectors obtained from the right hip to knee and knee to ankle); it is unknown what angles were used by Pfister [40]; whereas this study used global angles (the hip angle is defined by the thigh orientation relative to global y-axis). These are very different measurements, so it is difficult to directly compare these studies.

The second part of the joint analysis examined single exercises that involved motion at various joints. This is very clinically relevant because most exercises use multiple joints simultaneously. It was shown in this study that within the same exercise, different joints have different error associated with them; the joints also have different error depending on the exercise. This shows that each exercise has a unique error profile for each joint.

When looking at the “Knee Strike with Overhead Arms” exercise, the hip and knee had comparable error and the shoulder had less error. This serves as a caution about overgeneralizing motions based on observed trends in the error. When controlling for plane and range of motion, the hip was more accurate than the shoulder which was more accurate than the knee. However, within the context of a specific exercise which cannot be as tightly controlled, that does not hold true. Because there are so many factors influencing the tracking ability of the Kinect-based exergaming system, it is important to reference the error tables produced by this study (see Appendix F) for each joint instead of simply assuming that the hip will always be more accurate than the knee.

Correcting the tracking error by adding elements into the software is a common suggestion of improvement for systems like the one used in this study. However, with the discoveries of this research, any corrections need to be joint specific for each exercise and more complicated than a standard offset value. The error tables created in this study start to lay the foundation for the development of these corrections. But the variance observed in this research may make any attempt at correction very difficult.

Aim 4: Complexity of the Motion

Aim 4 consisted of a case study examining the hip angle for several variations on a knee strike. It was hypothesized that adding complexity to the motion would not have an effect on the error associated with tracking the hip joint. The following variations were analyzed:

- Full Knee Strike
- Seated Knee Strike
- Knee Strike with Overhead Arms
- Knee Strike with Row

The hypothesis was shown to be true. As additional complexity was added to the motions, no significant effect on the error at the hip was observed. However, a slight trend toward higher error was seen when the arm motions were added. This could be due to occlusions of the hip joint by the arms, as both the "Overhead Arms" and "Row" motions involve the hands being near the hips. This increase in error should be kept in mind, along with the bigger issues seen with occlusion in the ROM study in the sagittal plane, when considering the inclusion of exercises that deal with occluded joints in an exergaming HEP.

Aim 5: Vitalize Decision-Making

Aim 5 differed from the previous four aims in that it analyzed the decision made by the software of the Vitalize system rather than the tracking accuracy of the hardware. The decision-making aspect of the exergaming software is an important element of an exergaming system for use in physical therapy outside the clinic. During a home exercise program, it is critical that the software makes an accurate decision about the correctness of a motion because that is some of the only feedback the patient will receive; it is very helpful for the patient to receive accurate and immediate feedback about the correctness of their motions. If a motion is being performed incorrectly during physical therapy it will likely not give the desired rehabilitative benefit and may actually be detrimental to the patient's recovery.

A similar analysis was completed by Zhao et al. in their making of "correctness rules" for a handful of exercises to be tracked by the Kinect [15]. The work of Zhao is an important extension the work completed in this study. Zhao attempted, on a small scale, to improve the error of their Kinect system by controlling for known tracking errors by accounting for them within the exercise specific “correctness rules” in their software. This current study did not attempt to integrate the errors found to be associated with specific exercises and the “rules” that governed the decision made by Vitalize. However, it has provided a vast framework of both exercise specific errors and a preliminary decision-making software design that could be integrated in future work.

The three possible responses of the Vitalize system when an exercise was completed were:

- The motion is accepted as correct, which will either load or fire the weapon
- The motion is not acknowledged by the system
- The motion is rejected as incorrect

It was found that Vitalize accepted the motion as correct when both the body position and ROM were within certain bounds deemed to be “correct”. But the motion was completely unacknowledged by Vitalize if the body position was incorrect. This is likely due to the rules used to judge the correctness of the motion. If the starting position, any of the “check point” positions during the motion or the ending position were very different from what the system expected, it did not register the motion. Vitalize rejected the motion as incorrect when the ROM was either above or below the set range. Figure 66 (reproduced from Aim 5 in the results), is a sample set of data showing two repetitions that were rejected due to ROM.

For this exercise for this subject, repetitions 3 and 8 (indicated by the red arrows) were rejected as incorrect. It can easily be seen that these two repetitions have a much lower ROM than all the other repetitions that were accepted as correct.

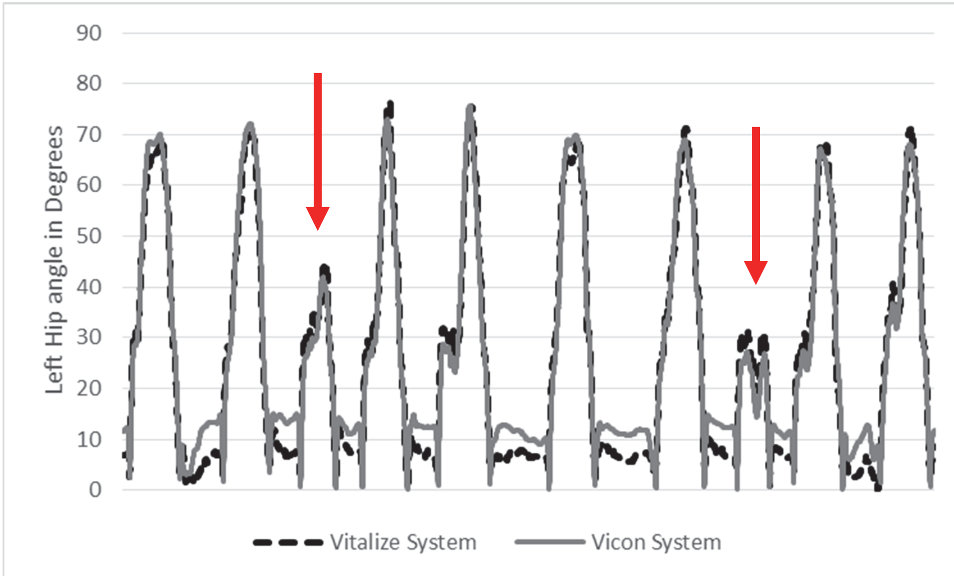


Figure 66. Exemplar Data showing two Repetitions that were rejected by Vitalize

Clinically, there are some important observations to make from these results. The Vitalize software did very well in not accepting motions that were incorrect because the ROM was outside of the specified bounds. Range of motion needs to be accurate during physical therapy because a ROM too small will not challenge the body and a ROM too high may cause damage to the joint being rehabilitated. However, that is only part of the correctness of the motion; the body positioning also must be correct. The Vitalize software did not accept motions with improper body positioning, but it also did not reject them as incorrect. If a patient is performing the exercise with improper body positioning, they need to be aware of their error in order to change it. Future decision-making exergaming software should continue to reject motions with incorrect ROM, but also should reject motions that have incorrect body positioning.

Summary of Discussion

This study has contributed several valuable findings to the field of clinical exergaming. The exercise-specific error tables give both software designers and physical therapists the ability to decide how much error they are willing to accept in an exercise. There is not agreement about the amount of error that is clinically acceptable. In one study [54] on gait analysis, an error of 5° was considered clinically significant. In another study, values of variation visible to the eye were found to often exceed 10° [43]. The current study does not attempt to decide how much error is acceptable for a clinical use of exergaming, it simply provides tables of exercise-specific errors to leave that decision to the clinician who knows how much error is tolerable for a certain exercise and patient.

In the current literature there is disagreement over whether the Kinect is accurate enough to be used as a component of an exergaming system for clinical use [32], [35], [36], [40]. This disagreement is likely due to the small number of exercises represented in previous work. The maximum number of exercises found in the previous research was six. There are many factors that contribute to the ability of the Kinect sensor to accurately track motions; therefore it is critical that an expansive study, such as this one, be completed where the confounding factors can be controlled. By analyzing a large number of exercises, this study provides valuable information on the strengths and weaknesses of the tracking abilities of the Kinect sensor for use in a clinical exergaming system.

The development of joint specific error reference tables is a very valuable contribution to the field of clinical exergaming. With the discovery that every joint in every exercise has a different error profile, it becomes much more difficult to predict errors. The reference tables produced in this study remove some of the necessity of extrapolating error trends to new exercises. If the desired exercises are among the 69 included in this study, the physical therapist or exergaming software developer can simply look up the error value for each joint.

CHAPTER FIVE

Limitations and Next Steps

There are several acknowledged limitations to this study that provide the basis for the suggested next steps in this project.

Subject Homogeneity

The first limitation is that a very homogeneous sample of able-bodied subjects was used (15 subjects, 7 female; age 22.6 (3.5) years; BMI 22.1 (2.3)). This was intended to attempt to control for extraneous factors while analyzing the abilities of the Vitalize system. However, because of this homogeneity there are several factors that are not considered in this study, the most important being the effect of body type on the tracking ability of the Kinect sensor.

For the next step in this study, the data that has been collected by the CFI on several wounded warriors with varying levels of amputation and limb salvage should be analyzed to determine the effects of atypical or missing limbs on the performance of the Kinect. Additional subjects with vastly different BMIs should also be collected to better understand the limitations of the Kinect sensor based on user body type.

Manual Time Sync

A manual visual time sync, as described in the "Visual 3D processing" section of Chapter 2, was used for this study. This method of syncing the datasets had been used in previous studies [35], [38]. However, during analysis it was discovered that artificial error was introduced by this method of time syncing. This was especially true for the

RMS error calculated along steep slopes of the motion waveform, where a small variation in the sync between the datasets amplified small errors in the data comparison due to the high rate of change of the angle. This error is shown in Figure 67, below.

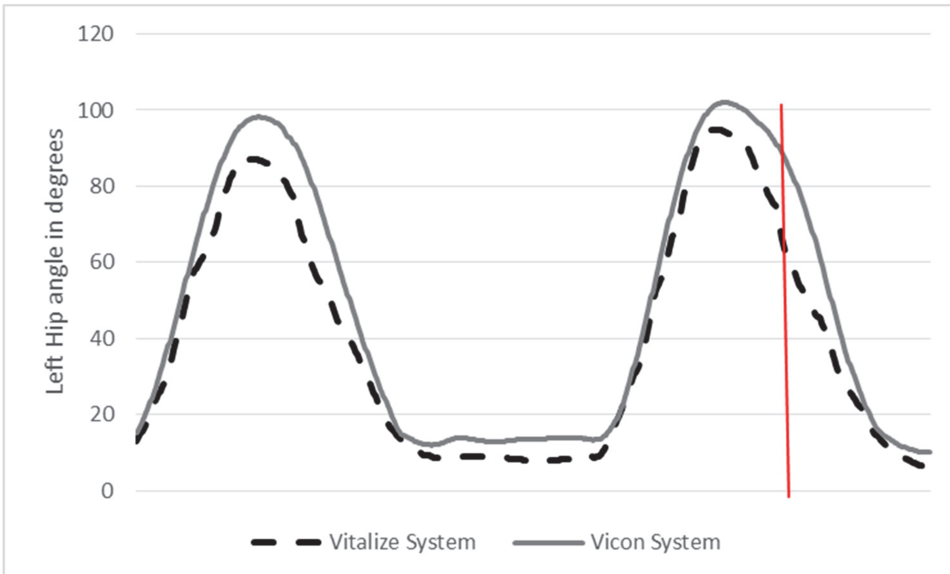


Figure 67. Exemplar Data showing Artificial Error caused by Time-Sync Methods

At the time indicated by the red line, the Vitalize system measures around 65°, and the Vicon system around 90°; this would cause a reported error of 25° at that time point (when directly subtracting the Vitalize data from the Vicon data). However, visually the two points being compared do not represent the same point on the waveform of the motion. The actual difference between corresponding points on the two waveforms is much smaller than 25°. In this way, small errors in the time-syncing of the datasets can incorrectly amplify the errors observed.

The effects of this artificial error are minimized by primarily using range of motion error and error at the peak of the motion in this study, both of which are independent of time.

In the next steps of this study, an automated optimization method for time-syncing should be utilized. A possible method was explained and used by Xu, et al [41]; where the mean-square residual between the datasets was minimized by time-shifting the Kinect-based data.

Kinect Version

This study was started before the release of the Kinect for XBOX One (generation 2), therefore the software was designed to be compatible with only the Kinect for XBOX 360 (generation 1). However, Microsoft boasts of the new technology having greater accuracy than the original Kinect. Next steps with this project should involve changes to the software compatibility in order to utilize the Kinect for XBOX One sensor.

Global Angles

Another decision that was made in the development of this project was the use of global angles, as seen in Galna's study [35]. These angles are defined by taking the body segment relative to the global y-axis. However, during the data analysis for this study, concerns were raised about using angles defined in this way. The primary concern being that the directionality of the angle is lost. 20 degrees of hip abduction and 20 degrees of hip flexion both register as a 20 degree hip angle, but the distinction between abduction and flexion is lost. This issue was encountered when trying to categorize hip exercises as being performed in the frontal or sagittal plane. All the frontal plane hip exercises used in this study have a small amount of sagittal motion (hip and knee flexion) to enable the frontal plane motion (side step or jump). It has been shown that sagittal plane motion is subject to higher error that frontal plane motion, but the two distinct, directional components cannot be separated when only the global hip angles are calculated. It was still found that the frontal plane has significantly lower error than the sagittal plane; but this issue likely increased the error associated with frontal plane motions.

In the future, the data from this study should be split into three planar components, using either the global x, y and z coordinates or the subject's anatomical frontal, sagittal and transverse planes (as seen in [38]). Which will enable a quantitative way to distinguish between frontal and sagittal plane motions and allow for a thorough analysis of the effects of the planes and the range of motion within specific planes.

Additionally, the segment length data, which was collected but not used in this phase of the project, should be analyzed in the next steps of this project. This data is less clinically relevant, but very informative about the errors involved in the motion tracking. For example, the upper arm segment length should remain constant regardless of the motion being completed. Any variation in reported length can be considered error in the motion tracking abilities of the system.

Static Error

The last acknowledged limitation of this study involves the static error of the Vitalize system as compared to the Vicon system. For some subjects, a static error was observed at the start positions of certain exercises. A small case study was completed which indicated that hyperextension of the knees while standing may not be registered by the Kinect sensor which would lead to a static error as compared to the Vicon system. This could not be further analyzed using only global angles, so it remains a limitation of the study. However, in the next steps, the components of the angles should be analyzed to determine the cause of this occasionally observed static error and the effect it has on the tracking accuracy of the rest of the motion.

CHAPTER SIX

Conclusion

For an exergaming system to be successful, two things must happen: the system hardware must be able to accurately track motion and the system software must be able to accurately decide if a motion was performed correctly. This study focused on the tracking ability of a unique exergaming system's hardware (Kinect for XBOX 360), but also considered the decision-making abilities of the custom software used (Vitalize). Several studies have been performed to attempt to validate the Kinect's accuracy for possible clinical use. However, the results of these studies have not agreed as to whether the Kinect is accurate enough for clinical use. This disagreement is likely due to different motions being analyzed in the different studies. Before this study, six exercises was the most used in similar research. The choice of which exercises to use can greatly change the results about tracking accuracy of the Kinect. This study used sixty-nine exercises common in physical therapy to discover the broad trends governing the tracking abilities and limitations of an exergaming system using the Kinect and an exergame, Vitalize.

Key Findings

It was clearly shown that the plane of motion has an effect on the error and variance of error of the Vitalize system. Motions in the frontal plane are tracked with significantly more accuracy than motions in the sagittal plane; sagittal plane motions were observed to have higher variance of error as well. It was also shown that the range of motion has an effect on the error, but that effect is dependent on the plane of motion.

For motions in the sagittal plane, the tracking error and variance of error increase as the range of motion increases. This is likely due to occlusions from the camera; for example, the deep flexion required in a lunge causes the knee joint to be positioned directly in front of the hip joint, which causes the hip to be occluded from the Kinect. But for motions in the frontal plane, there was no relationship between the magnitude of tracking error and range of motion. In analyzing the effect of different joints on the tracking accuracy of the system, error was dependent on both the joint and exercise being tracked. This leads to the conclusion that every exercise has a unique error profile for each joint involved.

An analysis was also completed on the decision-making abilities of Vitalize, the custom exergaming software used in this study. It was found that Vitalize accurately accepted motions that were performed correctly (correct ROM and body position), and it rejected motions that were performed with a range of motion that was outside the specified bounds. However, if a motion was performed with incorrect body position, Vitalize neither accepted nor rejected the motion. Additional work is needed to ensure that motions are rejected if the user's body position is incorrect. But this decision-making software is a huge development toward the goal of using an exergaming system for a physical therapy home exercise program.

Clinical Implications

There are several direct clinical implications from the findings of this study. The most important is that the error profile of each joint should be examined for exercises before including them in an exergaming home exercise program. The error depends on the joint and exercise being tracked, so before using an exercise the error associated with each joint should be examined in the reference tables produced in this study.

Frontal plane exercises, such as jumping jacks, are tracked well and accurate data regarding the patient's movement is provided to both the patient and clinician. However, exercises in the sagittal plane, especially those with large ranges of motion, such as deep squats, have higher error. If sagittal plane exercises are needed in the home exercise program, the physical therapist should consider decreasing the range of motion, for example, by using a half squat instead of a deep squat. This should increase the tracking accuracy and give less error during game play.

Importance of Reference Error Tables

With the finding that each joint for each exercise has its own unique error profile, the need for an error database arises. Therefore, four tables were developed in this study (Tables F.1-F.4, included in Appendix F) listing the errors associated with each exercise represented in this study that involved the respective joint (Hip, Shoulder, Knee, and Elbow). These reference tables of errors will serve to inform both the exergaming software developer and the physical therapist in deciding which exercises should be used clinically in exergaming therapy.

Future Work

The future of exergaming in physical therapy, specifically with the home exercise program is very exciting, but some areas remain that need additional work. More work should be completed to improve the at-home motion tracking ability while maintaining simplicity for the user. This could entail improvements to the camera, multiple cameras used, or the addition of inertial measurement units to improve information quality. However, a balance must be found between the accuracy of the motion tracking data and the simplicity of using the system. Highly accurate systems, such as the Vicon system used in this study, are far too intricate for a patient to set up and use at their home. The exergaming system must produce data accurate enough to be useful, but it must also be simple enough for a patient with minimal technical expertise to successfully use at their home. Improvements to future systems should improve tracking accuracy while maintaining the user simplicity that is seen in the Kinect sensor.

Additionally, the decision making abilities of the software should be improved. Ideally, the software will be able to accurately distinguish a correct motion from any incorrect variations of that motion. Another improvement to the software would be an expansion of the feedback given to the patient in order to correct motions performed incorrectly. For example, if the subject is performing an arm raise but has incorrect elbow positioning; the system should reject the motion and also be able to instruct the patient how to fix the elbow position in order to perform the motion correctly.

Clinically, the next step of this project is to put this use of exergaming in an HEP through clinical trials. This will investigate the potential short and long term benefits of Vitalize, or a more advanced exergaming system, on the efficacy of home exercise programs through randomized, prospective studies.

The data collected in this study has provided valuable information about the broad trends in the tracking abilities and limitations of a Kinect-based exergaming system as well as the error profiles unique to specific exercises. Using the reference tables of errors produced in this study and software similar to Vitalize, physical therapists will soon be able to assign certain exercises to be completed at home by playing an exergame which will likely improve compliance with the home exercise program leading to improved patient outcomes.

APPENDICES

APPENDIX A

List of Exercises Collected and Analyzed

Table A.1 List of Exercises Collected and Analyzed

Exercise Number	Exercise Name
1	Bilateral Arm Raise (Full)
2	Left Arm Cross Body Reach In (Full)
3	Right Arm Cross Body Reach In (Full)
4	Left Arm Cross Body Reach Out (Full)
5	Right Arm Cross Body Reach Out (Full)
6	Left Arm Raise (Full)
7	Right Arm Raise (Full)
8	Left Jab (Full)
9	Right Jab (Full)
10	Jumping Jack (Full)
11	Side Jump (Full)
12	Squat Jump With Arm Swing (Full)-- Unused
13	Jumping Jack (No Arms) (Full)
14	Side Hop (Full)
15	Squat Jump (No Arms) (Full)
16	Sit to Stand (Full)
17	Squat (Full)
18	March with Arm Swing (Full)
19	Side Step (Full)
20	Left Lunge (Full)
21	Right Lunge (Full)
22	Left Seated Knee Strike (Full)
23	Right Seated Knee Strike (Full)
24	Left Low Kick (Full)
25	Right Low Kick (Full)
26	Left Seated Low Kick (Full)
27	Right Seated Low Kick (Full)
28	Left Step Forward and Back (Full)
29	Right Step Forward and Back (Full)

Exercise Number	Exercise Name
30	Left Knee Strike (Full)
31	Right Knee Strike (Full)
32	Bilateral Trunk Rotation (Full)
33	Left Trunk Rotation (Full)
34	Right Trunk Rotation (Full)
35	Left Dodge Cross (Full)
36	Right Dodge Cross (Full)
37	Left To Right Wood Chop with Squat (Full)
38	Right To Left Wood Chop with Squat (Full)
39	Left Dodge Cross With Squat (Full)
40	Right Dodge Cross With Squat (Full)
41	Left Lunge with Wood Chop (Full)
42	Right Lunge with Wood Chop (Full)
43	Left Knee Strike with Overhead Arms (Full)
44	Right Knee Strike with Overhead Arms (Full)
45	Left Knee Strike with Row (Full)
46	Right Knee Strike with Row (Full)
47	Left To Right Wood Chop (Full)
48	Right To Left Wood Chop (Full)
49	Bilateral Arm Raise (Mid)
50	Left Arm Cross Body Reach In (Mid)
51	Right Arm Cross Body Reach In (Mid)
52	Left Arm Cross Body Reach Out (Mid)
53	Right Arm Cross Body Reach Out (Mid)
54	Left Arm Raise (Mid)
55	Right Arm Raise (Mid)
56	Sit to Stand (Raised Seat) (Mid)
57	Squat (Mid)
58	Left Lunge (Mid)
59	Right Lunge (Mid)
60	Jumping Jack (Mid)
61	March with Arm Swing (Mid)
62	Bilateral Arm Raise (Partial)
63	Left Arm Cross Body Reach In (Partial)
64	Right Arm Cross Body Reach In (Partial)
65	Left Arm Cross Body Reach Out (Partial)
66	Right Arm Cross Body Reach Out (Partial)
67	Left Arm Raise (Partial)
68	Right Arm Raise (Partial)
69	Squat (Partial)
70	March with Arm Swing (Partial)

APPENDIX B

Descriptions of all Exercises Used

1. Bilateral Arm Raise (Full) - Starting with the both arms hanging by the side, both arms are kept straight at the elbow and raised in the frontal plane until they are vertical next to the head

2. Left Arm Cross Body Reach In (Full)- Starting with the left arm vertical next to the head, move the arm across the front of the body ending at the right hip

3. Right Arm Cross Body Reach In (Full)- Starting with the right arm vertical next to the head, move the arm across the front of the body ending at the left hip

4. Left Arm Cross Body Reach Out (Full)- Starting with the left arm at the right hip, move the arm across the front of the body ending next to the head.

5. Right Arm Cross Body Reach Out (Full)- Starting with the right arm at the left hip, move the arm across the front of the body ending next to the head.

6. Left Arm Raise (Full)- Starting with the arm hanging by the left side, the left arm is kept straight at the elbow and raised in the frontal plane until it is vertical next to the head

7. Right Arm Raise (Full)- Starting with the arm hanging by the right side, the right arm is kept straight at the elbow and raised in the frontal plane until it is vertical next to the head

8. Left Jab (Full)- Starting with both arms held in front of the face with elbows bent at 90 degrees, move the left arm straightforward in the sagittal plane by straightening the elbow.

9. Right Jab (Full)- Starting with both arms held in front of the face with elbows bent at 90 degrees, move the right arm straightforward in the sagittal plane by straightening the elbow.

10. Jumping Jack (Full)- Starting with both arms hanging at the side, both arms are raised in the frontal plane until they are above the head. The legs start together and are simultaneously moved outward in the frontal plane. Then both the arms and legs are brought back to the starting position.

11. Side Jump (Full)- Starting with both hands placed on the hips and legs together, jump sideways in the frontal plane, then back to the starting position. Move both legs together in the jump

12. Squat Jump with Arm Swing- Unused

13. Jumping Jack (No Arms) (Full)- Starting with both arms hanging at the side and the legs together, the legs are moved outward in the frontal plane then back to the starting position

14. Side Hop (Full)- Starting with both hands placed on the hips and legs together, jump sideways in the frontal plane, one leg at a time; once the legs are together again, jump back to the starting position, one leg at a time.

15. Squat Jump (No Arms) (Full)- Start with both hands placed on the hip and standing with the legs together. Bend the knees at a 90-degree angle keeping the back straight, as the legs are being straightened, jump off the ground before landing back in the starting position.

16. Sit to Stand (Full)- Start with both knees bent at a 90-degree angle, sitting on a small bench. Keep the back straight and stand straight up.

17. Squat (Full)- Start with both hands place on the hips and the legs together and straight. Bend the knees at a 90-degree angle keeping the back straight; then stand back up into the starting position.

18. March with No Arms (Full)- Start with both arms hanging by the side. Lift the right knee to 90-degrees. Lower the right knee then lift the left knee to 90-degrees, lower the left knee back to the starting position.

19. Side Step (Full)- Starting with both hands placed on the hips and legs together, step sideways in the frontal plane, one leg at a time; once the legs are together again, step back to the starting position, one leg at a time.

20. Left Lunge (Full)- Start standing straight with both arms hanging by the side. Step forward with the left leg in the sagittal plane bend the knee and hip to 90 degrees; step back and up to the starting position.

21. Right Lunge (Full)- Start standing straight with both arms hanging by the side. Step forward with the right leg in the sagittal plane bend the knee and hip to 90 degrees; step back and up to the starting position.

22. Left Seated Knee Strike- While seated on a small bench, lift the left thigh upwards without straightening the knee; then lower it back to the seated position

23. Right Seated Knee Strike- While seated on a small bench, lift the right thigh upwards without straightening the knee; then lower it back to the seated position

24. Left Low Kick (Full)- Start standing with legs together with both arms hanging by the side. Extend the left leg forward in the sagittal plane swinging it at the hip; then return to the standing position.

25. Right Low Kick (Full)- Start standing with legs together with both arms hanging by the side. Extend the right leg forward in the sagittal plane swinging it at the hip; then return to the standing position

26. Left Seated Low Kick (Full)- While seated on a small bench, start with the legs bent at 90 degrees, kick the left shank out swinging it at the knee, then return it to the 90 degree starting position.

27. Right Seated Low Kick (Full)- While seated on a small bench, start with the legs bent at 90 degrees, kick the left shank out swinging it at the knee, then return it to the 90 degree starting position.

28. Left Step Forward and Back (Full)- Stand with both arms hanging by the side. Step forward in the frontal plane with the left leg, plant the left foot momentarily then step back into the starting position.

29. Right Step Forward and Back (Full)- Stand with both arms hanging by the side. Step forward in the frontal plane with the right leg, plant the right foot momentarily then step back into the starting position.

30. Left Knee Strike (Full)- Starting from a standing position, rotate the left thigh upwards in the sagittal plane without straightening the knee; then lower it back to the starting position.

31. Right Knee Strike (Full)- Starting from a standing position, rotate the right thigh upwards in the sagittal plane without straightening the knee; then lower it back to the starting position.

32. Bilateral Trunk Rotation (Full)- Start with both arms hanging by the side. Rotate the trunk 90 degrees to the left, then 90 degrees to the right then back to the neutral starting position.

33. Left Trunk Rotation (Full)- Start with both arms hanging by the side. Rotate the trunk 90-degrees to the left.

34. Right Trunk Rotation (Full)- Start with both arms hanging by the side. Rotate the trunk 90-degrees to the right.

35. Left Dodge Cross (Full)- Starting with both arms held in front of the face with elbows bent at 90 degrees, move the head and trunk down and to the left in the frontal plane. Then punch the left arm across the centerline of the body while moving the trunk back to vertical.

36. Right Dodge Cross (Full)- Starting with both arms held in front of the face with elbows bent at 90 degrees, move the head and trunk down and to the right in the frontal plane. Then punch the right arm across the centerline of the body while moving the trunk back to vertical.

37. Left to Right Wood Chop with Squat (Full)- Start with both hands held together above the left shoulder with the elbows bent and stranding straight with the legs together. Keeping the hands together, bring the arms across the front of the body to the right hip. Simultaneously bend the knees at a 90-degree angle keeping the back straight then stand back up while bringing the arms back into the starting position.

38. Right to Left Wood Chop with Squat (Full)- Start with both hands held together above the right shoulder with the elbows bent and stranding straight with the legs together. Keeping the hands together, bring the arms across the front of the body to the left hip. Simultaneously bend the knees at a 90-degree angle keeping the back straight then stand back up while bringing the arms back into the starting position.

39. Left Dodge Cross with Squat (Full)- Starting with both arms held in front of the face with elbows bent at 90 degrees and standing with legs together, move the head and trunk down and to the left in the frontal plane. Then punch the left arm across the centerline of the body while moving the trunk back to vertical. Simultaneously bend the knees at a 90-degree angle keeping the back straight then stand back up while punching across. Ending position has the right arm in the starting position and the left arm extended after the punch.

40. Right Dodge Cross with Squat (Full)- Starting with both arms held in front of the face with elbows bent at 90 degrees and standing with legs together, move the head and trunk down and to the right in the frontal plane. Then punch the right arm across the centerline of the body while moving the trunk back to vertical. Simultaneously bend the knees at a 90-degree angle keeping the back straight then stand back up while punching across. Ending position has the left arm in the starting position and the right arm extended after the punch.

41. Left Lunge with Wood Chop (Full)- Start with both hands together by the left shoulder with elbows bent. Step forward with the left leg in the sagittal plane bend the knee and hip to 90 degrees. While in the deepest part of the lunge, bring the arms across the body to the right hip, then return them to the starting position by the left shoulder. Lastly, stand back up out of the lunge.

42. Right Lunge with Wood Chop (Full)- Start with both hands together by the right shoulder with elbows bent. Step forward with the right leg in the sagittal plane bend the knee and hip to 90 degrees. While in the deepest part of the lunge, bring the arms across the body to the left hip, then return them to the starting position by the right shoulder. Lastly, stand back up out of the lunge.

43. Left Knee Strike with Overhead Arms (Full)- Starting from a standing position, and the arms held above the head, lift the left thigh upwards in the sagittal plane without straightening the knee; simultaneously lower the arms in the sagittal plane stopping when they are in line with body. Then lower knee back to the starting position while lifting arms back to the starting position.

44. Right Knee Strike with Overhead Arms (Full)- Starting from a standing position, and the arms held above the head, lift the right thigh upwards in the sagittal plane without straightening the knee; simultaneously lower the arms in the sagittal plane stopping when they are in line with body. Then lower knee back to the starting position while lifting arms back to the starting position.

45. Left Knee Strike with Row (Full)- Starting from a standing position, and the arms held out parallel to each other directly in front of the body, lift the left thigh upwards in the sagittal plane without straightening the knee; while doing this, bring the hands in towards the hips, bending the elbows; then lower knee back to the starting position while returning arms to starting position.

46. Right Knee Strike with Row (Full)- Starting from a standing position, and the arms held out parallel to each other directly in front of the body, lift the right thigh upwards in the sagittal plane without straightening the knee; while doing this, bring the hands in towards the hips, bending the elbows; then lower knee back to the starting position while returning arms to starting position.

47. Left to Right Wood Chop (Full)- Start with both hands together by the left shoulder with elbows bent, bring the arms across the body to the right hip, then return them to the starting position by the left shoulder.

48. Right to Left Wood Chop (Full)- Start with both hands together by the right shoulder with elbows bent, bring the arms across the body to the left hip, then return them to the starting position by the right shoulder.

49. Bilateral Arm Raise (Mid)- Starting with the both arms hanging by the side, both arms are kept straight at the elbow and raised in the frontal plane until they are horizontal next to the shoulders

50. Left Arm Cross Body Reach In (Mid)- Starting with the left arm next to the head with the elbow slightly bent, move the arm across the front of the body ending close to the right hip; then return to starting position.

51. Right Arm Cross Body Reach In (Mid)- Starting with the right arm next to the head with the elbow slightly bent, move the arm across the front of the body ending close to the left hip; then return to starting position.

52. Left Arm Cross Body Reach Out (Mid)- Starting with the left arm at the right hip, move the arm across the front of the body stopping close to the head with the elbow slightly bent; then return to starting position.

53. Right Arm Cross Body Reach Out (Mid)- Starting with the right arm at the left hip, move the arm across the front of the body stopping close to the head with the elbow slightly bent; then return to starting position.

54. Left Arm Raise (Mid)- Starting with the arm hanging by the left side, the left arm is kept straight at the elbow and raised in the frontal plane until it is horizontal next to the shoulder.

55. Right Arm Raise (Mid)- Starting with the arm hanging by the right side, the right arm is kept straight at the elbow and raised in the frontal plane until it is horizontal next to the shoulder

56. Sit to Stand (Raised Seat) (Mid)- Start with both knees bent, sitting on a raised bench. Keep the back straight and stand straight up.

57. Squat (Mid)- Start with both hands place on the hips and the legs together and straight. Bend the knees to roughly a 120-degree angle (thigh to shank angle) keeping the back straight; then stand back up into the starting position.

58. Left Lunge (Mid)- Start standing straight with both arms hanging by the side. Step forward with the left leg in the sagittal plane bend the knee to roughly 120 degrees (thigh to shank angle); step back and up to the starting position.

59. Right Lunge (Mid)- Start standing straight with both arms hanging by the side. Step forward with the right leg in the sagittal plane bend the knee and hip to roughly 120 degrees (thigh to shank angle); step back and up to the starting position.

60. Jumping Jack (Mid)- Starting with both arms hanging at the side, both arms are raised in the frontal plane until they are in line with the shoulder. The legs start together and are simultaneously moved outward in the frontal plane. Then both the arms and legs are brought back to the starting position.

61. March with No Arms (Mid)- Start with both arms hanging by the side. Lift the right knee so the hip is at roughly 60-degrees. Lower the right knee then lift the left knee so the hip is at roughly 60-degrees, lower the left knee back to the starting position.

62. Bilateral Arm Raise (Partial)- Starting with the both arms hanging by the side, both arms are kept straight at the elbow and raised in the frontal plane until the arms make roughly a 45 degree angle with the body; then return to starting position.

63. Left Arm Cross Body Reach In (Partial)- Starting with the left hand next to the head, with the elbow close to the body move the forearm across the front of the body ending close to the right hip; then return to starting position.

64. Right Arm Cross Body Reach In (Partial)- Starting with the right hand next to the head, with the elbow close to the body move the forearm across the front of the body ending close to the left hip; then return to starting position.

65. Left Arm Cross Body Reach Out (Partial)- Starting with the left hand near the right hip, pivot the forearm across the front of the body ending with the left hand near the head; then return to starting position.

66. Right Arm Cross Body Reach Out (Partial)- Starting with the right hand near the left hip, pivot the forearm across the front of the body ending with the right hand near the head; then return to starting position.

67. Left Arm Raise (Partial)- Starting with the arm hanging by the left side, the left arm is kept straight at the elbow and raised in the frontal plane until the arm makes roughly a 45 degree angle with the body; then return to starting position.

68. Right Arm Raise (Partial)- Starting with the arm hanging by the right side, the right arm is kept straight at the elbow and raised in the frontal plane until the arm makes roughly a 45 degree angle with the body; then return to starting position.

69. Squat (Partial)- Start with both hands place on the hips and the legs together and straight. Bend the knees to roughly a 120 degree angle (between shank and thigh) keeping the back straight; then stand back up into the starting position

70. March (Partial)-Start with both arms hanging by the side. Lift the right knee so the thigh is roughly 30 degrees from vertical. Lower the right knee then lift the left knee so the thigh is roughly 30 degrees from vertical, lower the left knee back to the starting position.

APPENDIX C

Details of Marker set used for Data Collection with the Vicon System

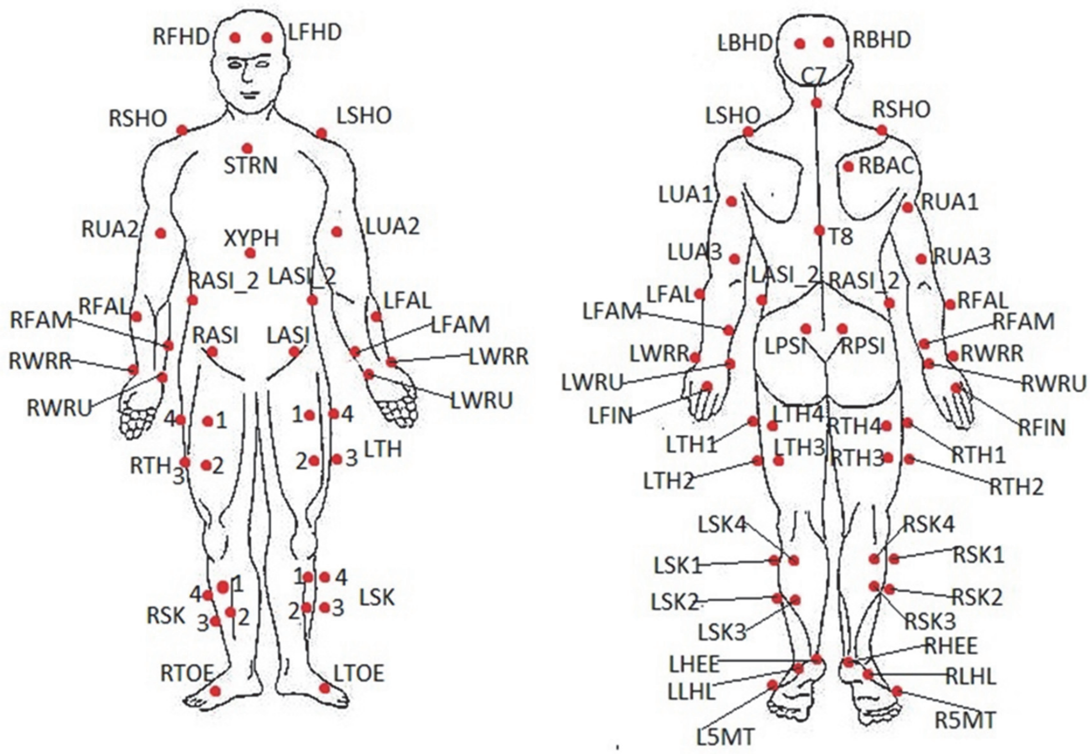


Figure C.1 Details of Markerset used for data collection including labels for all markers

APPENDIX D

Markers and Coordinate Definitions for Visual 3D Skeleton

Table D.1 Definitions for each Segment used to Define the custom Visual 3D Skeleton for each subject

Segment	Markers and Landmarks	Axis	Coordinate Definition
Pelvis	Right Anterior Superior Iliac Spine (RASI)	Origin(p)	Midpoint of line joining landmarks RASI & LASI.
	Left Anterior Superior Iliac Spine(LASI) Right Posterior Superior Iliac Spine (RPSI) Left Posterior Superior Iliac Spine (LPSI)	X	Passing through midpoint of landmarks RASI & LASI and midpoint of landmarks RPSI & LPSI. Positive axis forward.
	Additional tracking markers RASI2 and LASI2	Y	Orthogonal to X and Z axes. Positive axis upward.
		Z	Aligned with landmarks RASI & LASI, passing through the Origin(p). Positive axis left to right.
Thigh	Thigh Plate (anterior, superior) (TH1) Thigh Plate (anterior, inferior) (TH2) Thigh Plate (posterior, inferior) (TH3) Thigh Plate (posterior, superior) (TH4)	Origin(t)	Hipjoint center, defined from Origin(p), in the Pelvis reference frame as follows: HJC=(±0.36*ASIS_Distance,-0.19*ASIS_Distance,-0.3*ASIS_Distance).
	Lateral Femoral Condyle (KNL)	X	Orthogonal to Y and Z axes.
	Medial Femoral Condyle (KNM)	Y	Passing+D11 through Origin(t) and midpoint of landmarks KNL & KNM.
		Z	Aligned with landmarks KNL & KNM.
Shank	Shank Plate (anterior, superior) (SK1)	Origin(s)	Midpoint of line joining landmarks KNL & KNM.
	Shank Plate (anterior, inferior) (SK2)	X	Orthogonal to Y and Z axes.
	Shank Plate (posterior, inferior) (SK3) Shank Plate (posterior, superior) (SK4)	Y	Passing through Origin(s) and midpoint of landmarks ANL & ANM.
	Lateral Malleolus (ANL) *Medial Malleolus (ANM)*	Z	Aligned with landmarks ANL & ANM.
Foot	Heel (HEE)	Origin(f)	Midpoint of line joining landmarks ANL & ANM.
	2nd Metatarsal Head (TOE)	X	Passing through Origin(f) and landmark TOE.
	5th Metatarsal Head (5MT)	Y	Orthogonal to X and Z axes.
		Z	Aligned with landmarks ANL & ANM.
Trunk/Abd	7th Cervical Vertebra (C7)	Origin(a)	Midpoint of line joining landmarks C7 & STRN.
	Sternal Notch (STRN)	X	Orthogonal to Y and Z axes.
	Xyphoid Process (XYPH) 8th Thoracic Vertebra (T8)	Y	Passing through Origin(a) and midpoint of landmarks T8 & XYPH. Positive axis upward.
		Z	Perpendicular to the plane containing landmarks C7, STRN and the midpoint of landmarks t* & XYPH.
Upper Arm	Upper Arm 1 (proximal, posterior) (UA1)	Origin(h)	Midpoint of line joining landmarks SHA & SHP.
	Upper Arm 2 (anterior) (UA2)	X	Orthogonal to Y and Z axes.
	Upper Arm 3 (distal, posterior) (UA3) *Shoulder Joint Center - Anterior (SHA)*	Y	Passing through Origin(h) and midpoint of landmarks ELL & ELM.
	Shoulder Joint Center - Posterior (SHP) *Medial Epicondyle (ELM)* *Lateral Epicondyle (ELL)*	Z	Aligned with landmarks ELL & ELM. Positive axis to right in anatomical position
Forearm	Forearm 1 (medial) (FAM)	Origin(r)	Midpoint of line joining landmarks ELL & ELM.
	Forearm 2 (lateral) (FAL)	X	Orthogonal to Y and Z axes.
	Radial Styloid (WRR) Ulnar Styloid (WRU)	Y	Passing through Origin(r) and midpoint of landmarks WRR & WRU.
		Z	Aligned with landmarks WRR & WRU. Positive axis left to right in anatomical position

APPENDIX E

Explanations of all Values Calculated for Error Database

- MaxVicon: The maximum value (absolute value) of the angle within the given repetition for the Vicon dataset
- MaxV_Loc: The location (frame) where the maximum Vicon value occurs
- MaxKinect: The maximum value (absolute value) of the angle for the Vitalize dataset near the location of the Maximum Vicon value
- MaxK_Loc: The location (frame) where the maximum Vitalize value occurs
- StartKinect: The angle value for the start of the repetition for the Vitalize dataset
- StartVicon: The angle value for the start of the repetition for the Vicon dataset
- EndKinect: The angle value for the end of the repetition for the Vitalize dataset
- EndVicon: The angle value for the end of the repetition for the Vicon dataset
- ROMKinect: The difference between MaxKinect and StartKinect
- ROMVicon: The difference between MaxVicon and StartVicon
- ExerSpeed: ROMVicon/length of the repetition in seconds
- ROMError: The difference between ROMVicon and ROMKinect
- StartError: The difference between StartVicon and StartKinect
- MaxError: The difference between MaxVicon and MaxKinect
- MaxError_Loc: The location (frame) where the MaxError occurs
- RMSE: the root-mean-square error across the entire repetition

APPENDIX F

Error Tables

Table F.1 Error Table for Hip Motions

Exercise Name	ROM Error	Error at Start	Error at Peak	RMS Error	ROM	Plane	Category
Side Step (Full)	3.4	2.9	0.5	3.4	13.1	Frontal	Step
Jumping Jack (Full)	3.5	2.3	0.9	3.4	14.3	Frontal	Jumping Jack
March with No Arms (Partial)	3.9	1.9	0.9	3.9	26.0	Sagittal	March
Squat (Partial)	4.0	1.7	2.1	3.9	27.1	Sagittal	Squat
Side Jump (Full)	4.0	1.7	0.9	3.6	16.2	Frontal	Jump
Jumping Jack (Mid)	4.1	2.3	-0.6	3.5	13.7	Frontal	Jumping Jack
Lunge (mid)	4.5	3.5	3.5	4.9	42.4	Sagittal	Lunge
Jumping Jack (No Arms) (Full)	4.6	2.1	-1.8	3.4	14.8	Frontal	Jumping Jack
Squat (Mid)	4.9	1.0	1.1	5.0	42.2	Sagittal	Squat
Step Forward and Back	5.5	3.4	-1.7	3.3	12.9	Sagittal	Step
Low Kick	5.5	0.5	1.0	4.2	28.8	Sagittal	Kick
Side Hop (Full)	5.6	1.7	4.6	4.6	44.7	Frontal	Hop
Lunge (full)	5.7	3.8	7.7	6.7	39.4	Sagittal	Lunge
March with No Arms (Mid)	6.1	2.1	6.0	5.6	62.6	Sagittal	March
Squat Jump (No Arms) (Full)	6.3	-0.6	-1.7	6.1	45.1	Sagittal	Squat
Seated Knee Strike	6.3	11.6	8.7	16.3	45.9	Sagittal	Knee Strike
Lunge with Wood Chop	6.7	3.1	4.5	6.9	59.1	Sagittal	Lunge
Knee Strike	6.9	2.3	8.8	8.3	79.8	Sagittal	Knee Strike
March with No Arms (Full)	7.1	2.2	8.3	7.7	92.2	Sagittal	March
Wood Chop with Squat	7.2	1.9	-3.5	5.4	36.5	Sagittal	Squat
Seated Low Kick	7.6	11.8	6.0	12.4	16.8	Sagittal	Kick
Dodge Cross with Squat	7.7	0.7	1.0	6.0	43.8	Sagittal	Squat
Knee Strike with Overhead Arms	8.5	4.6	3.4	9.4	96.7	Sagittal	Knee Strike
Squat (Full)	9.0	1.1	-5.1	6.1	54.1	Sagittal	Squat
Knee Strike with Row	9.6	1.1	9.8	10.1	93.5	Sagittal	Knee Strike
Sit to Stand (Raised Seat) (Mid)	10.7	-4.5	4.2	6.7	60.3	Sagittal	Sit to Stand
Sit to Stand (Full)	11.5	-9.4	1.0	8.9	72.9	Sagittal	Sit to Stand

Table F.2 Error Table for Shoulder Motions

Exercise Name	ROM Error	Error at Start	Error at Peak	RMSE	ROM	Plane	Category
Arm Raise (full)	4.1	-0.4	-1.3	9.0	134.0	Frontal	Arm Raise
Cross Body Reach in (Partial)	4.2	-1.4	-1.3	5.3	29.2	both	Reach
Arm Raise (mid)	4.4	-1.0	-2.4	8.7	98.2	Frontal	Arm Raise
Jumping Jack (Full)	5.0	0.4	-6.8	9.3	132.1	Frontal	Jumping Jack
Arm Raise (partial)	5.7	-0.2	-5.8	6.4	36.9	Frontal	Arm Raise
Overhead Arms	6.6	3.3	1.0	8.9	112.5	Sagittal	Overhead Arms
Jumping Jack (Mid)	6.8	0.4	-6.1	8.6	93.3	Frontal	Jumping Jack
Cross Body Reach in (Mid)	9.1	-1.5	-2.2	8.8	50.6	both	Reach
Cross Body Reach Out (Full)	9.1	6.7	-2.3	7.8	45.8	both	Reach
Cross Body Reach Out (Mid)	10.4	1.6	-2.3	5.8	30.5	both	Reach
Row	11.1	-1.1	-1.6	10.8	58.8	Sagittal	Row
Jab	11.7	-4.2	-13.0	13.7	46.8	Sagittal	Jab
Cross Body Reach In (full)	11.9	-2.2	-12.3	12.6	81.3	both	Reach
Dodge Cross w/ Squat	12.4	-3.7	-16.3	21.8	53.0	both	Dodge Cross
Dodge Cross	13.9	-4.3	-17.4	18.6	55.0	both	Dodge Cross
Wood Chop w/Squat	16.5	10.7	-3.1	13.3	72.5	both	Wood Chop
Wood Chop w/ Lunge	16.9	12.9	-2.4	14.1	34.7	both	Wood Chop
Wood Chop	17.2	7.7	-4.9	9.9	62.9	both	Wood Chop

Table F.3 Error Table for Knee Motions

Exercise Name	ROM Error	Error at Start	Error at Peak	RMSE	ROM	Plane	Category
Side Step (Full)	4.5	1.3	-1.8	3.9	17.7	Frontal	Step
Jumping Jack (No Arms) (Full)	5.0	2.6	6.8	6.4	27.0	Frontal	Jumping Jack
Step forward and back	5.2	-0.2	-4.0	6.5	19.5	Sagittal	Step
Low Kick	5.3	0.1	-0.4	8.7	56.0	Sagittal	Kick
Jumping Jack (Full)	5.6	2.7	8.0	6.4	28.7	Frontal	Jumping Jack
Jumping Jack (Mid)	6.3	1.3	7.5	6.4	28.8	Frontal	Jumping Jack
Squat (Full)	6.9	-0.1	-2.4	9.4	28.9	Sagittal	Squat
Sit to Stand (Full)	7.5	-4.2	1.6	6.4	14.2	Sagittal	Sit to Stand
Lunge with Wood Chop	7.5	0.6	-6.6	42.6	26.0	Sagittal	Lunge
Side Jump (Full)	8.0	2.8	9.9	7.5	27.2	Frontal	Jump
Knee Strike with Overhead Arms	8.0	0.2	7.4	6.8	22.6	Sagittal	Knee Strike
Seated Knee Strike	8.0	-1.3	0.6	8.1	23.2	Sagittal	Knee Strike
Squat Jump (No Arms) (Full)	8.1	0.9	4.4	10.4	32.6	Sagittal	Squat
Wood Chop with Squat	8.7	-0.5	5.0	8.1	31.0	Sagittal	Squat
March with No Arms (Full)	8.7	0.8	9.5	6.4	25.0	Sagittal	March
Squat (Mid)	9.0	-0.4	7.8	10.3	28.3	Sagittal	Squat
Knee Strike with Row	9.4	-0.1	9.1	7.1	26.1	Sagittal	Knee Strike
Dodge Cross with Squat	9.6	-0.8	3.3	8.6	17.9	Sagittal	Squat
Knee Strike	9.7	-0.2	9.5	7.6	22.9	Sagittal	Knee Strike
March with No Arms (Mid)	11.0	0.8	11.7	7.5	28.1	Sagittal	March
March with No Arms (Partial)	11.1	0.5	11.6	6.2	23.6	Sagittal	March
Side Hop (Full)	12.0	3.5	15.4	9.7	41.7	Frontal	Hop
Squat (Partial)	13.9	-0.4	13.5	10.4	24.8	Sagittal	Squat
Lunge (mid)	17.4	0.0	-4.4	23.5	24.8	Sagittal	Lunge
Seated Low Kick	19.5	2.4	17.5	14.5	69.7	Sagittal	Kick
Lunge (full)	27.9	0.0	-6.1	31.5	26.9	Sagittal	Lunge

Table F.4 Error Table for Elbow Motions

Exercise Name	ROM Error	Error at Start	Error at Peak	RMSE	ROM	Plane	Category
Arm Raise (full)	3.8	-2.5	-1.7	10.4	142.1	Frontal	Arm Raise
Jumping Jack (Full)	4.2	-2.7	-1.9	9.3	146.5	Frontal	Jumping Jack
Arm Raise (mid)	4.3	-2.5	-0.7	9.6	111.0	Frontal	Arm Raise
Arm Raise (partial)	4.6	-3.4	-0.7	7.7	45.5	Frontal	Arm Raise
Jumping Jack (Mid)	5.2	-2.5	-1.2	9.4	122.6	Frontal	Jumping Jack
Cross Body Reach Out (full)	5.4	1.2	0.2	7.6	89.4	Both	Reach
Cross Body Reach Out (mid)	5.7	3.5	1.5	9.1	73.6	Both	Reach
Jab	6.9	-0.2	-3.2	8.2	53.7	Sagittal	Jab
Cross Body Reach In (full)	8.4	-1.0	-5.7	10.8	94.5	Both	Reach
Cross Body Reach In (mid)	8.6	-0.7	-1.6	11.4	100.7	Both	Reach
Cross Body Reach In (partial)	8.9	-1.4	1.4	11.5	97.8	Both	Reach
Cross Body Reach Out (partial)	9.0	9.6	2.3	10.1	65.5	Both	Reach
Row	9.7	1.6	-2.1	10.6	69.8	Sagittal	Row
Wood Chop	11.1	-1.9	-2.7	12.3	98.2	Both	Wood Chop
Overhead Arms	11.3	4.5	-5.3	10.3	121.4	Sagittal	Overhead Arms
Dodge Cross	12.8	-1.9	-9.8	17.2	51.9	Both	Dodge Cross
Wood Chop with Lunge	13.2	-3.9	-4.8	12.4	82.0	Both	Wood Chop
Wood Chop with Squat	14.3	-1.5	-1.5	14.1	95.7	Both	Wood Chop
Dodge Cross with Squat	23.2	0.7	-16.1	22.3	49.6	Both	Dodge Cross

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