UNIVERSITY OF CALGARY

Physio@Home: Exploring Visual Guidance and Feedback Techniques for At-home Rehabilitation

by

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A THESIS

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Abstract

Physiotherapy patients learn exercises for rehabilitation with the help of a physiotherapist, but are at risk of re-injury while exercising alone at home. This thesis explores the design and usage of visualizations for guiding patients through physiotherapy exercises at home. I interviewed a practicing physiotherapist to gain knowledge on physiotherapy practices, and then developed a set of visual characteristics for movement guidance: plane/range of movement, positions/angles to maintain, extent of movement, and rate of movement. I applied these in the design of movement-guiding visualizations in two prototype systems: Zipples and Physio@Home. Zipples was a Microsoft Kinect-based prototype featuring robust movement recording and playback functionality, supported by a variety of visualizations. Physio@Home was a Vicon-based iteration that improved on Zipples with an annotation tool, an iteratively-designed Wedge visualization, and multiple camera perspectives. I evaluated both systems with laboratory studies to measure their effectiveness in having participants follow pre-recorded exercises. I conclude with findings from both systems and studies, and discuss potential areas for future work.

Publications

Some figures and material in this thesis have previously appeared in these prior works:

Tang, R., Yang, X., Bateman, S., Jorge, J., and Tang, A. (2015) Physio@Home: Exploring Visual Guidance and Feedback Techniques for Physiotherapy Exercises. In CHI 2015: Proceedings of the 2015 SIGCHI Conference on Human Factors in Computing Systems. ACM, pages 4123-4132

Tang, R., Alizadeh, H., Tang, A., Bateman, S., Jorge, J. (2014). Physio@Home: Design Explorations to Support Movement Guidance. In Proceedings of CHI 2014 Extended Abstracts on Human Factors in Computing Systems (CHI EA `14). 6-page abstract + poster

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Chapter One: INTRODUCTION

Physiotherapy is a post-injury rehabilitation activity to improve and restore a patient's physical function after injury or surgery[1]. This is practiced between a recovering patient and their physiotherapist, where the physiotherapist assesses their patient's condition and prescribes exercises and activities so they may regain function over time. For example, after a dislocated shoulder is put back in place, patients are taught several shoulder exercises to help restore strength and range-of-movement. In performing these exercises over time, the patient will gradually rebuild their shoulder's strength and dexterity. Over a 12-16 week period[2] of rehabilitation, a patient may then be able to regain full or partial physical functioning.

Physiotherapy is rapidly becoming a vital component for health and well-being as populations continue to age. Improving healthcare is allowing populations to survive previously

[1] From the Canadian Physiotherapy Association's (CPA) Description of Physiotherapy, http://www.physiotherapy.ca/getmedia/e3f53048-d8e0-416b-9c9d-38277c0e6643/DoPEN(final).pdf.aspx
[2] http://www.nhs.uk/conditions/dislocated-shoulder/Pages/Introduction.aspx

fatal injuries and live longer—in both cases, there is a greater emphasis on follow-up care and rehabilitation for regaining function[3].

1.1 Motivation

Patients work with a physiotherapist in co-located sessions for diagnosis and education of their condition and required treatment. The physiotherapist assesses their patient's condition and teaches them exercises to regain function with an affected joint, and the patient performs these exercises with their physiotherapist. During this process, the physiotherapist provides detailed feedback to their patient, particularly corrective feedback to let the patient know if they are performing the exercises right.

However, patients will also need to perform these exercises at home, where they will be without the guidance of their physiotherapist. Without guidance, patients risk performing their exercises incorrectly with negative results for their recovery and condition. For example, a patient prescribed stretching exercises for their arm may not be stretching far enough to properly regain function, thereby taking longer to recover. A worse scenario may be that the patient will stretch too far and re-injure their shoulder. This is especially troubling, as re-injured patients may then require additional surgery and follow-up operations that may complicate their condition and keep them in pain and reduced functioning for even longer.

Currently available methods rely little on advanced technologies. Patients often receive pictorial diagrams or exercise DVDs (Ayoade & Baillie, 2014) as guides for their required

[3] http://www.servicecanada.gc.ca/eng/qc/job_futures/statistics/3142.shtml

exercise movements that provide no corrective feedback at all. Video conferencing tools allow an immobile or distance-separated patient at home will be able to contact a physiotherapist in their office and receive feedback. However, commercial video conferencing software and cameras are intended only for video communication and cannot provide the bodily awareness required for accurate guidance. The other issue is that video conferencing still relies on a physiotherapist working directly with a patient to provide corrective feedback, and is still subject to the physiotherapist's limited scheduling and availability.

This is an area where computer science and human-computer interactions may offer promising solutions by use of computer vision technologies. The development and commoditization of low-cost, encumbrance-free devices such as the Microsoft Kinect, and more recently the Kinect 2, is making it possible to deploy increasingly capable depth and skeleton-tracking cameras into homes. This approach would potentially allow such devices to be placed in a patient's home away from their physiotherapist, where the camera could read and understand the patient's posture to provide feedback. These systems could work without requiring a physiotherapist to be co-located with the patient, either in-person or via telepresence. Several researchers have explored the use of the Microsoft Kinect in this way—tracking motion, and then providing visual feedback to help teach and guide people new movements (e.g. Anderson et al, 2013; Uzor & Baillie, 2014).

Leveraging depth and skeleton-tracking devices for physiotherapy requires several qualities that fall within computer science and HCI. Such systems would require a capable sensing infrastructure that could take advantage of depth- and skeleton-tracking, and video.

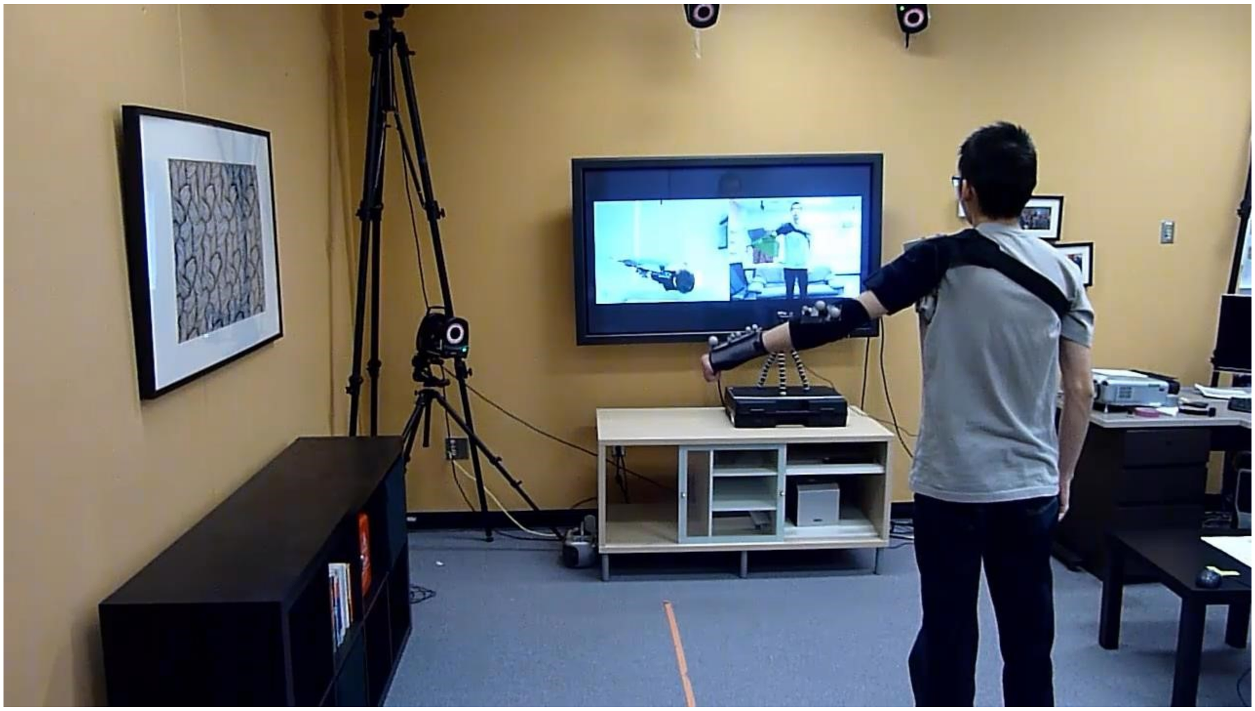

Figure 1.1: Physio@Home prototype in use. The system is intended to be used in a patient's home to guide patients through physiotherapy exercises.

These systems must also provide detailed feedback mechanisms to communicate movement instructions with patients, which relies on HCI to develop adequate methods for visual thinking. In turn, developing these methods require HCI evaluation methods to verify and demonstrate the usability of such systems and concepts for physiotherapy.

1.2 Foreshadowing Physio@Home

I approached this physiotherapy problem by developing a prototype system called Physio@Home (Figure 1.1). This prototype was designed to provide precision guidance and corrective feedback for users performing shoulder exercises by showing visual guides and cues over a mirror view of the user's body.

The primary visual guide[4] in Physio@Home, the 'Wedge', uses an arrow to show the user where they must move their arm in real-time as they follow an exercise, and shows the user when their arm movement is incorrect. Physio@Home also makes use of multiple views—a forward- facing mirror view of the user's front, and a top-down view looking down on the user's head—to provide additional guidance.

Physio@Home provides exercise recording and playback features. The recording functionality allows the system to record arm exercises from a teacher—such as a physiotherapist—exactly as it should be performed. The playback functionality then allows a user to perform the same exercise as it was recorded by their teacher, with assistive guidance to show where the user must move. When the user's movements do not match their teacher's pre-recorded movements, the system then provides corrective feedback to show the patient how they should be moving.

1.3 Research Goals

The overarching research question I address in this thesis is:

> **How do we provide effective and accurate movement guidance and corrective feedback for people doing physiotherapy exercises at home?**

I explore this question from a physiotherapy perspective, where a patient will be expected to perform complex exercise movements at home. After exploring this specific question, however, I believe these forms of feedback could then be applied more broadly beyond physiotherapy.

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[4] The terms 'visualization', 'visual guide', 'guide', and 'movement guide' will be used interchangeably in this thesis.

Other fields, such as dance instruction, also rely on their users learning and performing complex movements and requires detailed guidance and corrective feedback similar to physiotherapy. These fields also have similar availability problems where a user would have to practice at home or away from their instructor and not receive the same level of feedback.

Exploring this question provides the basis for the four thesis questions that I will answer later in my thesis:

Thesis Question 1: What are the characteristics of at-home physiotherapy exercises, and what implications for visual feedback design do they have?

Thesis Question 2: How can we design a system that provides visual feedback for physiotherapy exercises that make leverage these insights?

Thesis Question 3: How can we evaluate visual and multi-view feedback for movement guidance?

Thesis Question 4: What are the effects of visual feedback and multi-view feedback for movement guidance?

1.4 Research Scope

Technology-driven physiotherapy systems are a wide and varied field of research with related topics in CSCW, motion sensing, and graphics. My thesis focuses specifically on how to provide visual feedback and corrective cues for guiding discrete limb movements similar to those in physiotherapy exercises. Related approaches using different methods are also viable and I will briefly describe them here, and how my work differs.

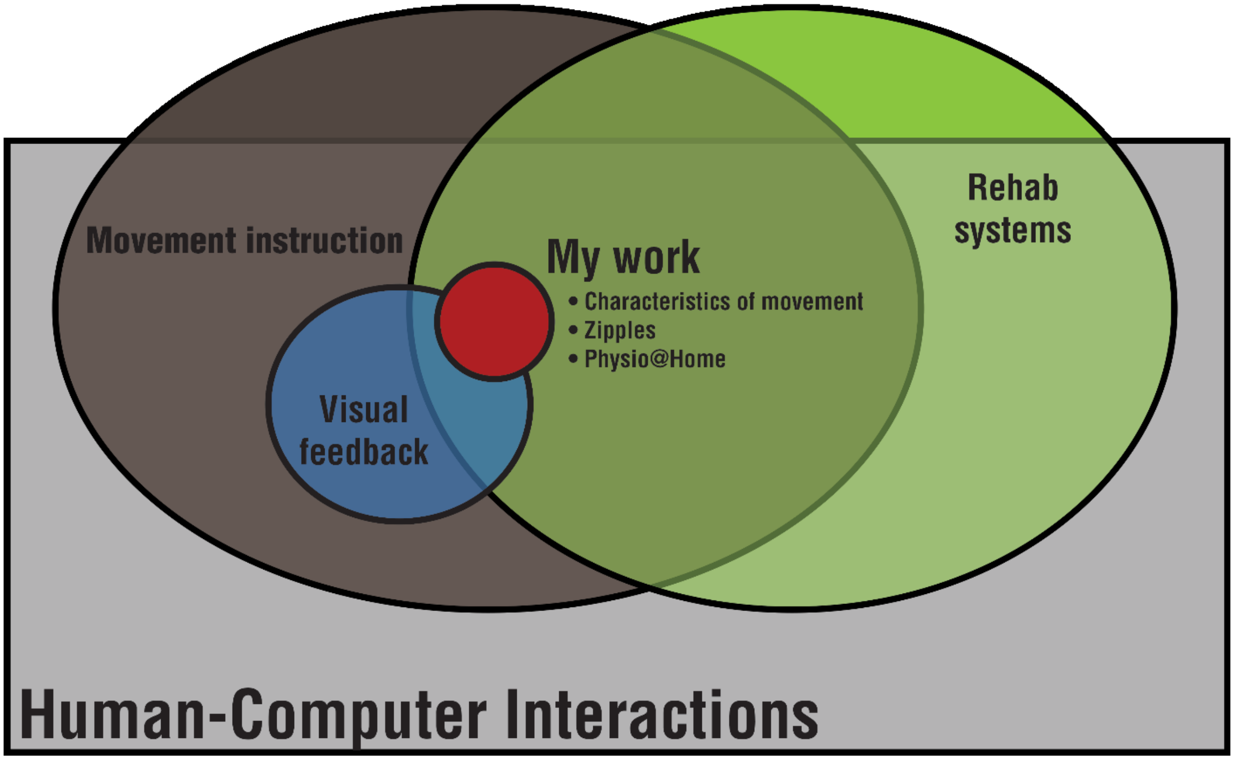

Figure 1.2: Research context and scope.

As indicated earlier in my Research Goals, movement instruction systems may cover a greater variety of fields than just physiotherapy. Dance instruction is particularly significant, and different forms of dance may require different methods of guidance and instruction that would differ from physiotherapy. For this reason, I approach my research problem and questions with a physiotherapy perspective, where finely-grained correction and accuracy in regards to specific types of exercises are very important. For the same reason, my research is also focused specifically on shoulder and elbow exercises. Physiotherapy includes rehabilitating other body parts, such as the spinal cord or knees, and often includes balancing exercises for seniors. Not all exercises may be adequately covered by guides designed for shoulder and elbow exercise movements and those movements represent another area of implementation outside the scope of this thesis.

Related to the previous topics is gradual training over time and knowledge retention. Regaining function in a joint, as described in this thesis, requires performing an exercise over time. Similarly, learning a dance requires a dancer to learn the steps and movements, but also requires continual practice so that the dancer remembers and eventually perfects it. In both cases, guidance would be required at the beginning of the learning process to show the user how to perform a movement correctly, but not as much once they have learned from past errors. In these examples, training effects and knowledge retention are at work, and these play a significant role in performing movements. For the purpose of my thesis, I focus solely on the use of guides to learn movements, particularly during the initial phases.

Also related to the previous topic of gradual training over time is the notion of exercise compliance. As mentioned, physiotherapy patients must perform their exercises over a lengthy period of time before seeing improvement. Therefore, it is also vital that patients are performing their exercises and adhering to the exercise schedule expected of them by their physiotherapist in order to recover. This is an important area for study and I do consider some characteristics of exercise compliance (Chapter 3), it is largely outside the scope of my work on guiding and correcting exercises.

Regarding feedback, I chose to focus on visual feedback that makes use of a mirror. These work best for the shoulder exercises I chose to focus on, and the use of an augmented mirror would allow for findings that could be generalized for other forms of movement. Other forms of feedback are certainly valid, such as audio and haptics, and have been studied in other works. I focus on a broader discussion of the characteristics required for useful visual guides that could work with an augmented mirror for movement guidance.

Finally, my work does not discount the role of the physiotherapist in working with the patient. My work assumes that a patient will be located away from their physiotherapist with the expectation that they can perform their exercises without their physiotherapist present. While this system removes the physiotherapist from exercise sessions, it does not mean the physiotherapist is entirely removed from the interaction. The physiotherapist is still vital when working with the patient, particularly for diagnosing their condition and prescribing exercises. Even with sophisticated remote systems and tracking, patients should still be required to see their physiotherapist in co-located sessions. My work is intended is reduce the work of the physiotherapist so that between co-located sessions, the patients may be adequately supported and be able to correctly perform their exercises.

1.5 Contributions

This thesis provides the following contributions:

1. An articulation of the design factors for a visual feedback system for physiotherapy.

2. The design and implementation of two prototypes that enable visual feedback for physiotherapy exercises away from a physiotherapist. I designed these visual feedback prototypes using the design factors derived earlier. These prototypes also included subsystems for recording and annotating exercises, and performing error calculations.

3. The design of a novel visual guidance interaction element ("Wedge") that displays the movement plane and direction of an exercise movement, and provides corrective feedback based on my earlier design factors.

4. Description of a novel evaluation method for visual feedback systems that can be used and applied in future systems.

5. An evaluation of the prototypes that demonstrates the effectiveness of my approach in terms of accuracy.

1.6 Overview

This thesis is structured as follows:

Chapter 2 provides background on physiotherapy and overviews prior work on supporting patients away from physiotherapists. This chapter will also overview methods of guiding and visualizing movement, and discuss more general movement instructional systems.

Chapter 3 discusses my design process and the qualities of movement and guidance derived from working with practicing physiotherapists. These guidance qualities include the use of feedback and feed-forward guidance and visual simplicity, while my qualities of guidance include conveying the plane and rate of movement, position and angle to be maintained, the extents of movement, and the rate of movement. These qualities will address Thesis Question 1.

Chapter 4 describes 'Zipples', my first attempt to apply some of the guidance characteristics described in Chapter 3. This chapter will introduce the initial problem scope Zipples was intended to solve and key technical components, the implementation using the Microsoft Kinect, and conclude with limitations and findings that influenced my work in Chapter 5.

Chapter 5 describes my second attempt, 'Physio@Home'. Here I describe the updated scope and design requirements from my prior work with Zipples and my new implementation built upon the Vicon motion tracking cameras. Both this and the previous chapter address Thesis Question 2 by providing two examples of prototypes for movement guidance.

Chapter 6 describes the laboratory study I performed on Physio@Home and analyzes data collected from participants and qualitative findings. This chapter addresses Thesis Questions 3 and 4 by providing analysis of how movement guidance effects users, and describes the methods needed for evaluating visual and multi-view feedback techniques.

Chapter 7 concludes this thesis, and discusses my overall contributions and implications of my work for remote physiotherapy and movement instruction, and future work.

Chapter Two: BACKGROUND

In this chapter, I provide an overview of some related work relevant to my thesis and discuss how this informed my own explorations, and how I extended this prior work in developing Zipples and Physio@Home. Understanding the motivations of these prior works and how they approached their problems provides a foundation for how to answer Thesis Question 1 ('what are the characteristics of at-home physiotherapy exercises?'), and gives a starting point for Thesis Question 2 ('how can we design a system that provides visual feedback for physiotherapy exercises?') that will be better answered later in this thesis.

This chapter should serve to convey the current state of related work in this field by showing a sample of relevant projects and their features. With these works, I point to several key lessons: rehabilitation systems can be more helpful than traditional methods, these systems make use of tracking technologies that are growing more ubiquitous, most use visual or augmented reality methods for displaying movement guidance, and that there is not yet any support for finely-grained corrective feedback for physiotherapy.

2.1 Scope of related work

The related work I looked towards were designed for *supporting physical movement*. Within my specific physiotherapy and rehabilitation context, I classify 'physical movement' as any movement involving the body or parts of the body for a physiotherapy exercise. I will also briefly examine some related works that focus on other physical movement not restricted to physiotherapy—such as whole body dance and touch gestures on a touchscreen. By 'supporting' these movements, I focus specifically on how to have the actor perform them correctly as the movements should be ideally performed.

I must note first that my work on supporting physical movement differs from that of exergaming. Exergaming is focused on encouraging and motivating movement and physical activity through interactive games. This is an on-going field in HCI and prior work by Alankus et al (2010) and Uzor & Baillie (2014) has shown successes in developing interactive games for stroke rehabilitation patients and seniors at risk of falling. However, exergames are focused more on compliance and ensuring the patient is moving and will continue to move and exercise. Corrective feedback in these projects are minimal and the types of movements used in the games are large, coarse-grained movements where fine-grained correction is not as necessary as having the player simply move. My focus in this thesis is on performing correct and careful movements as those seen in physiotherapy, with an additional focus on how feedback and corrective guidance may be provided.

I categorized prior works into three categories: physiotherapy and rehabilitation systems using worn sensors, and those using vision-based devices, and then general movement instruction. The first two categories represent a recent push to develop physiotherapy and other rehabilitation tools, particularly for treating patients at home using advanced tracking technologies that I will discuss. Among them are the more recent use of vision-based devices like the Microsoft Kinect. This is a new and novel field that is still growing and will likely see continuing developments in near future. These works will discussed because their underlying technologies will likely be the foundation for future developments.

The third category represents a more generalized family of instructional systems that are not focused solely on rehabilitation, but still provides concepts relevant for my research. These systems include general instruction systems that focus on dance or generic body movements that could be adapted to physiotherapy, but also systems for learning touchscreen gestures, and augmented reality.

2.2 Rehabilitation Systems Requiring Worn Sensors

A broad spectrum of prior work focuses on rehabilitation using wireless kinematic sensors worn directly on the patient's body to track limb movement. I focus on four prior works: Doyle (2010), Yeh (2012), Ananthanarayan (2013), and Ayoade & Baillie (2014). These works are not the only ones who use wearable sensors, but they provide a concise overview of their usage in at-home rehabilitation. They all demonstrate the usefulness of computerized systems over traditional methods for patients needing to practice rehabilitation exercises at home. Such patients include those recovering after surgery and seniors practicing strength and balancing exercises. In these cases, there are often not enough trained personnel to teach and assess exercises, insufficient motivation, and risk of incorrect exercises that require follow-up surgery. They stressed the importance of being able to visualize what the affected joints look like during exercising to quantify how correct the movement is.

BASE (Balance and Strength Exercises) focused on training exercises for seniors (Doyle et al., 2010) (Figure 2.1[5]). It consists of a laptop running the software, a webcam, and wearable sensors. The kinematic sensors are worn on the patient's ankles and tracked by the webcam, while the laptop displays a variety visual feedback styles: video of the physiotherapist for the patient to follow along with, an abstract set of guides, a stylized representation of themselves, and webcam video of themselves with overlaid guides. BASE also consisted of a connected component that would allow a patient to connect with a physiotherapist and have them monitor their exercises.

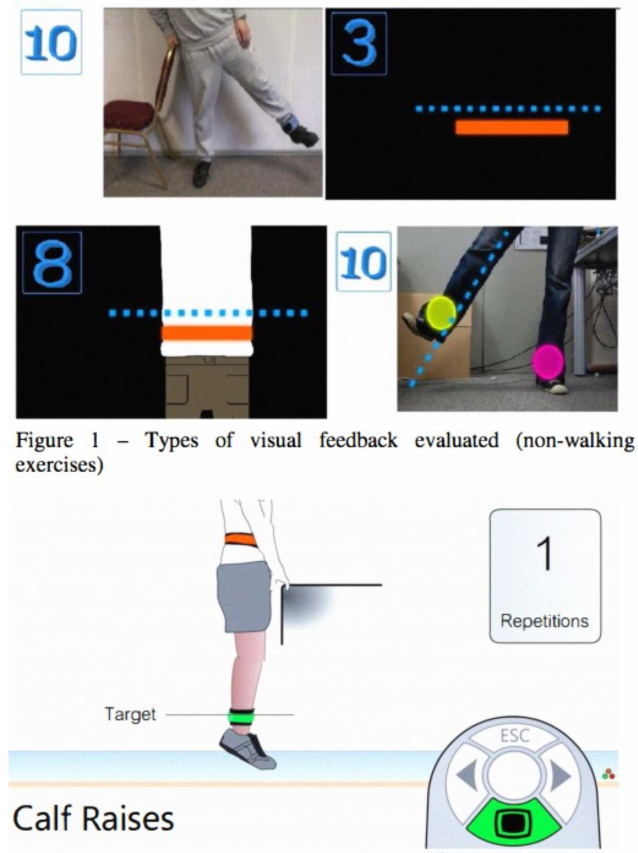

Figure 2.1: BASE (Balance and Strength Exercises)

The authors evaluated BASE in a limited study with seniors in their homes, focusing on the usability of the in-home system and patient attitudes towards their system. Their initial

[5] Figures reproduced from Doyle et al. (2010)

findings were positive, and their participants indicated they would use such a system and had greater reason to comply with their exercises when receiving feedback over time. The authors also noted the participants preferred the stylized representation over the webcam with overlaid guides.

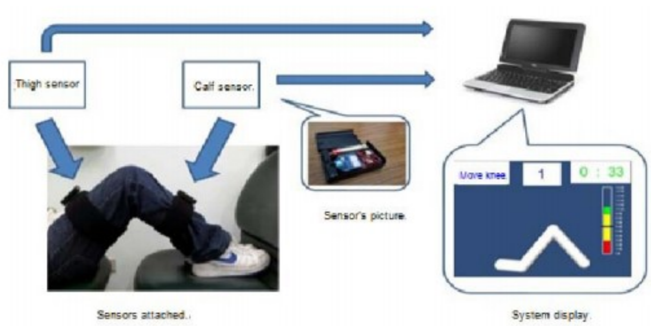

Figure 2.2: Prototype system by Yeh et al (2012). Their system uses wearable sensors to track the leg.

Yeh et al's work from 2012 on patients recovering from lower limb fracture surgery (Figure 2.2[6]). Their system used a pair of inertial measurement units worn on the patient's thigh and calf and a connected laptop running their software. The sensors provide detailed tracking of their leg's movements during exercises, while the laptop software displays a 3D rendering of their leg using the sensor data. While performing leg exercises, the software shows the number of completed repetitions and indicates the achieved angular change and how closely the patient leg meets the required angle in the exercise. Yeh et al performed a limited pilot study to evaluate how users performed in the exercises using the system compared to a control group, and measured their perception of their exercise methods. They noted that users with their system achieved better results when exercising, but were especially more willing to use such a system for exercising. In this light, Yeh et al's study focused more on *compliance* and willingness to continue exercising rather than closely

[6] Figure reproduced from Yeh et al. (2012)

evaluating the patient's performance and improvement—owing to the limited scale of their reported pilot study.

Ananthanarayan et al (2013) also focuses on visualizing a patient's movement with a wearable sensor, but does so in a physical manner. They built PT Viz (Figure 2.3[7]), a wearable device to probe to explore how it may be used in such circumstances. The PT Viz prototype consisted of two enclosures with bend sensors and electronics intended to be worn on the upper thigh and calf. The thigh enclosure contained a series of electroluminescent wire that light up as the user bends their knee, with all the wires lit up indicating a full knee bend. The authors evaluated PT Viz with a think-aloud pilot study with participants previously or currently attending physiotherapy. They noted a distinction between patients recovering from surgery and patients with chronic conditions, where the former would benefit more from their prototype due to them making greater improvements over a shorter period of time and being able to see the changes more readily in the lines—meanwhile, chronic patients would not. Both groups, however, found the

Figure 2.3: PT Viz wearable prototype.

[7] Reproduced from Ananthanarayan et al. (2013)

visualization useful for motivation, pushing themselves further, and knowing their movement limits.

The most recent is work by Ayoade & Baillie (2014), which uses wearable sensors in their Rehabilitation Visualization System (RVS) (Figure 2.4[8]) for senior patients undergoing knee rehabilitation due to osteoarthritis. The Rehabilitation Visualization System uses two custom-built sensors worn on the patient's thigh and ankle. The system runs from a laptop, where the application displays a 3D representation of the patient's leg and the angle of their knee during exercises. The system displays angled arcs to show the requiring angle they must bend their knee towards, with colouring to indicate the ideal angles. The system also keeps track of the number of repetitions performed, also with colouring to indicate the ideal number of repetitions for the patient to perform. For instance, the patient may be required to perform ten repetitions of a straight leg raise. Ayoade & Baillie's system shows how straight their leg is and keeps count of how

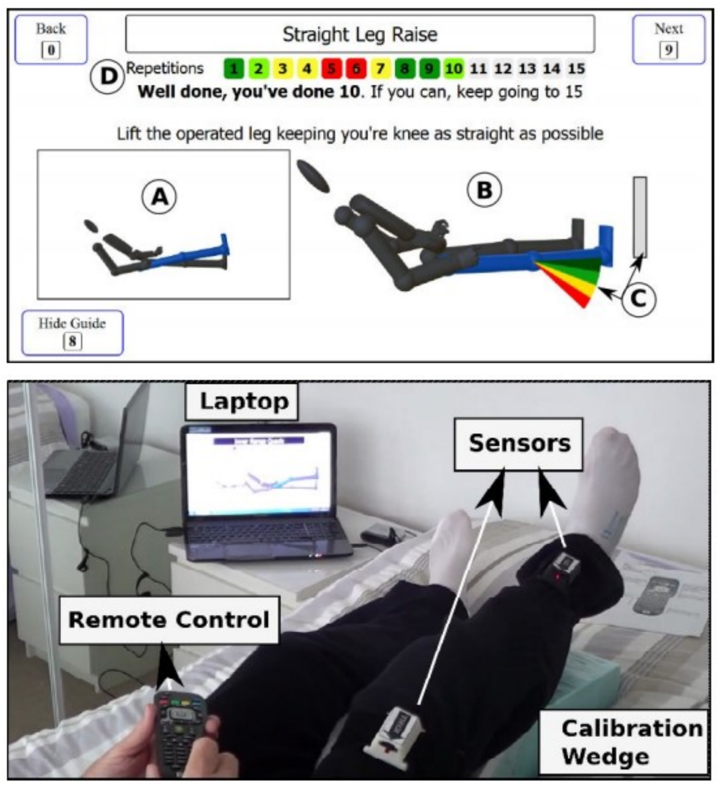

Figure 2.4: Rehabilitation Visualization System (RVS).

[8] Reproduced from Ayoade & Baillie (2014)

many repetitions of the leg raising they finish. Upon reaching ten, the patients are encouraged to finish fifteen if they feel capable. The system then provides a summary of the patient's performance after a number of trials.

In contrast to Yeh et al (2012), Ayoade and Baillie also evaluated RVS with actual patients undergoing knee rehabilitation over a lengthier six-week period, comparing their recovery and qualitative findings to a control group using traditional exercise DVDs. They found that patients working with RVS showed greater improvement by the end of the six-week period than the control group.

These projects are relevant in my research because they focus on physiotherapy. They describe focused systems that are intended to apply computers and advanced technologies directly to rehabilitation and patients. With this strict focus, however, also limits the scope of their work. With Ayoade & Baillie (2014) and Yeh et al (2012), in particular, their projects were focused entirely on knee exercises. More complex joints like the shoulder also involve movements in depth that none of these works were developed for. With the exception of Doyle et al's BASE, which briefly considered the choice of visual representation, none of these works evaluated the design of the guides and visual methods required for providing feedback. These are areas that I intend on exploring throughout this thesis.

2.3 Vision-based Systems for Rehabilitation

Figure 2.5: First-generation Microsoft Kinect. A commodity depth sensor with skeleton tracking.

As with the previous category, these works focus on patients undergoing rehabilitation at home, but struggling with lack of support and guidance, or poor motivation and compliance. In contrast, however, these related projects use vision-based technologies—most prominently, the Microsoft Kinect (Figure 2.5). These systems could be used without requiring the patient to wear kinematic sensors on the body. Often, the previously used kinematic sensors are custom-built devices tailor-fitted to their patients and specific exercises, and are not viable for commercial release. Meanwhile, the Kinect is a complete and off-the-shelf product that is easy to acquire and set up.

Once again, these works are not the only Kinect and vision-based applications for physiotherapy. As the Kinect is still relatively new, the following works are provided to demonstrate some prominent early examples of it in use and how such a device would be advantageous over custom-built on-body sensors.

Figure 2.6: Kinerehab.

Early work with the Kinect by Huang (2011) established the Kinect could be used to support rehabilitation exercises. Kinerehab (Figure 2.6[9]) was an early prototype that tracked arm rehabilitations with young adults with motor disabilities such as cerebral palsy. Kinerehab attempted to address this by using the Kinect's skeleton tracking to inform the patient while exercising how correctly they are performing. Kinerehab was only studied with an initial pilot to evaluate if its intended users would use it, to which system feedback was positive.

Later rehabilitation-focused works with the Kinect, such as Tseng et al (2014), also promotes its usability at home. They implemented a series of games using the Kinect, including ping pong and balancing, and concluded as with the works on exergames that deploying the Kinect into homes would benefit users by promoting movement and exercise.

Lee et al (2014) also used the Kinect for their rehabilitation prototype. Instead of implementing games, they used the Kinect to support Tai Chi exercises—another form of movement exercises that can help patients improve balance and health. They invited Tai Chi instructors to perform exercises while using a Kinect to record their skeleton for example exercises. Patients using their system are shown instructions on a computer monitor for how to complete the motions while the system extracts their skeleton and compares it against the recorded data. They evaluated their system with a single senior participant over a two-week period, first with a traditional rehabilitation program, and then with their rehabilitation system. The participant improved and performed more correct movements when using their system.

[9] Reproduced from Huang (2011)

Other types of exercise movement have benefited from the use of the Kinect. Eye-free Yoga (Rector et al., 2013) used the Kinect to provide audio feedback for visually impaired persons practicing yoga. Their system (Figure 2.7[10]) used the Kinect to track the body posture and position of a patient as they performed yoga poses. The system then provides audio feedback and tells the patient how to correctly reposition their body to achieve the correct pose. The authors evaluated their system with blind or low vision participants, counterbalanced in groups to use both their prototype and a traditional baseline. They found that while the quality of the final poses between conditions were not statistically significant, the participants enjoyed using the system and provided motivation and understanding of the exercises. This work is important to note due to its lack of visual feedback. It addresses an existing population that benefits from the easier setup and usage of the Kinect.

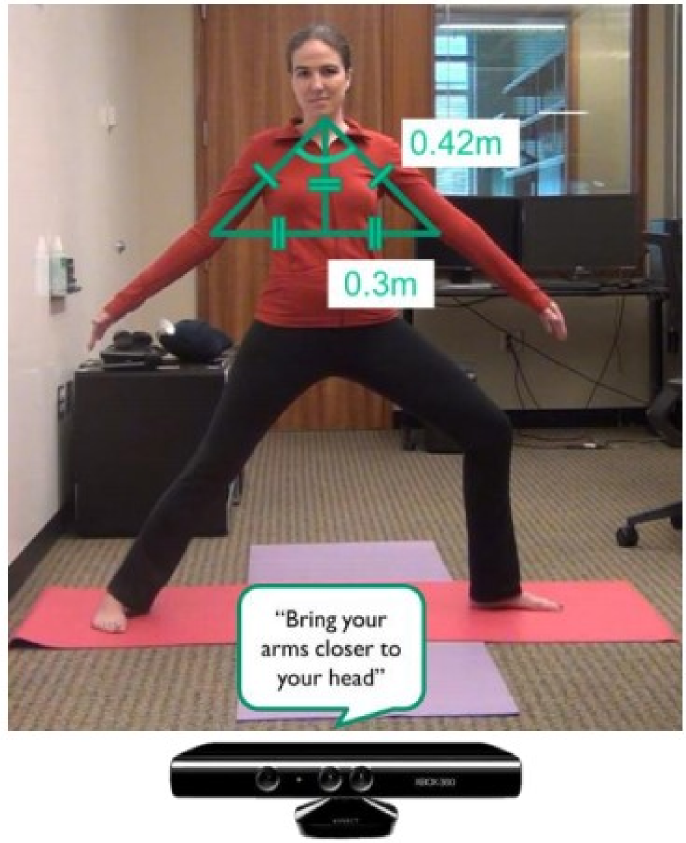

Figure 2.7: Eyes-free Yoga prototype using the Kinect. Reproduced from Rector et al., 2013.

[10] Reproduced from Rector et al (2013)

The variety of these rehabilitation and exercise-based systems using the Kinect should serve to demonstrate the usefulness of devices like it. The selling points of the Kinect include its standardized design and off-the-shelf availability, affordable price, and capable depth and skeleton tracking that was previously not available in a commercial product. All aforementioned projects use the Kinect in the context that it would be easily provided and set up in a patient's house so they may exercise while away from their therapist.

While the Kinect is proving to be a viable platform, there are still shortcomings with the device. Huang noted the Kinect was not able to achieve perfect movement detection due to it occasionally mistaking wheelchairs and walkers as part of the patient's body. Work by Tao and Levin (2013) on Kinect placement found its optimal position to be between 1.45 and 1.75 meters in front of the user and 0.15 meters left or right. Ayoade & Baillie (2014), described in the previous section, also noted the Kinect's space requirements and difficulty tracking knee exercises, and opted for their wearable sensors instead.

Despite these problems, the Kinect is still promising as it provides functional body tracking. For some of these projects, Eyes-free Yoga (Rector et al., 2013) in particular, there was no significant difference between the groups with the prototype system and without, but it still allowed for patients to use them with positive qualitative results. The other projects also highlight that such systems can still encourage and motivate patients to comply with exercises, while work by Reflexion Health (Figure 2.8[11]) is showing a recent commercial use of the next-generation Kinect 2.

As well, Kinect limitation will be less of an issue as better depth cameras are developed. At the time of this thesis, the latest generation Kinect has been released for researchers with greater sensing abilities than the initial version. Intel is also currently developing its own depth sensor[12], while Google's Project Tango[13] is incorporating a depth-sensing camera to a smartphone. These developments mean that cheaper and more capable vision-based devices will be released in the coming years and these devices could be used to support at-home rehabilitation.

Figure 2.8: Reflexion Health's home-based Kinect system.

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[11] Reproduced from http://reflexionhealth.com/brooks-rehabilitation-and-reflexion-health-partner-to-bring-microsoft-kinect-based-physical-therapy-into-patients-homes/
[12] http://www.intel.com/content/www/us/en/architecture-and-technology/realsense-3d-camera.html
[13] https://www.google.com/atap/project-tango/

2.4 Movement Instruction

Related to the previous categories are movement guidance systems. These systems are similar the previous categories in that they focus on teaching movement and they may involve the use of depth and skeleton-tracking cameras like the Kinect. However, they differ in that they focus on movement in general, not limited to physiotherapy and rehabilitation. With the limited coverage of the movement guides from rehabilitation systems, it is also useful to study non-rehabilitation movement systems to learn what techniques may be applied to better improve exercise guidance.

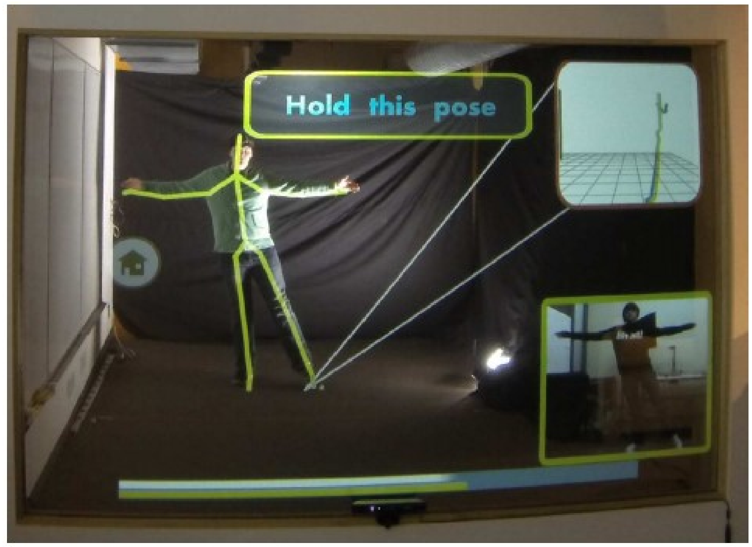

Figure 2.9: YouMove. The prototype uses both a Kinect and novel display surface to display instructional guides for learning and performing movement.

An example of such system that also combines aspects from the previous related work categories is YouMove (Anderson et al., 2014), a full-body movement instruction system with personalized recording, annotation, and gradual learning using an augmented mirror (Figure 2.9[14]). YouMove was designed for learning and mastering physical movements, such as those in dance, martial arts, and sports. The focus of YouMove, however, was on self-paced learning for

[14] Reproduced from Anderson et al. (2014)

hobbyists or supplemental coaching and in-home practice. YouMove used a Kinect for tracking users and a semi-reflective projection screen that acted both as a mirror and computer display. Users could use YouMove to record a movement and annotate it to highlight important parts. Other users could then learn the movement in gradual steps with YouMove scoring movement similarity and removing guides as the performer becomes proficient. The feedback is presented in the mirror that allows people to see themselves, similar to those used in ballet. The authors evaluated their system and noted how YouMove improved learning and short-term retention compared to more traditional methods.

Similarly, MotionMA (Velloso et al., 2013) used the Kinect and wearable sensors to support a virtual demonstration, performance, and feedback loop. Normally, a teacher will demonstrate a movement for a student, the student will perform it, and the teacher will provide feedback to help them improve, but this loop is lost when the students must perform away from the teacher. MotionMA (Figure 2.10[15]) addresses this problem by having the teacher demonstrate an exercise and having the Kinect and sensors record the performance. MotionMA then extracts the model and interpret the fine-grained exercise movements and uses

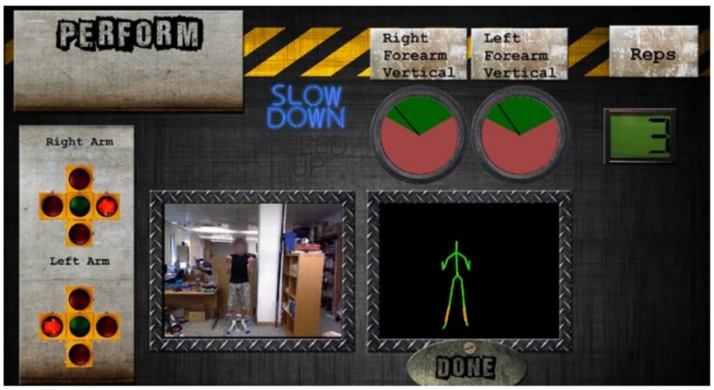

Figure 2.10: MotionMA

[15] Reproduced from Velloso et al (2013)

these to provide detailed feedback for a student. Feedback is displayed on a computer screen using visual elements inspired by traffic lights and speedometers generated from the model to convey speed and alignment of relevant joints. Velloso et al evaluated MotionMA with participants performing pre-recorded movements and found that MotionMA could accurate detect movement differences between the participants and recorded exercises.

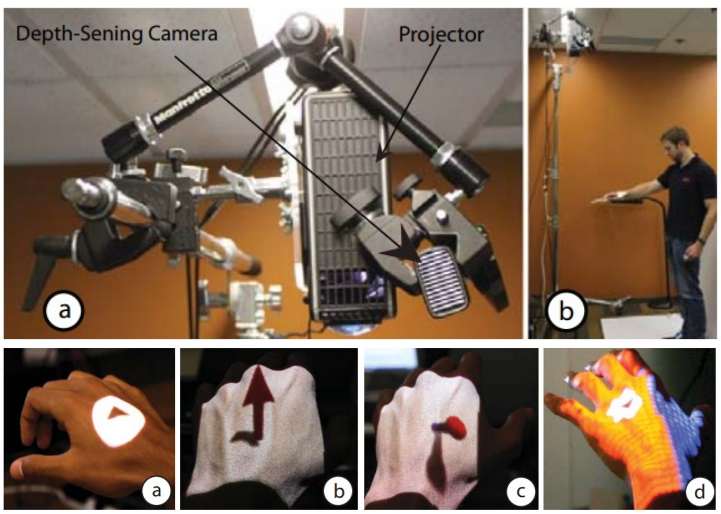

Figure 2.11: LightGuide. This system uses a Kinect and projector to display guides directly on a user's body.

Another project is LightGuide (Sodhi et al., 2012) but this differs vastly from the previous by showing the guides directly on the user's body (Figure 2.11[16]). While the other projects use some type of computer screen and camera feed, LightGuide uses a projector and depth-tracking Kinect to shine a variety of animated guides directly on a user's hand. The guides included 2D and 3D arrows, paths, and colouring that update in real-time to show incremental feedback while the user follows hand movements. Sodhi et al (2012) evaluated all their guides and video-based conditions to see which one would allow a user to perform a hand motion with the least error, and found that a simple 2D arrow did

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[16] Reproduced from Sodhi et al (2012)

the best, followed by a direction pointing 3D arrow. While effective, this projection approach may not be appropriate when body parts cannot be seen such as on the back of one's shoulder.

These systems are experimental examples that could be deployed in homes of physiotherapy patients to supplement co-located physiotherapist sessions. These systems would allow a physiotherapist to prepare exercises for their patient, and such systems would allow a patient to perform them at home while receiving detailed feedback to ensure they are moving correctly. These systems, however, focus on larger movements such as those from dance, where finely-grained correction is not as necessary and where there is considerable leeway in the movements. With the exception of LightGuide, these systems also focus very little on what type of feedback is provided, how they should be designed, and what is shown to the user performing the movement.

To study feedback styles and types, we can look at how the broader HCI community has explored movement guidance with other projects. For example, OctoPocus (Bau & Mackay, 2008) explored the use of a dynamic guide for learning gesture commands on a touchscreen (Figure 2.12a[17]). OctoPocus updates as the user draws gestures on their touchscreen to show them what to draw next to complete a specific command. As the user draws part of a gesture, they can see templates for what to draw next to complete commands such as copying or pasting, and they see parts of the currently drawn gesture change thickness and disappear to show error and the currently recognizable gesture. Bau & Mackay evaluated OctoPocus compared to

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[17] Reproduced from Bau & Mackay (2008)

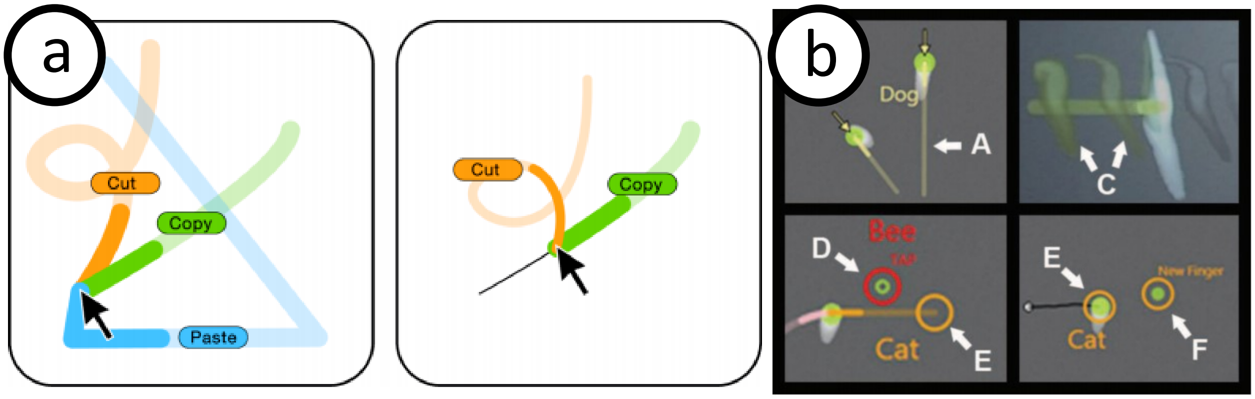

Figure 2.12: (a) OctoPocus and (b) ShadowGuides. While these were designed for guiding touch gestures, both demonstrate the usefulness of feedback and feedforward cues in guides.

traditional help menus over numerous trials and found that users were able to learn and remember gestures faster and that OctoPocus was faster and easier to bring up than traditional menus.

ShadowGuides (Freeman et al., 2009) is similar to OctoPocus, but expanded to include multiple touch points and the whole shape of the hand. ShadowGuides (Figure 2.12b[18]) teaches users gestures on a touchscreen using a combination of hand-shaped shadows to convey the poses of the hand throughout the gesture, and dynamic markers and arrows similar to those from OctoPocus. They evaluated ShadowGuides and found that users could more easily learn and remember gestures than with using video.

These projects introduce the concepts of *feedback* and *feedforward*. Feedback is information conveyed during or after the execution of movement indicating what gestures the user is close to performing (e.g., OctoPocus) and the visualization of current posture (e.g.,

[18] Reproduced from Freeman et al (2009)

ShadowGuides). Feedforward provides information about how to complete future movements: OctoPocus realizes this through possible tracing paths, while ShadowGuides and Just Follow Me realize these as future hand poses and ghostly arm images, respectively.

Augmented reality also presents some interesting contributions to movement instruction and guidance. Just Follow Me (Yang & Kim, 2002) taught arm movements using a head-mounted display and virtual reality. When viewed through the HMD, the wearer sees ghostly arm outlines to convey movement instructions. Similar work in AR by White et al (2007) evaluated visual hints for instructing physical gestures with cards, such as showing ghostly trails of where to move or rotate an AR marker to. Henderson & Feiner (2011) displayed arrows and visual guides directly on objects to complete assembly tasks.

2.5 Conclusions

In this chapter, I provided an overview of related work on physiotherapy, tracking, and movement guidance. I looked at a sample of physiotherapy works using on-body sensors and vision-based devices like the Microsoft Kinect, and a variety of systems for movement instruction. The physiotherapy works, using both sensors and cameras, all demonstrated improvements in patient care over more traditional at-home methods. The works using commodity depth cameras such as the Kinect show great promise, and in spite of some inaccuracy, are being pursued due to their easy setup and availability and adequate tracking. The other finding from these works have been that most feedback methods have been visual. With the exception of Eyes Free Yoga, which focuses specifically on the visually-impaired, the related works involve showing feedback, often on a computer monitor or television screen, of how the patient is exercising.

These works provided a basis for where to begin my own work in this thesis. It pointed me towards devising a visual scheme for guiding finely-grained physiotherapy movements. I draw upon these works to develop a set of guidelines for providing feedback on physiotherapy movements in the following chapter.

Chapter Three: VISUAL DESIGN OF GUIDES

In this chapter, I address Thesis Question 1: ‘What are the characteristics of at-home physiotherapy exercises, and what implications for visual feedback design do they have?’ To do this, I describe the design process I took to develop the design of the visual guides present in Zipples and Physio@Home that help guide movement exercises.

One of the crucial problems the physiotherapist discussed was the lack of guidance for patients at home. As discussed in Chapter 2, patients are at a disadvantage at home because they no longer have a physiotherapist to provide feedback while performing exercises, and brochures and diagrams do not offer any assistance and often results in poorer performance (Ayoade & Baillie, 2014). It is difficult for people to accurately understand and picture movements based solely on these selective snapshots. As well, patients may also forget their exercises. These problems result in low adherence or poor performance, which would result in slower recovery or re-injury in the worst case. Prior works from Chapter 2 demonstrated that computerized rehabilitation systems offering feedback and correction are viable for encouraging correct exercising (Ayoade & Baillie, 2014), while the recent proliferation of vision-based devices like the Microsoft Kinect are making these systems easier to deploy.

As the majority of these systems are currently vision-based, it raises the question of what must patients be shown in order to correctly perform their exercises? Are there concise guidelines or features of movement that could be used to develop guides for performing exercises? To answer these questions, I present my exploratory work with a physiotherapist in this chapter.

I will first describe my design process with a physiotherapist and the questions I asked regarding common physiotherapy exercises and where patients require assistance. I then summarize the findings with a set of important shoulder exercises, and I use these to present a set of qualities of movement common to the exercises that should be conveyed. These qualities include showing: the plane/range of movement, the extents of movement, positions/angles to maintain, and rate of movement. I used these design qualities to inform the design of the guides I later implemented in my two prototype systems, to be described in Chapters 4 and 5.

3.1 Design Process

To understand the required design characteristics for physiotherapy guides, I sought professional feedback and viewpoints from a practicing physiotherapist. I chose physiotherapists as opposed to the patients themselves because my goal was to develop a system for teaching and guiding physiotherapy exercises, and these are tasks best performed by a physiotherapist. I wanted to understand how and what they would teach their patients in-person to see if I could represent these as a set of general characteristics. In doing this, I believed I could find these qualities and mirror them in an at-home system to also support patients away from their physiotherapist.

In working with a physiotherapist, my goals were to learn about the current difficulties and problems experienced by their patients, the basic exercises they teach patients and how to perform them correctly, and how they explain and correct their patients' movements. In doing so, I intended to develop a deeper understanding of my problem domain by taking the perspective of experts who work with the affected users.

To do this, I interviewed a practicing physiotherapist with over five years of experience, and who also runs a home physiotherapy service. I interviewed her because of her willingness to incorporate technology with patient care, particularly for seniors, and her prior contact with my research lab. I met her for interviews three times, for hour-long sessions, with additional shorter interviews during and after my Zipples implementation for feedback. I followed a semi-structured interview process described by Lazar et al (2009) in Research Methods in Human-computer Interactions. In this, I had a list of questions to ask, but I left the interview open and unstructured enough so I could ask for clarification or follow-up questions. I followed an unstructured procedure in particular because I intended to ask about exercises with demonstrations and adhering to a strict structure would prevent me from clarifying exercise movements. The questions and topics I asked were:

- What exercises do you teach patients?
- What are the important qualities of each exercise?
- What mistakes do patients often make?

- How do you teach these exercises?
- What do you give patients for use at home?

After asking these questions and clarifying on movements and fine-grained detail, I analyzed the exercises and grouped findings by common mistakes and qualities.

3.2 Common shoulder exercises from physiotherapy

To focus my inquiry, rather than ask about physiotherapy in general, I asked specifically about shoulder injuries—an injury that is very common and debilitating, and one that is also very sensitive to corrective physiotherapy. The physiotherapist demonstrated several exercises she routinely prescribes for her patients undergoing shoulder rehabilitation. While the specific exercise program depends on the patient's condition and severity, these exercises were commonly prescribed as "homework" for patients. Furthermore, these exercises are often performed in a number of repetitions—the number of these depends on the patient's condition, and are determined by the number required for the patient to be tired.

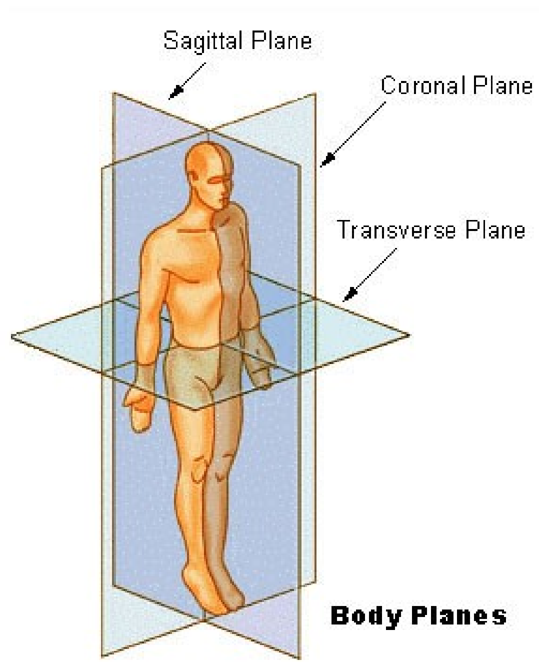

Figure 3.1: Anatomical body planes. The 'coronal plane' will be referred to as the 'frontal plane' for the remainder of this thesis.

To simplify the description of exercise movements, I use anatomical body planes as shown in Figure 3.1[19]. These are imaginary planes that bisect parts of the body and are often used to formally describe movements either on or parallel to them, or moving towards or away from them. The *sagittal plane* bisects the body and splits it into left and right halves; the coronal or *frontal plane* (this term will be used throughout this thesis) splits the body into forward and rearward facing halves; and finally, the *transverse plane* splits the body into upper and lower halves.

Exercise movements are described using the following terms: abduction/adduction, flexion/extension, and internal/external rotation. Abduction refers to a movement of a limb away from a body's plane, while adduction refers to the opposite—a movement towards a body's plane. Flexion and extension refer to the angle of a joint—flexion happens when the angle of a joint is reduced and extension is when the angle is increased. For example, flexion of the elbow joint is when the patient bends their elbow and reduces the angle between their bicep and forearm, while extension is when they straighten their arm, increasing the angle. Rotation refers to a movement towards or away from the body's center. An internal rotation is when a limb rotates towards the body, while an external rotation is when the limb rotates away and outwards. These terms are used to describe movements, but are often not used with the patient, where instructions are far more colloquial (e.g. "Keep your arms straight to the side with your thumb pointed upwards as you sweep up with your arm.").

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[19] Reproduced from https://upload.wikimedia.org/wikipedia/commons/3/34/BodyPlanes.jpg

3.2.1 Shoulder abduction & adduction

This is a simple exercise, consisting of a shoulder abduction followed by adduction. It is a strengthening exercise that involves raising the arm (abducting) along the frontal plane (Figure 3.2[20]) to shoulder level while keeping elbow locked and the whole arm straightened, and then lowering (adducting) the arm back down to the patient's side. This exercise may be performed with the arm being raised along the frontal plane, or 45 to 60 degrees from the patient's front. They are also often performed with thumb facing upwards in order to work specific muscles in the shoulder—performing this exercise movement with the thumb pointing the opposite direction works other muscles.

Figure 3.2: Example of a basic shoulder abduction.

In this exercise, it is vital that the shoulder is kept down. Patients often incorrectly raise the shoulder while raising the arm—doing so does not work the muscles in the shoulder. When the arm is abducting, it must also be raised up to shoulder level—a full 90 degrees from the sagittal plane—to correctly build strength in the shoulder and regain range-of-movement. It is also essential that the arm is kept straight during the exercise, as not keeping it straight may result in the patient not raising their arm high up.

[20] Reproduced from https://www.physiotherapyexercises.com/

3.2.2 Shoulder rotation

This is another exercise that works the muscle in the shoulder, but also involves the elbow. This exercise (Figure 3.3[21]) begins with the patient's forearm being held at 90 degrees from their bicep, with their hand and forearm pointing forward and elbow against their side. The patient must then externally rotate, while keeping the elbow tucked against their side, until their forearm is aligned with their frontal plane, and then bring their forearm back to their initial starting position. When the patient has aligned with their frontal plane, they often must hold their alignment for a few seconds before returning. Alternatively, patients must attempt to rotate as far as they can before returning. Overall, while this exercise involves work with the elbow, it works with muscles in the shoulder.

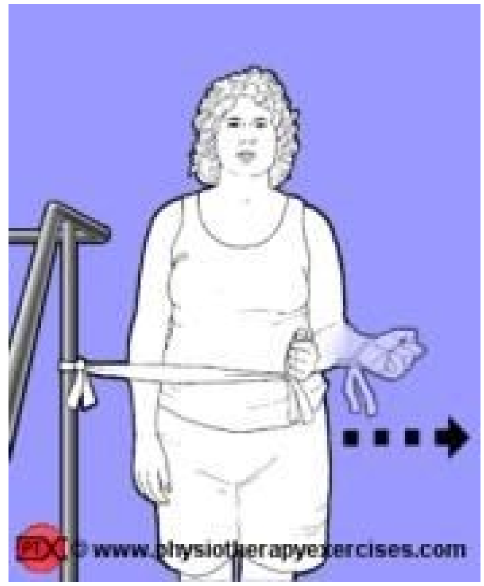

Figure 3.3: Example of an external shoulder rotation.

It is important throughout this exercise to keep the elbow tucked tightly against the patient's side. The angle of rotation is also essential for range-of-motion, and is vital for the patient to fully reach the required angle, all while the elbow is kept in the same position.

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[21] Reproduced from https://www.physiotherapyexercises.com/

3.2.3 Proprioceptive exercises

Another variety of exercises are proprioceptive exercises that involve the body's sense of space and position. There were no strict versions of these exercises, but a key example of these provided by the physiotherapist involves the patient holding their arm out and moving their hand to spell out their name or to draw shapes. Doing this allows a patient to work with multiple muscles in their arm and shoulder at the same time.

3.2.4 Other exercises

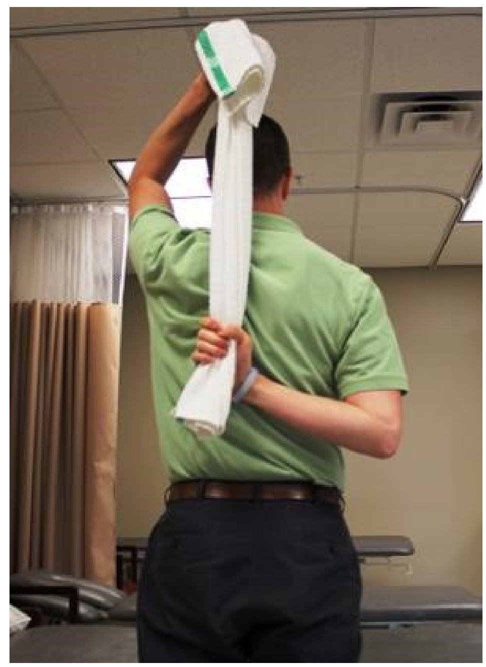

Figure 3.4: Stretching behind the back.

The physiotherapist also described a number of other exercises not categorized by the previous types, such as push-ups. Other common shoulder exercises are varieties of arm and shoulder stretches done behind the patient's back (Figure 3.4[22]). These exercises require the user to put their arm behind their back and pull downwards and hold for stretching. These exercise may either be done with their arm reaching over their head and using a towel to pull, or by grabbing the stretching arm and pulling towards the user's back pocket. A specific example of a strengthening exercise was one where the patient holds their arm out at shoulder level and move it back and forth in small circles for 30 seconds.

[22] Reproduced from http://0.tqn.com/y/physicaltherapy/1/W/b/2/Towel-stretch-IR.jpg

To keep the scope of my work manageable, I focused on the first three types of exercises, as they represent a good portion of shoulder exercises prescribed by physiotherapists.

3.3 Working with patients

The physiotherapist's workflow is similar to the demonstration-performance-feedback communications loop described by Velloso et al. (2013). She would teach her patients by first demonstrating an exercise to them while pointing out the important characteristics of the exercise. After, she would let the patient perform the exercise. During or after they perform, she would physically correct them and explain how to perform the correct movement. Her patients would unintentionally forget specific parts of an exercise—for instance in the shoulder abduction, they may forget to keep their elbow down while focusing too much on raising their arm to shoulder height, or forgetting to keep their elbow tucked into their side for the shoulder rotation. Other times, they are not stretching far enough due to their reduced range-of-movement. To correct these, she would verbally and physically correct her patients, such as moving the patient's limbs or joints to their correct positions in the previously described exercises.

The physiotherapist currently provides generic line diagrams of the exercises, with written notes as reminders for parts to focus on and number of repetitions to perform. At home, these diagrams and notes only function as references. They do not provide the same degree of real-time corrective feedback and guidance as working directly with physiotherapists. They are more likely to perform their exercises incorrectly, or completely forget to do them.

3.3.1 Implications

A system for supporting a physiotherapy patient's exercises at home would have to be capable of body tracking in order to give feedback. In essence, such as system would act like a physiotherapist, but be located in the patient's home. Such a system would tell the patient when they are exercising incorrectly and provide corrective feedback, just as a physiotherapist would during co-located sessions.

Not all physiotherapist activities can be done with such a system. Physical guidance may be required for some activities, but this is outside the scope of this thesis and is not possible here. In lieu of physical correction, what the patient needs from an at-home system is detailed, real-time movement guidance and feedback pertaining to their movement and their exercises.

In analyzing the exercises taught by the physiotherapist, we can see that there are important qualities that must be captured and conveyed. For instance, abduction/adduction and flexion exercises typically move *along a plane*—and this plane could be aligned with a body plane, or at an angle with respect to one. Angles are very important measurements of most exercises. Parts of the patient's limbs might also stay still during the movement and should be conveyed.

From these qualities, I derived a set of characteristics (Figure 3.5a-d) that apply to the previously-described exercises. These characteristics describe important qualities that must be shown in order to provide the same degree of guidance when performing exercises as from a physiotherapist.

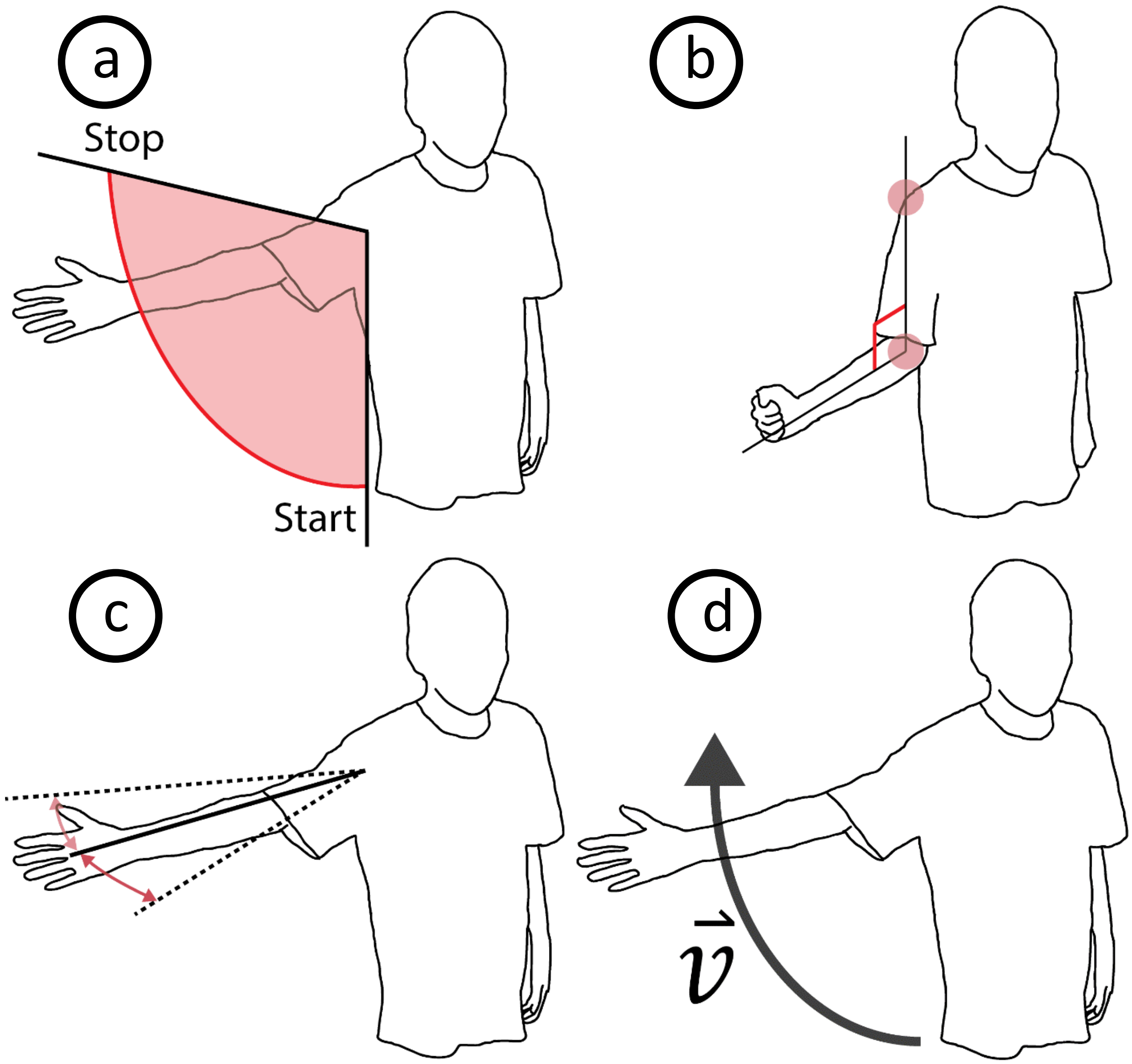

Figure 3.5: Characteristics of Guidance. (a) Plane/range of movement, (b) Position/angle to maintain, (c) Extent of movement, (d) Rate of movement.

3.4 Characteristics of Guidance

3.4.1 Plane or Range of Movement.

The *plane of movement* (Figure 3.5a) refers to the plane that the body part will move along during the exercise. The *range* refers to the "start point" and "end point" of this movement. For instance, during non-angled shoulder abduction, the patient's arm moves up along the frontal plane, starting from a resting position to where it is exactly aligned with the shoulder.

3.4.2 Maintaining position or angle.

For many exercises, certain joints need to be kept in either a fixed position, or at a fixed angle (Figure 3.5b). In the case of abduction/adduction, the arm must be kept straightened, and the shoulder kept level with the ground. Other exercises are stricter—for example, with an external rotation exercise, the elbow needs to stay next to the body, and be bent at 90°.

3.4.3 Extent of movement.

The *extent of movement* limits how a body part's motion can and should deviate from the plane of movement. For example, during angled shoulder abduction, the arm must maintain its angle relative to the body's sagittal plane (Figure 3.5c).

3.4.4 Rate of movement.

This refers to how fast a body part should move (Figure 3.5d). For some exercises, performing them slowly ensures the right muscles are being used. This characteristic applies to a variation of the shoulder adduction where the arm must travel slower as it returns to the patient's side. In many cases, an exercise does not have a set rate of movement and patients are free to proceed at their own pace.

3.4.5 Other characteristics

I described four key characteristics of movement that should be conveyed by an at-home system for accurate guidance. However, in interviewing the physiotherapist and analyzing prior works, I have also identified other smaller—but still helpful—characteristics that movement guides should contain in order to clearly communicate movement instructions. I will briefly describe them:

Feedback and Feedforward. As described by OctoPocus (Bau & Mackay, 2008) and ShadowGuides (Freeman et al., 2009), feedback informs the patient of what is currently happening, while feedforward conveys what is going to happen next. When applying these concepts to exercise movements, feedback must inform the patient of their correctness as they are moving. Feedforward should then tell the patient what the next step of the exercise movement is so they may anticipate the coming movement.

Visual Simplicity and Expressiveness. While the guides must be designed to convey many of these characteristics, care must also be taken to ensure the guides are simple, easy-to-interpret, and expressive without visual overload. As more information is displayed on-screen, the more information the user must process and be overwhelmed by. For this reason, the guides must be visually simple and contain as few details as possible to express valuable guidance.

To accomplish this, I looked to Scott Macleod's Understanding Comics (Macleod, 1993). Expressive movements are drawn in comics using few visual elements, often with single lines and strokes, or stylized arrows to convey rich details such as direction and force of movement.

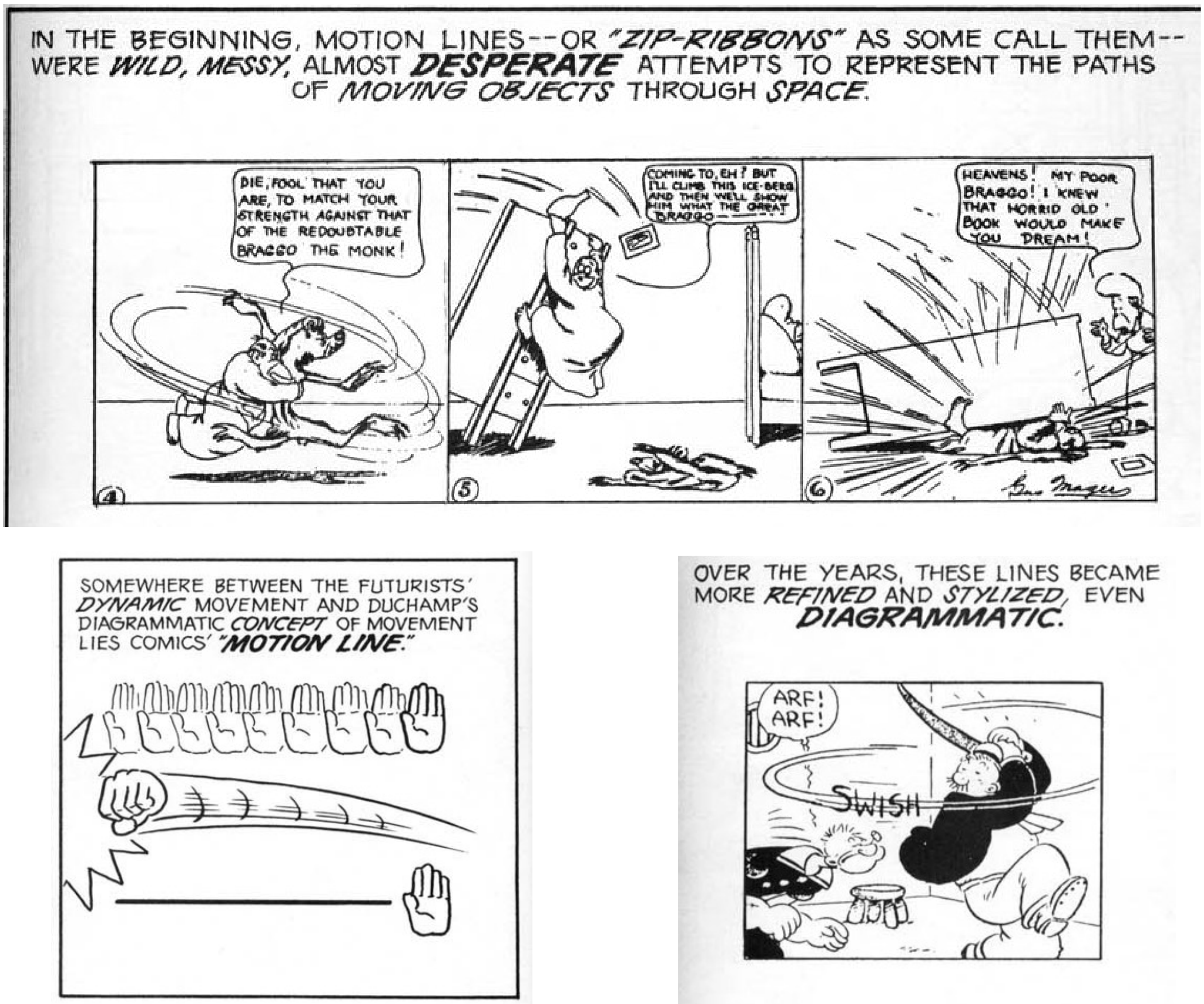

Figure 3.6: Examples of moovles and zip-lines used in comics.
Reproduced from Macleod (1993)

Positive reinforcement. While home-based rehabilitation systems must show patients when they are performing their exercises wrong, these systems also should not penalize a patient. Both the physiotherapist and previous works noted how exercise compliance was an issue for patients and was partly due to pain. Rehabilitation is an often painful process that lasts several months, which patients must endure while performing exercises that may aggravate them. To support the patient, rehabilitations systems should also work to encourage them and thereby ensure they maintain their exercises regardless of their condition. For instance, Ayoade & Baillie (2014) use simple messages that simply told the patient how many more leg raises they needed and encouraged them to do more when they finished the required amount.

With regards to visual methods, this would mean showing more when the patient is performing correctly than showing when they are wrong. Another aspect would be focusing on how much progress they have made in their exercise, or focusing on how much better they are performing.

3.5 Conclusions

This chapter described the guidelines I derived for the design of visual guides for movement guidance and feedback. To develop these guidelines, I interviewed a practicing physiotherapist to better understand some common practices and exercises. After interviewing her, I determined there were a set of characteristics of movement that could be formalized: the plane/range of movement, positions/angles to maintain, the extent of movement, and the rate of movement.

I applied these characteristics in my two prototype systems, Zipples and Physio@Home. Both systems will be described in detail in chapters 4 and 5.

Chapter Four: ZIPPLES

In this chapter, I address Thesis Question 2: 'How can we design a system that provides visual feedback for physiotherapy exercises?' To answer this question, I designed and implemented two different prototypes to support physiotherapy exercises in a home-located context. In this chapter, I describe the first system, 'Zipples': how Zipples was designed, its shortcomings, and the lessons learned from this effort. These provide context for the second system I designed, Physio@Home, which built off these lessons, and was consequently more successful.

I will first provide an overview of how Zipples is used, explain the purpose and intended context-of-use of the system, describe how Zipples was implemented, and the software components that comprise Zipples. I then describe the different kinds of visual guides I implemented for Zipples based on the design qualities discussed in Chapter 3. Next, I briefly discuss an evaluation of Zipples that revealed several limitations. In doing this, I address part of Thesis Question 3 and provide a basis for addressing Thesis Question 4 in Chapter 5.

4.1 Zipples overview

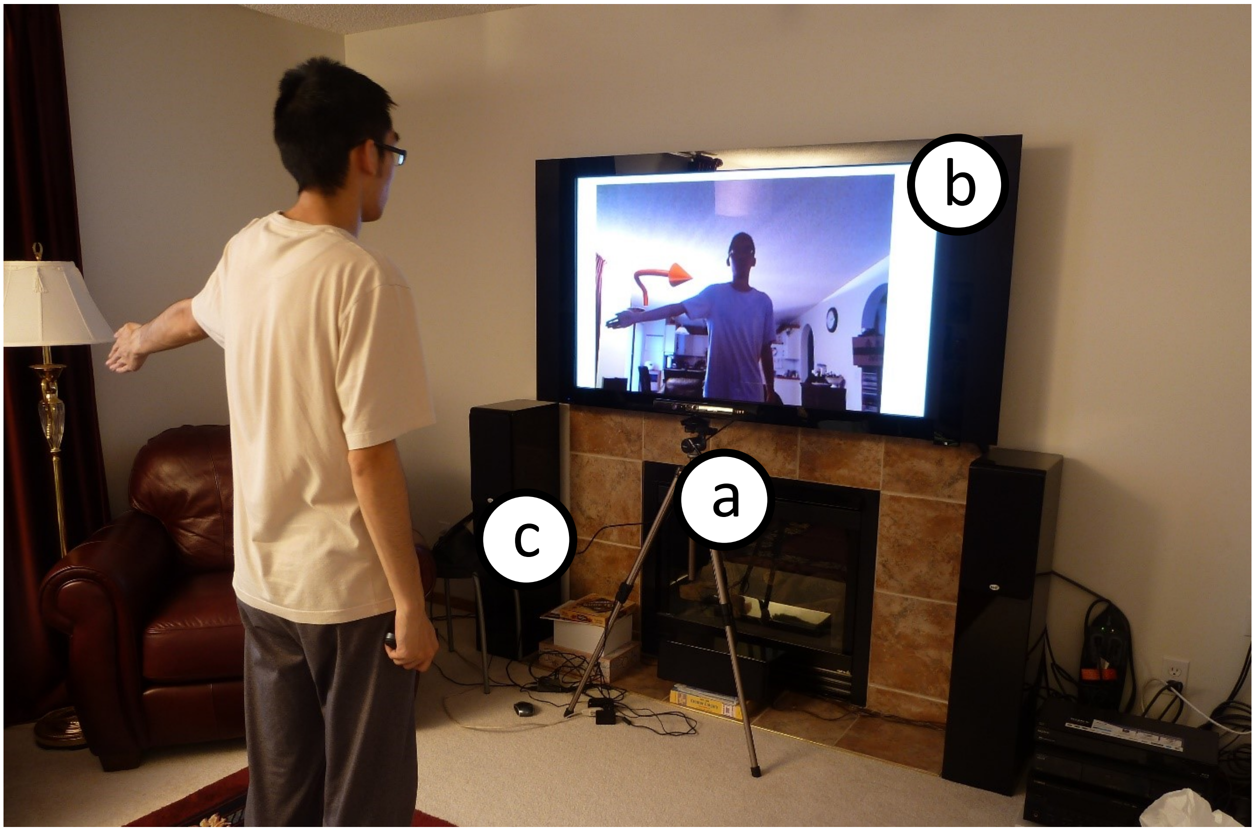

Figure 4.1: Zipples prototype being used in a home setting. Setup and usage is simple due to (a) Kinect, (b) television display, (c) laptop computer running Zipples software.

Zipples is a prototype system powered by a Microsoft Kinect, and is intended to be used in a patient's home and/or their physiotherapist's office. It provides three functionalities: it can record video and skeleton data from the Kinect, it can playback recorded movements, and it can display visualizations for guiding and correcting patients.

4.1.1 Recording video and skeleton

With this feature, Zipples is used by the physiotherapist in co-located sessions with their patient. Functionally, these sessions are the same as current co-located sessions without Zipples—the physiotherapist meets their patient, diagnoses their condition, and prescribes exercises for them to perform to assist in recovery.

However, where the physiotherapist would previously give exercise DVDs or brochures to the patient to use at home, the physiotherapist uses Zipples to record an ideal performance of the exercise and gives this to the patient instead. The physiotherapist can use Zipples to record the Kinect's RGB and skeleton data (joints read by the Kinect are shown in Figure 4.2[23]) as they are performing the exercise. The Kinect's RGB can be used to create a video of the exercise, but the Kinect skeleton fully captures the exercise movements. This data can be saved to a USB stick, or similar storage medium, and be given to the patient.

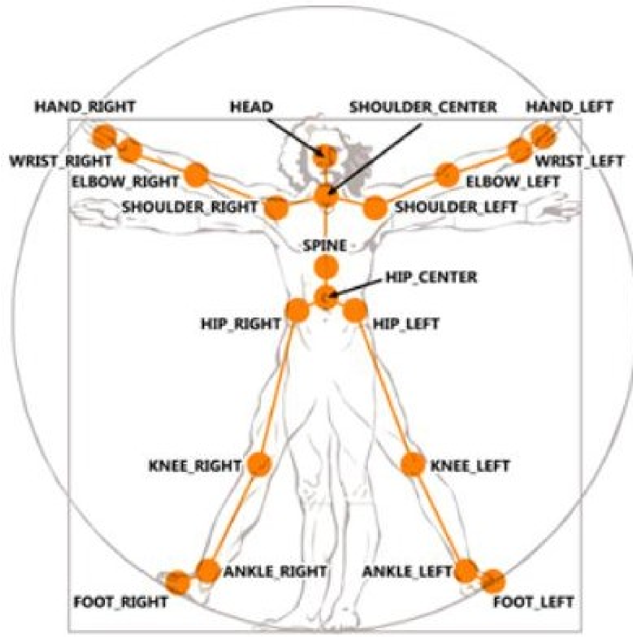

Figure 4.2: Skeleton joints tracked by the Kinect. Zipples tracked the left shoulder, elbow, wrist, and hand.

4.1.2 Playback

The saved exercise data could then be opened in Zipples for playing back. The recorded RGB can be played back as a video to see the physiotherapist's movements as they were originally recorded, much like videos given to physiotherapy patients in traditional use. This feature is used

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[23] Reproduced from https://msdn.microsoft.com/en-us/library/jj131025.aspx

in particular when the patient is at home with Zipples. Using Zipples, they can open their prescribed exercises to see how the physiotherapist performed them. Similarly, the Kinect skeleton data can also be played back in-time like the video to animate the physiotherapist's skeleton as they moved during the exercise.

4.1.3 Feedback

Patients using Zipples at home can either playback the recorded file like a video to remind them of the exercise movements, or playback the skeleton data while performing to receive real-time guidance and feedback. Zipples uses the Kinect to read the patient's skeleton and compares it against the recorded physiotherapist's skeleton to tell them where to move next. When the patient is moving incorrectly, Zipples can see the difference and provide the appropriate feedback visualization to notify them and ensure they are following correctly. The styles and types of visualizations are described later in this chapter.

Because Zipples uses a Kinect like some of the previously mentioned works (Anderson et al., 2014; Velloso et al., 2013), it can theoretically be easily deployed in patient homes. The Kinect is easy to setup and all the patient would require is a monitor or television display connected to a computer running the Zipples software and the recorded exercise files from their physiotherapist.

4.2 System design

4.2.1 Purpose and intended usage

Based on prior work and feedback from my interviews with the physiotherapist (described in Chapter 3), the solution was to develop a prototype system for teaching and guiding exercises at home. In the expected usage of this system, a patient would see their physiotherapist after injury, whereupon the physiotherapist would diagnose their condition and prescribe specific exercises for them to perform. If the patient is seeing the physiotherapist, s/he will receive feedback and correction as expected. But when the patient is away at home, s/he will perform exercises with the tool in place of the physiotherapist. Such a system would need to be easy to setup and use. In my implementation, I made use of a consumer-grade, commodity depth sensor (Microsoft Kinect) and a large display (e.g. big-screen LCD TV). Zipples uses the large display as an augmented mirror (similar to Anderson et al, 2013), where the Kinect-captured video of the patient is displayed along with body-contextualized guides to show the patient in real-time where and how to move his/her body. Thus, it ensures that the patient is performing their required exercises correctly, just as they would if they were working with their physiotherapist. By using this system, the patient can correctly perform their exercises at home between routine visits to their physiotherapist. Strictly speaking, this system is not intended to replace a physiotherapist—its design is meant to complement the physiotherapist's role between visits.

4.2.2 Scope

Zipples was focused specifically on the accuracy and precision of the patient following exercises. Its name was derived from the movement lines ('moovles') often used in comics that provided much inspiration for the guides to be described in 4.3. Rather than build a generalized system for all exercises (as described in Chapter 2, rehabilitation can be necessary for any joint in the body), I focused my approach in the following three ways:

- **Arm/shoulder exercises only.** Rather than designing for exercises that might comprise the entire body, my aim was to design for a challenging body part, and generalize later. With Zipples, my focus was strictly on arm movements. The shoulder joint is a versatile ball-and-socket joint that exhibits many challenging characteristics for design (i.e. range of movement). Thus, much of the work could be later extended to other body parts.
- **Fine-grained vs. coarse-grained movement.** My interests was on fine-grained movements—and in particular, on ensuring that these movements with a complex joint like the shoulder are done correctly—rather than on coarse-grained, whole-body movement. This distinguishes my work from exergame research, which were previously focused on compliance and motivation.
- **Movement guidance vs. application design.** I also focused entirely on the movement guidance part of this system. Other characteristics of home-based systems include the controls the patient would use to start the application and select exercises (Anderson et al, 2013; Ayoade & Baillie, 2014). Due to my focus on accurately guiding exercise movements, I ignored this aspect of the system for now.

4.3 Implementation

Zipples was developed using the Microsoft Kinect, a popular commodity depth camera with skeleton tracking used for both gaming and research. To make use of the Kinect, I developed a WPF/C# application using the then-current Kinect SDK version 1.5 and 1.6. I also used the SDK's built-in skeleton smoothing functions to eliminate jitteriness, and I also made sure the

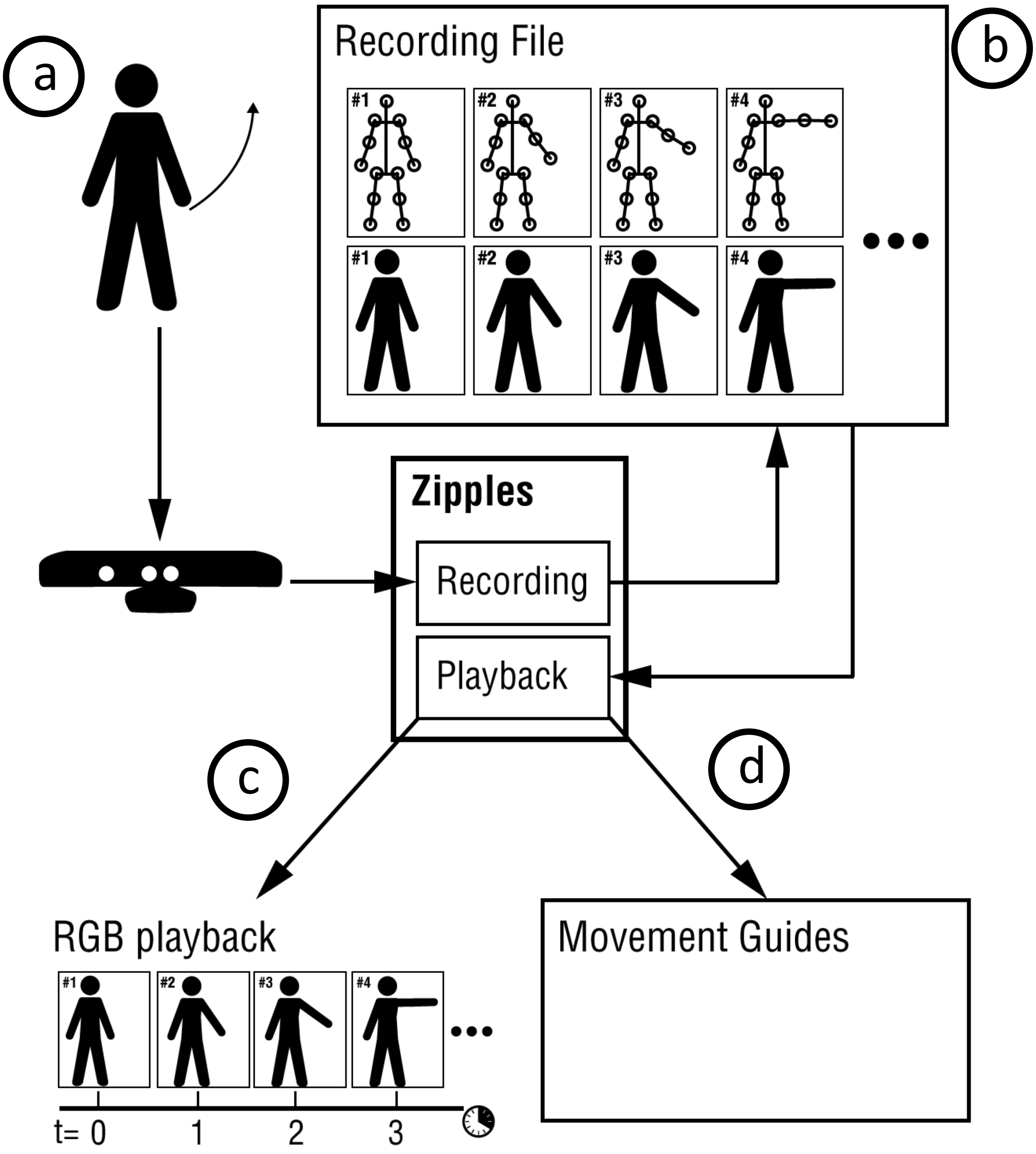

Figure 4.3: Recording and playback design of Zipples. (a) A physiotherapist records an exercise using a Kinect and Zipples' recording function. (b) This produces a recording file containing RGB of the physiotherapist and their Kinect skeleton. A patient using Zipples at home can load this recording and either (c) playback the video of the exercise, or (d) playback the skeleton with guides to receive guidance and feedback.

system and visualizations were still responsive. The resulting application consisted of a single window displaying the Kinect's RGB camera feed.

Zipples uses a mirror view of the patient's body as a display space for visualizations and guides. My interviews with the physiotherapist stressed the importance of mirrors when performing exercises to establish context on the patient and their movements. To achieve the effect of an augmented mirror, I ran Zipples on a wall-mounted television display so that the Kinect's RGB camera feed is shown fullscreen on the wall.

Zipples uses the Kinect to create a 'recording' of an exercise in motion (Figure 4.3[24]a-b), which is a collection of individual 'frames' for each instant of time of the exercise. Each frame consists of frame number and date stamp, and the Kinect data as it was read at that moment—consisting of the raw RGB camera feed, the Kinect's depth map, and the Kinect's skeleton. To do this, Zipples uses a timer set to 41.66 milliseconds to ensure a 24 frames-per-second capture. After every interval, Zipples takes the Kinect data and stores it to a C# data structure and serializes it so that it may be written to the computer's hard drive. The result is the recording file that contains all the Kinect data of the physiotherapist performing an ideal performance of the exercise.

This recording file could then be given to the patient to use with their system at home. While the delivery and use of the file between home and physiotherapist was beyond the scope

[24] Icons 'person', 'Kinect', and 'clock' created by Ferran Brown, fcFrankChung, and Taylor Medlin from Noun Project. 'Person' was modified for use in figure.

of Zipples, the file could be stored on a portable storage medium such as a USB stick and then be given to the patient to open and play back when exercising.

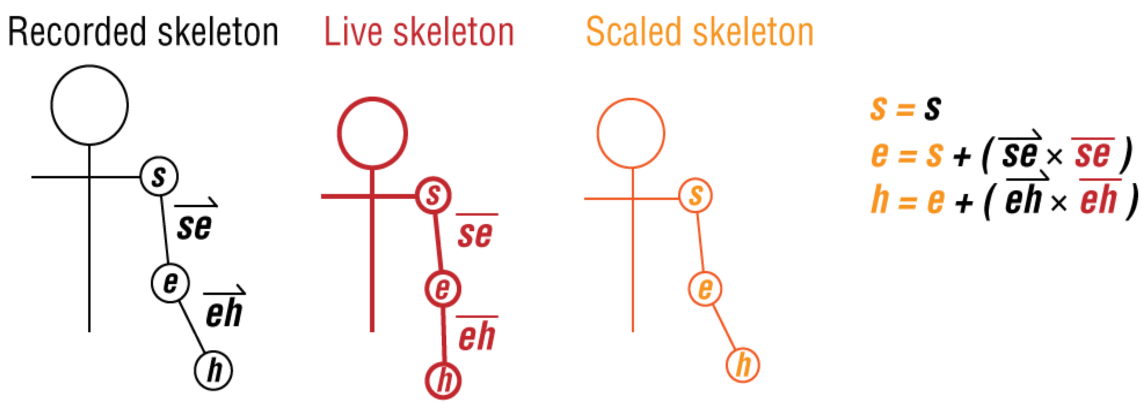

Figure 4.4: Scaling recorded Kinect skeletons to a live person's size.

4.3.1 Playback and scaling

Zipples can open the recording file for playback when a patient wishes to exercise. The file is deserialized and the frames are retrieved and stored to disk in a list data structure. This allows the exercise data to be accessed to either replay the exercise, or for use with the guides. The first can be accomplished by using a timer similar to the one used for recording to iterate through each frame in order as they were recorded (Figure 4.3c). By accessing each frame's RGB data and displaying it in the application, the recorded exercise may be viewed as a video so the patient can see how the exercise appears in motion.

In the second case, the frames are used by Zipples to create the guides and render them on-screen for the patient to follow (Figure 4.3d). This is done by having Zipples read the Kinect skeleton of the live patient and checking their skeleton posture against the recorded frames to match the most similar frame in order to interpret where the patient is in the recording. This was accomplished in Zipples by finding the closest frame based on absolute Euclidean distance of the hand position as tracked by the Kinect (Figure 4.5[25]). As the patient moves through the exercise, their current posture is constantly being matched to the recorded file and being used to update the guide. When they reach the end of the exercise, playback is concluded and the exercise is unloaded and guide reset. To simplify the procedure and avoid having Zipples skip too far ahead, Zipples only matches ahead and behind by 15 frames.

When using the guides, playback is controlled by the patient and the exercise only progresses when they move. This was done to account for speed differences between the pre-recorded exercise and the user's own speed. This would allow a patient to initially perform an exercise at their own pace in order to focus on performing the correct movements rather than trying to keep up if their joints could not yet support faster movements. Of course, it is possible to play these frames back with the guides on a timer—similar to video playback—in order to train movement speed; however, based on the feedback from the physiotherapist, movement speed is not as important to "get right" in comparison to the movement itself.

To account for different user positions at time of recording and playback and user sizes, Zipples also performs repositioning and scaling. Zipples can detect the patient's position in front of the Kinect and adjust the recorded skeleton data to where the patient is standing. To handle differences in arm lengths and user height, Zipples uses a calibration stage before use to compute the length of a patient's bicep and forearm. Each recorded frame is scaled by computing a ratio

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[25] Icons 'person' and 'Kinect' created by Ferran Brown and Taylor Medlin from Noun Project. 'Person' was modified for use in figure.

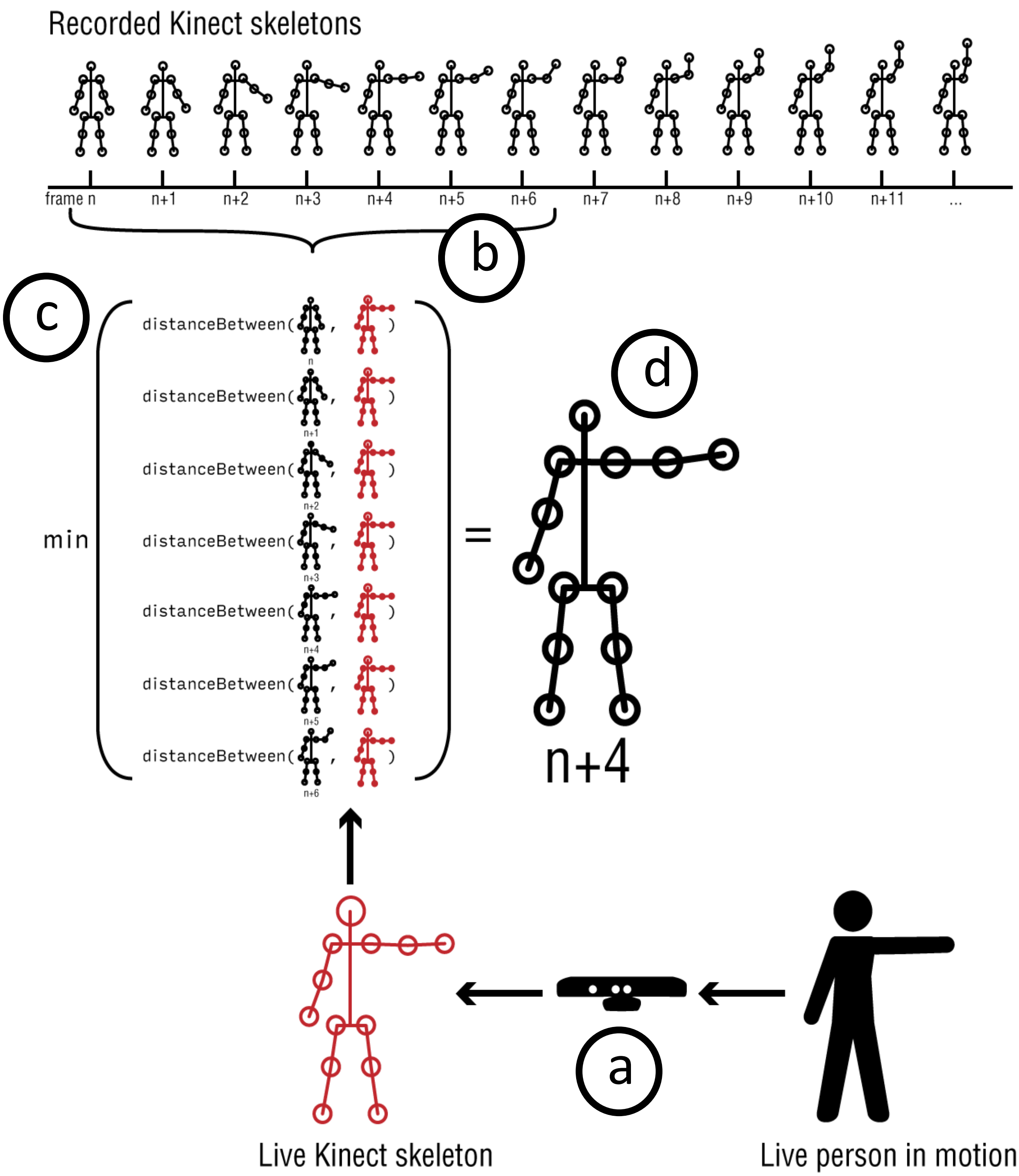


Figure 4.5: Finding most similar Kinect skeleton to the patient's live posture. (a) The patient's body is read by the Kinect. (b) Zipples takes a small subset of recorded skeletons to compare the live skeleton against. (c) Skeletons are compared based on joint distances. (d) Skeleton with minimal joint distance is selected. This has been simplified here to only match 7 frames.

between the patient and recorded data's biceps and forearms and converting it into a 3D vector. Using the shoulder as a starting point for the new scaled arm, Zipples multiplies its position by the bicep vector to create a new elbow position, now scaled to the user's bicep length. I repeat this again with a forearm vector to get a new wrist position. The resulting elbow and wrist positions are now scaled according to the length of the participant's arm to account for size differences. This process is illustrated in Figure 4.4.

4.4 Initial guides

I implemented two sets of guides for Zipples; the first set in this section (2D Arrow, Arrowhead, Arm Lines, and Dashed Triangles) were evaluated with the study described later in this chapter. After the study, I used my findings to implement a second iteration (3D Arrow, Feed-through Arrowhead, and 3D Arm Lines), but these were not evaluated.

Movement guides were implemented using either WPF vector graphics or the .NET compatible Helix3D toolkit. WPF provides included functionality for drawing two-dimensional vector graphics and shapes, while the third-party Helix3D toolkit is used to create three-dimensional guides. To achieve the effect of an augmented mirror described from the literature (Anderson et al. 2014), I layered the feedback canvas and 3D viewport over the RGB camera feed, such that when viewed together, visual elements are overlaid on top of the user and their joints as tracked by the Kinect. 2D elements in the WPF vector graphics canvas are aligned using the Kinect SDK's native 3D-to-2D point translation functionality. The Helix3D viewport is similarly layered on top of the RGB feed with a transparent background such that the 3D

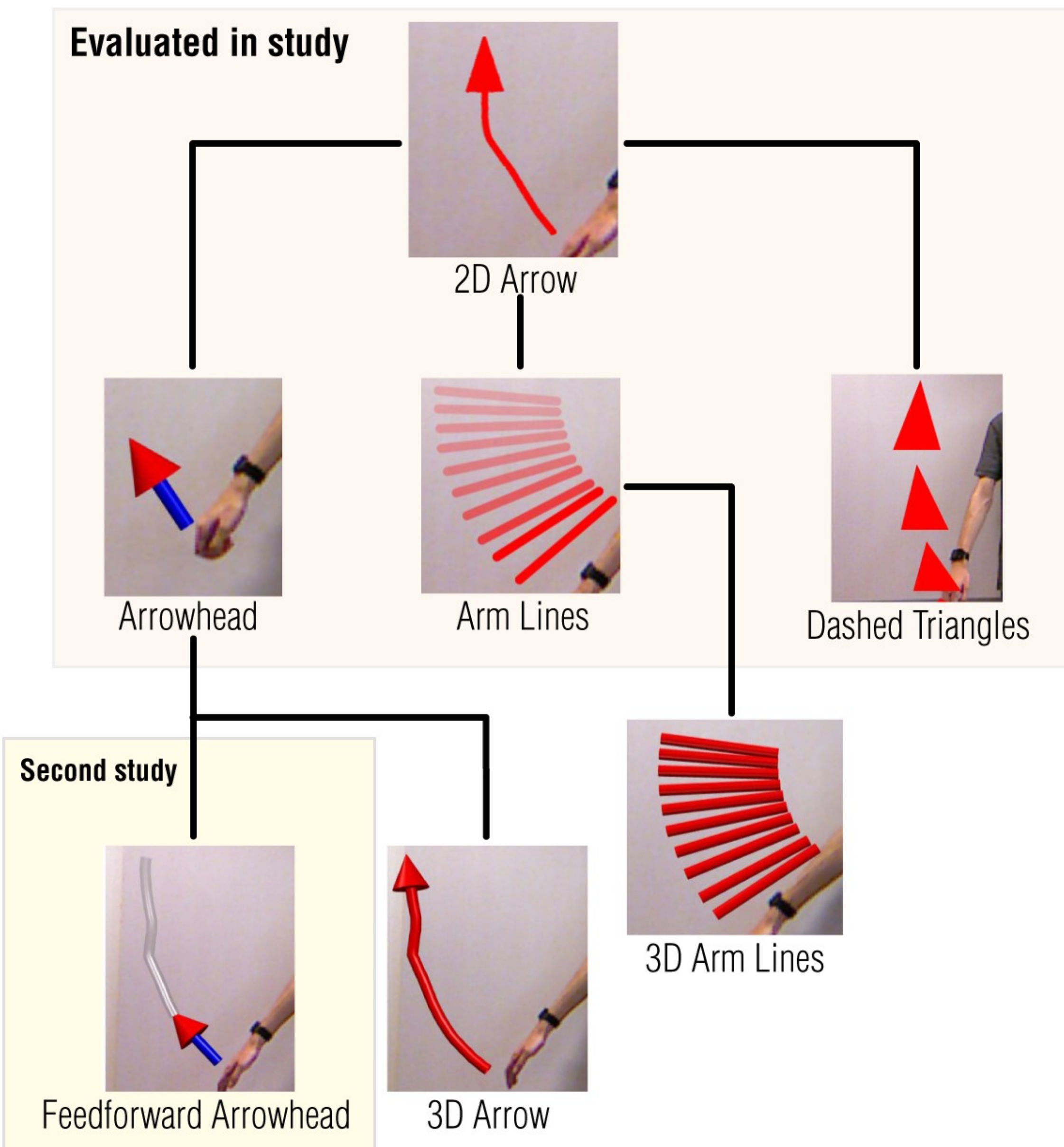


Figure 4.6: Iteration of Zipples' guides. 2D Arrow was developed first and iterated into Arrowhead, Arm Lines, and Dashed Triangles. These were the first to be evaluated with a study. Feedforward Arrowhead was evaluated with second (pilot) study

elements are made visible. The viewport's camera is then set at roughly the same spot a user would be standing in the real world so that 3D elements are layered directly on the user.

Each of the following guides were implemented to support some of the design characteristics described in the previous chapter. All guides were implemented as separate classes that would receive recorded frames for playback and use the scaled skeleton joint positions to render all or part of a movement. As the user follows the guide and moves through the exercise, the guide is updated so that it could show the user whether they are correctly following it.

The method for finding nearest frame was done so that if the user was incorrect, they would still be matched to the nearest frame, but not need to be corrected before continuing. This would allow a user to keep moving through an exercise, but have the chance to correct if the guide could adequately show them. This was designed for the study so that participants would have to rely on the guides for the exercise movements.

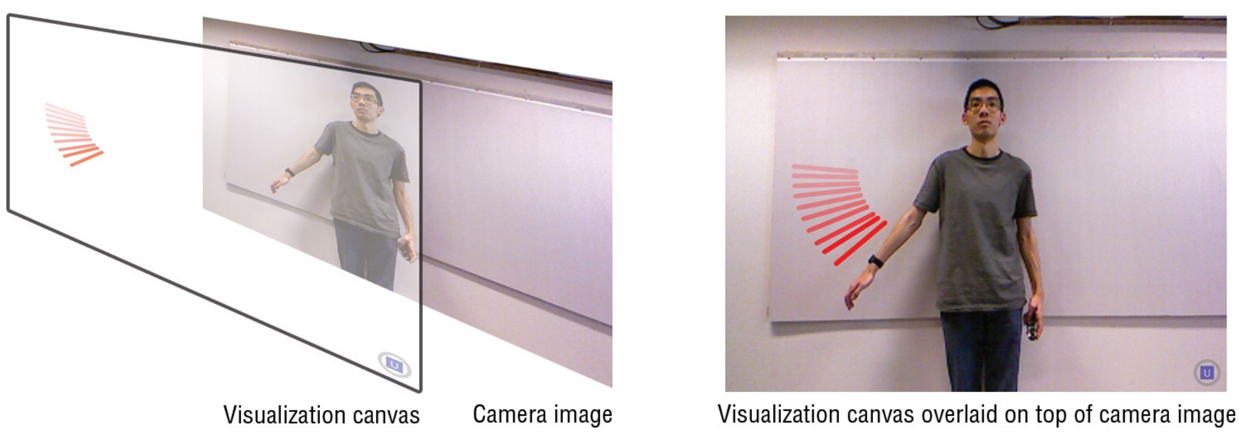
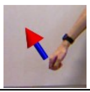
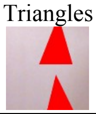
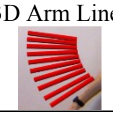


Figure 4.7: Overlaying 2D and 3D visualizations on the Kinect's RGB feed. WPF canvas and 3D viewports are layered on top of the RGB such that when viewed together (right), visualizations appear over the patient's body.

Table 1: Summary of visualizations implemented in Zipples

Name	Description	Plane/range of movement	Maintain position	Extent of movement	[26]Rate of movement	Strengths	Weaknesses
2D Arrow 	Two-dimensional arrow that shows path of movement and direction			✓	-	• Simple to understand	• Poor depth
Arrowhead 	Fixed-size/length three-dimensional arrow attached to person's hand	✓	✓		-	• Shows depth • Shows corrective feedback	• Difficult to use • No feedforward
Arm Lines 	A set of 5 lines representing future forearm and bicep positions, with fading opacity	✓		✓	-	• Shows movement plane • Visually attractive • Easy to understand	• Misleading depth
Dashed Triangles 	A series of triangles forming a dashed-line that shows where to	✓		✓	-	• Represents depth • Easy to read for some movements	• Cannot show forward/backwards movements • Cannot visualize some movements
Feedforward Arrowhead 	Combination fixed 3D arrow with a transparent feed-forward path	✓	✓	✓	-	• Shows depth • Shows correction Shows feedforward	• Folds into itself
3D Arm Lines 	Three-dimensional adaptation of 2D arm lines	✓		✓	-	• Easy to understand • Shows depth/orientation	• Folds into itself • No corrective feedback
3D Arrow 	Three-dimensional adaptation of previous 2D Arrow	✓		✓	-	• Shows depth • Easy to interpret	• Folds into itself • No feedback

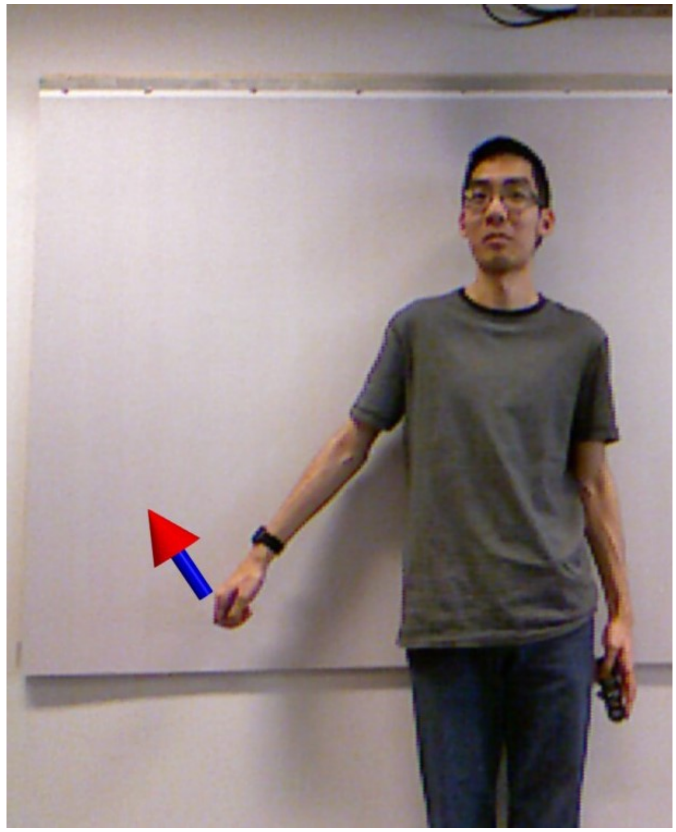
[26] All visualizations could technically show Rate of Movement if the skeleton is animated, but this was not evaluated in either Zipples or Physio@Home.

4.4.1 2D Arrow

One of the simpler guides implemented was a basic two-dimensional arrow. This arrow consists of a stem and a triangular arrowhead, all drawn in a WPF canvas using basic WPF graphics. The end of the arrow's stem is attached to the user's hand in order to show where the user must move their hand in order to move their entire arm by extension. To draw the arrow, the scaled and repositioned hand positions from the next 25 frames are used to build the stem, and a triangular polygon is attached to the top to show the required direction of movement. In movement, this results in the stem and arrowhead constantly jumping ahead as the user moves.

To denote depth and directionality, the arrowhead also animates. When the next movements are in front of the user, the arrowhead is wider and subsequently narrows when moving closer. The arrowhead also folds when it changes direction on the edges of movements.

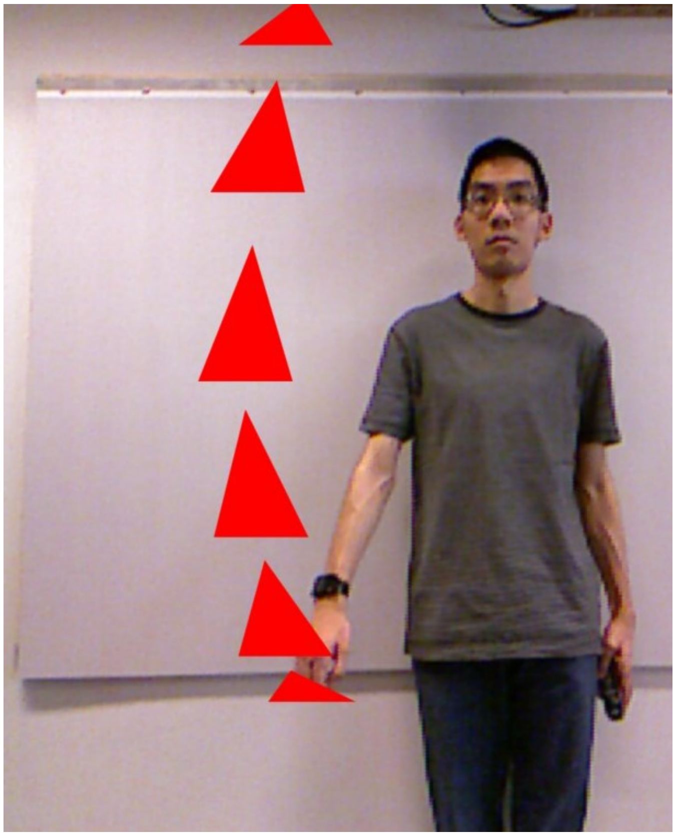
4.4.2 Arrowhead



The 2D Arrow was the simplest, but was limited in being only two-dimensional. While the size of the arrow was used to show movements in depth, it was clear that it would still be limited in how much depth it could accurately depict, and in how much warping and transformations it would require to show more depth. The 2D Arrow's stem also did not move to convey corrective feedback.

To avoid these limitations, I implemented a similar guide in 3D using the Helix3D toolkit. Using the toolkit, I created a 3D model of an arrow that would be attached to the patient's hand, and could freely point in all directions. As the patient moves, the Arrowhead reorients itself to show where they must move their hand next. By doing this, I would not need to worry about how to animate a 2D shape to show movements in depth, as the Arrowhead would simply point in the required direction and the appearance and shading of the model would more easily convey depth.

4.4.3 Dashed Triangles



This guide drew on the use of dashed lines often used in comics to denote movement path, particularly from the Dotted Lines comics of Bill Keane's Family Circus comic strips[27]. This guide shows the entire movement path of the hand for the exercise from beginning to end and requires the user to perform it. This guide represents the path using a series of dashed segments—originally rectangles, but later changed to triangles to denote movement direction. Similar to the 2D arrowhead, the size and width of each segment represents the depth of that movement, where larger segments indicates further from the user. As the user progresses through the exercise, individual segments disappear.

4.4.4 Arm Lines

This guide was a simplified variation of using stills to show the required movement. Time-lapsed stills of a motion can be layered to show how the movement developed over time. The arm

[27] See Appendix A.1 for example

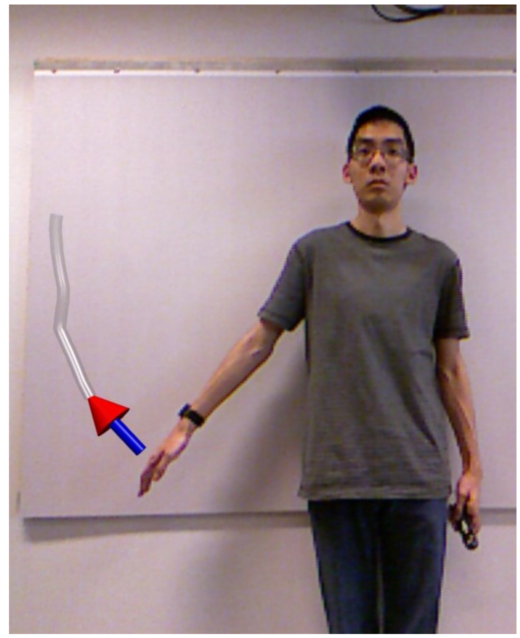
postures from future frames would be shown ahead of the user to convey where to go, and would update as the user progresses through them.

The initial variation used RGB images of the recorded exercise, but this was dropped in favour of drawing stick-figure arms in place of photo stills. Using RGB arm stills proved challenging due to the different sizes of user arms and different standing positions of the original exercise and user not allowing for proper alignment when attempting the exercise. I chose to simplify the guide and instead display the arm as a stick-figure, as tracked from the Kinect.

4.5 Second iteration of guides

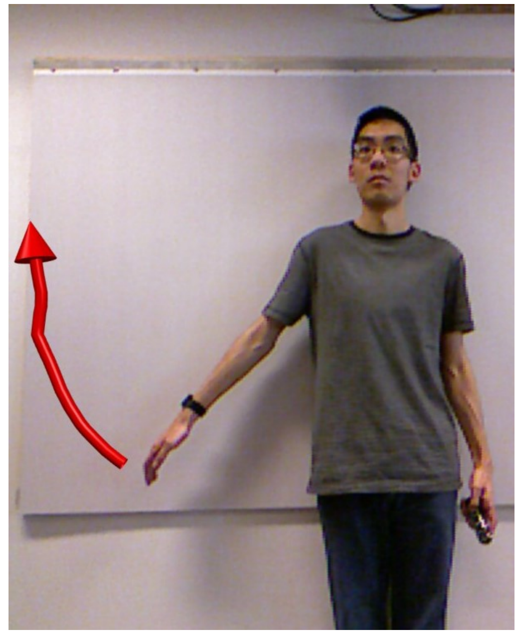
Following the study, I used my findings to implement a second set of guides: the Feedforward Arrowhead, the 3D Arrow, and the 3D Arm Lines. These guides were not formally evaluated and were only implemented to explore alternative designs and address shortcomings with the initial guides. Findings from the second iteration would later influence the design of the singular Wedge visualization, to be discussed next chapter.

4.5.1 Feedforward Arrowhead



The Arrowhead could show required direction of movement and provide corrective feedback, but could not provide feedforward. The patient would only see how they are currently moving, but not what movements were coming next, thereby increasing their risk of performing a movement wrong by not seeing and preparing for sudden turn or direction change. To support this, I added a translucent pipe extending from the tip of the Arrowhead that shows part of the future movement path. The pipe crawls forward to continue showing the future path for the patient so they can anticipate future movement while following the immediate feedback of the Arrowhead. To avoid cluttering the display, the feedforward path only showed the next 20 frames—this number was selected because it made the feedforward path twice the length of the Arrowhead, which was a sufficient balance between screen clutter and feedforward.

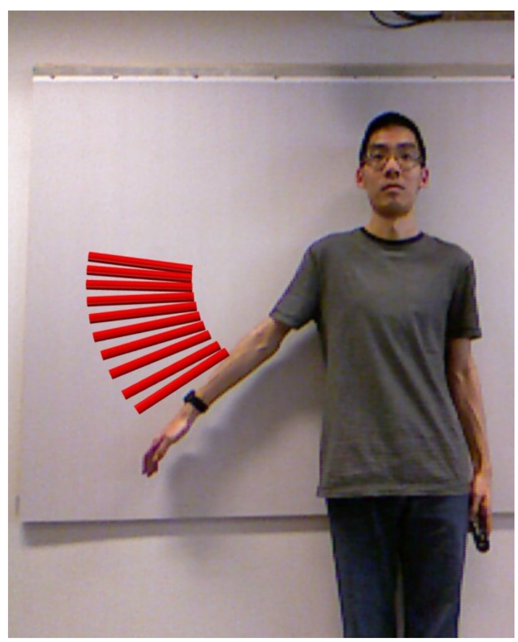
4.5.2 3D Arrow



This was essentially the 2D Arrow, re-implemented using the Helix3D Toolkit. The 2D Arrow could not show depth due to its two-dimensional design, even with the changing size of its head. The simplest way of addressing this was to implement it in Helix3D, where the three-dimensional model would have proper orientation and direction.

Like the 2D Arrow, the hand positions from the next 25 frames were used to create the arrow's stem and the top of the stem was topped with a cone to make a completed arrow. As with the 2D Arrow, the 3D Arrow updated and moved as the user followed it.

4.5.3 3D Arm Lines



The Arm Lines guide was unable to show depth like the 2D Arrow due to its two-dimensional design. To address this, I also re-implemented it using the Helix3D Toolkit. The design stays the same, where the next 10 forearms are shown in front of the patient's arm. These future arms are represented as a series of 3D pipes. As they are three-dimensional, it is easier to interpret their direction and orientation. All other functionality stays the same.

4.6 Study

After implementing the core functionality of Zipples and the initial guides—2D Arrow, Arrowhead, Dashed Triangles, and Arm Lines—I ran a laboratory study to evaluate the effectiveness of the system. The purpose of this study was to see how closely users could follow pre-recorded exercise movements when using the guides and how they felt about using them. By doing this, we can understand what types of guides would work the best for accurate guidance and be able to build a language for the design of such movement aides. In doing so, my work could be used to advise on the development of future systems.

4.6.1 Study Design

I used a within-subjects study design, where each participant is evaluated using each of the four initial visualizations with five physiotherapy-inspired exercises. I chose this design to evaluate how well individual participants performed using each of the visualizations and to gather comparative feedback between them. It also allowed me to run fewer participants and still retain greater statistical power. In contrast, I would have had to perform a between-subjects study with a greater number of participants and not be able to compare individuals across visualizations. The four initial guides were compared against Zipples' playback function, which was used to simulate a traditional exercise video.

My study recruited local university students via the Computer Science Graduate Studies mailing list. I used a controlled laboratory study instead of an actual at-home deployment due to the early state of Zipples and the lack of a refined interface and control scheme. I also did not recruit participants, including older adults, undergoing rehabilitation or with rehabilitation experience. This was also due to the early state of Zipples and the guides, which both still required feedback and more iterations before it would be prudent to work with such a specific population. My intention was to gather feedback to verify my ideas and direct an iterative redesign before I would consider working with the relevant populations. This choice was also motivated by inherent challenges in working with these populations, as seniors are difficult to bring for an early laboratory study, and participants undergoing physiotherapy may still be affected by their condition. However, I took some care to ask if the participants did have prior rehabilitation experience in order to gauge their impressions on Zipples. In total, 11 participants were recruited for the study.

In order to streamline the data recording, I implemented various automation controls. These controls included a timer to countdown before the participant could start the exercise, and an automatic shutoff for the recording. By implementing this, once the participant finished the exercise or was close to finishing, Zipples would automatically stop the recording. Zipples also featured a robust crash recovery functionality so that in the event of errors, the system could be started again and study settings and condition orders would not be lost.

4.6.2 Exercises

I used five exercises[28]to evaluate the participants. These exercises were used to represent stretching, range-of-movement, and proprioceptive exercises used in physiotherapy. The

[28] See Appendix A.9 for exercises

exercises are described below using the informal names I called them during development to distinguish them:

Circular. The patient moves their arm forward and loops to their left and ends back against their side. The complete movement forms a circle with their hand.

Up-down. The patient raises their arm from their side and up to shoulder level, and back down to their side. This is a basic shoulder abduction and adduction.

Vertical-up-down. The patient raises their arm forward and up to the ceiling and back down.

Rotation. Starting with forearm pointed forward and elbow at their side, the patient rotates their forearm outwards and back.

Figure-8. The patient raises their arm forward and draws a figure-8 with their hand before returning to their side.

I selected these exercises because their movements were based on those from physiotherapy. The first up-down exercise is a basic shoulder abduction, while the vertical variant is a stretching and reaching movement often prescribed for seniors. The rotation exercise is also a common physiotherapy exercise. The circular and figure-8 exercises are complex movements in multiple directions that necessitate the use of detailed guides to follow them.

4.6.3 Procedure

Each participant was run through the following steps:

1. Consent and demographics

Participants were first given a consent and demographics form to fill out prior to the study. The demographics form asked them if they had any prior physiotherapy experience and details such as their physical activities.

2. Calibration

   Participants did a brief calibration step with Zipples. They would hold their arm straight and out to the side and rotate inwards until it is pointed towards the display screen. This was intended to account for the Kinect occasionally misreading the length of a participant's arm.

3. Exercise tasks

   The participant would perform a set of exercises in each of the conditions. The order of the conditions for each participant was counterbalanced by Latin Square. In each condition, the participant would first practice with an unused exercise to become familiar with the guide. After this, they would be begin the study proper by performing each exercise with the guide while being recorded by Zipples. Each exercise is performed three times, with additional trials if the Kinect lost tracking. Participants were also instructed to think-aloud during the trials to provide immediate comments on the guides.

   The participant recordings provided by Zipples were similar to the exercise recordings. Each trial provided a data file consisting of the Kinect RGB, depth, and skeleton data.

4. Post-condition questionnaire

After each condition is finished, the participants are given a questionnaire to rate the condition. The questionnaire asks the participants to rate using a seven-point Likert scale questions such as how easy the guide was to use, how accurately they could follow the exercises, how helpful, etc.

5. Repeat steps 3-4 for the other guides.
6. Post-study questionnaire. After finishing, participants were provided a remuneration of $20 for their participation.

4.6.4 Error calculation

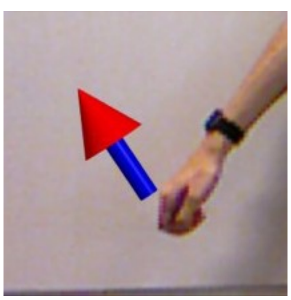
In addition to feedback from the questionnaire, I also wanted to measure how well participants performed using the different guides. To do this, I intended to measure their error, or how closely they were able to follow the pre-recorded exercise. I made use of the scaling algorithm described in 4.3.2 to first scale the exercise to the patient's size, and then I would compute the absolute Euclidean distance between the joint positions. By doing this, I would be able to see how closely the respective joints were able to stay on the pre-recorded exercise, where less error means the participants were able to do so the closest.

In addition, to simplify the data analysis and computations, the nearest exercise frame as detected by Zipples was also recorded. This was done so that each participant frame could be easily compared to compute error.

4.7 Findings from initial guides

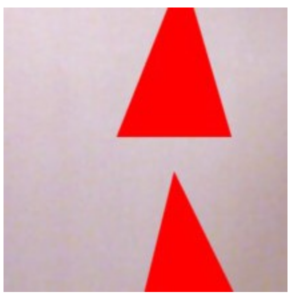
I was able to analyze some of the questionnaire results and comments from the think-aloud to discuss my four initial guides. From the post-study questionnaires, 6 out of 10 participants found the 2D Arrow the easiest to learn and 4 out of 10 also found it the easiest to use. 4 out of 10 also believed they were the most accurate with the Dashed Triangles, and a similar number selected it as the most helpful. Preferences for the 2D Arrow, Dashed Triangles, and Arm Lines were equally split and only one preferred the 3D Arrow. While these results were subject to implementation and biases, some patterns could be discussed on each of the guides.

2D Arrow. The long stem of the 2D Arrow was helpful for allowing participants to see what the movement path looked like. Having the stem as a feed-forward cue made the participants more comfortable with performing the movement because they could see what was coming next and prepare for it. However, using the size of the head as a depth cue was ineffective, and participants often moved in the incorrect plane. Participants simply could not accurately read their required depth from just the head itself.



Arrowhead. In contrast to the 2D Arrow, the Arrowhead could more easily convey required depth. As a 3D model, it could point into and away from the screen and this was more accurate for depth. However, the Arrowhead was simply an arrow model with no feed-forward cues—the only indication of where they were going was provided by the direction the arrow was pointing in. Due to the direction being influenced by hand positions read from the Kinect, the Arrowhead often appeared jittery and resulted in participants misinterpreting where it needed them to move.

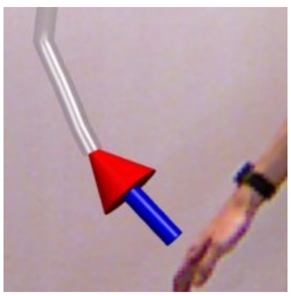
Arm Lines. The Arm Lines performed favourably. Some participants noted the attractive visual of the lines due to how they opened and flowed like a fan while in motion. Early feedback from the physiotherapist also found it particularly helpful for visualizing the plane of movement of an exercise. However, they often misinterpreted its depth due to its 2D appearance and the choice of gradual transparency of the lines. For this reason, I implemented the 3D variation after the study to evaluate if it could be more effective.



Dashed Triangles. The Dashed Triangles performed well due to how it combined feed-forward guidance, updated with participant movement, and was able to convey some sense of depth with the size of the triangles. The two-dimensional implementation, however, did not favour movements directly on the frontal plane, as the triangles were often rendered too small to see. Circular movements such as from the figure-8 exercise also resulted in the triangles appearing warped. Overall, while this guide appeared to perform very well in transverse and sagittal movements, it was difficult to adapt for others. As such, it was not iterated on for the second set of guides.

4.7.1 Feedback on second iteration

I iterated and created a second set of guides based on the Arrowhead and Arm Lines: the Feedforward Arrowhead, the 3D Arrow, and the 3D Arm Lines. The eventual goal was to evaluate these newer guides in a similar study, but I was only able to perform a limited pilot study[29] on the Feedforward Arrowhead before work on Physio@Home began. Overall, I gathered early usage feedback to build upon for later developments with Physio@Home.



Feedforward Arrowhead. The addition of the feedforward path was beneficial and its usage was greatly improved over using just the Arrowhead. However, it still had problems; among them, the directions provided by the arrow were still not always clear and participants often tended to not notice finer details. For instance, in exercises that required a participant to rotate their arm backwards before bringing forward, participants had difficulty knowing how far back to move. Often they would move as far back as they think they should, but not enough as required. This results in them trying to move back forward earlier, despite the arrow telling them they must keep moving. When the arrow then shows they need to keep moving back, the participants were confused on what it meant. As well, when the participant approached the turning point, the feedforward path would wrap around to show the return movement, resulting in it clipping through the arrow and obscuring the arrow, also leading to confusion.

[29] Results cannot be reported on because this was done without ethics clearance.

3D Arrow. While this was not formally evaluated, the 3D Arrow showed promise over the 2D Arrow. As a 3D model, it was more capable of showing movements forward and backwards and the curving of the stem also made it easier to view how far out to move. Visually, however, the 3D Arrow had some shortcomings. By using the future hand positions to make the stem, the stem often appeared jagged. As well, the stem and head would bend and clip into themselves similar to the Feedforward Arrowhead.

3D Arm Lines. As with the 3D Arrow, depth perception was greatly enhanced by turning it three-dimensional. The pipes now had distinct orientation and direction and these were less ambiguous to interpret than the gradual opacity. Similar to the Feedforward Arrowhead and 3D Arrow, however, it also suffered from clipping problems. Overall, its ability to show the movement plane in three dimensions was positive and played a role in influencing Physio@Home's Wedge design.

4.8 Study limitations

The study and subsequent evaluation of Zipples was cancelled after noticing problems with the study design and error calculation. The study contained significant learning biases due to the demonstration phases in step 3 and the numerous reuse of exercises. Because each participant would watch a demonstration of each guide and exercise before performing it themselves, the majority indicated they performed the exercises by memory rather than using the guides. As well, instructions in the study did not enforce that accuracy and careful performance and adherence to the guides were vital, which also led to participants performing the exercises by memory rather than the guides.

In addition, I discovered a flaw in Zipples' data recording. In order to ensure the nearest frame would not get stuck on the first recorded exercise frame and ensure the automatic shutdown would activate, Zipples automatically set the nearest frame to another positioned several frames ahead. While this was essential for the system to work, the Kinect skeleton from this frame was incorrectly recorded instead of the participant's actual skeleton. As such, all recorded participant data was incorrect and there was no way to undo this. For these reasons, no error calculations could be performed.

Certain technical limitations also affected the usage of the guides. Most notably, the Kinect often misplaced skeleton joints, particularly the elbow. If a participant's elbow was held too closely against their side, the Kinect has difficulty seeing the arm and cannot accurately place the elbow, or any visualizations relying on it. The same problems also happened when the elbow was obscured by hand or wrist joints in front of it. In these cases, the Kinect has to estimate the elbow's position and often offsets the elbow by significant amounts, or produces a jittery and shaking skeleton where it is constantly trying to place the elbow.

The Kinect also often lost tracking, sometimes misplacing the skeleton on background objects or lighting. It was also sensitive to participant clothing, being less accurate when viewing participants with darker or baggier clothing. These problems are forgivable in exergames, but for the precise error calculations I needed to perform, these introduced a substantial source of error that proved difficult to control.

4.9 Lessons learned

While I was unable to measure errors to show which of my implemented guides worked the best, I gained a better understanding of what features more ideal guides should contain. For example, in the case of the 2D Arrow, feedforward cues to convey movement to be completed next are essential. I also found that there must be a balance on how much detail to show—on one level, there should be fewer details to avoid overwhelming the user with too much information, but there should still be enough to provide direction and feedback. A recurring problem when using all the guides was that properly conveying depth is difficult. Just using a three-dimensional guide was insufficient to show depth. For this, I would require a new design, to be discussed in the next chapter.

I also learned various technical lessons while working on Zipples. The system setup of recording, playback, and movement guide components had worked for Zipples, as did the crash recovery. In preparing exercises for the study, however, I noticed that exercises often consisted of distinct steps. This was a characteristic not represented in Zipples, which treated exercises as continuous movements, and resulted in instances where the guide must wrap over itself. This would be avoided by splitting the exercise into multiple steps, where each step must be completed in turn, and only draw the guide for moving through each step. This would also reduce the search space for finding the nearest frame.

Tracking problems involving the Kinect proved challenging and necessitated selecting another tracking system. While the Kinect would be sufficient for some at-home use, I needed superior tracking to ensure cleaner data recording and ideal tracking to develop systems such as Zipples.

4.10 Conclusion

To put my concepts from Chapter 3 to use, I developed a prototype system called ‘Zipples’ that could record and guide physiotherapy exercises in an at-home setting. In this chapter, I described how the system was developed and laid-out, and the multiple styles of guides I developed for guiding exercises. I then described the study I ran for evaluating Zipples and how it was setup and what steps and procedures it needed. In analyzing the qualitative feedback, I was able to gain an understanding of how at-home systems like Zipples should be developed. Building off these findings, I iterated on Zipples to create its successor system, Physio@Home.

Chapter Five: PHYSIO@HOME

In this chapter, I build on the findings and lessons learned from implementing Zipples to design Physio@Home. By doing this, I answer Thesis Question 2 ('How can we design a system that provides visual feedback for physiotherapy exercises?') and address Zipples' limitations. As with Zipples, I evaluated Physio@Home with a study to answer Thesis Questions 3 ('How can we evaluate visual and multi-view feedback for movement guidance?') and 4 ('What are the effects of visual feedback and multi-view feedback for movement guidance?').

I will first describe the major system differences between Physio@Home and Zipples, and outline why I made these changes. I then describe the design of the new Physio@Home system, including the Wedge visualization and system implementation. In doing so, I will be able to better answer Thesis Question 2 and show how my requirements evolved since Zipples. I will then describe the controlled laboratory study I ran on Physio@Home, and how it differed from the Zipples study, to provide a better answer for Thesis Question 3. I will then discuss the results to answer Thesis Question 4.

5.1 Differences between Zipples and Physio@Home

I encountered numerous technical problems throughout Zipples' implementation and these were remedied in Physio@Home in the following ways:

- I used the Vicon motion tracking system instead of the Microsoft Kinect
- I implemented a tool for splitting exercises into chapters
- I implemented a single 'Wedge' visualization
- I incorporated multiple viewpoint cameras

I will explain the rationale for these changes below.

5.1.1 Kinect and Vicon

Figure 5.1: Kinect skeleton placement problems.

The crucial change between Zipples and Physio@Home was the switch from the Microsoft Kinect to the Vicon motion capture system. Zipples used the Kinect due to its relatively recent introduction and purpose as a commodity depth sensor. Throughout Zipples' development, however, the Kinect showed various shortcomings that encouraged me to switch to the Vicons. The Vicon motion capture system[30] was a valid

[30] http://www.vicon.com/

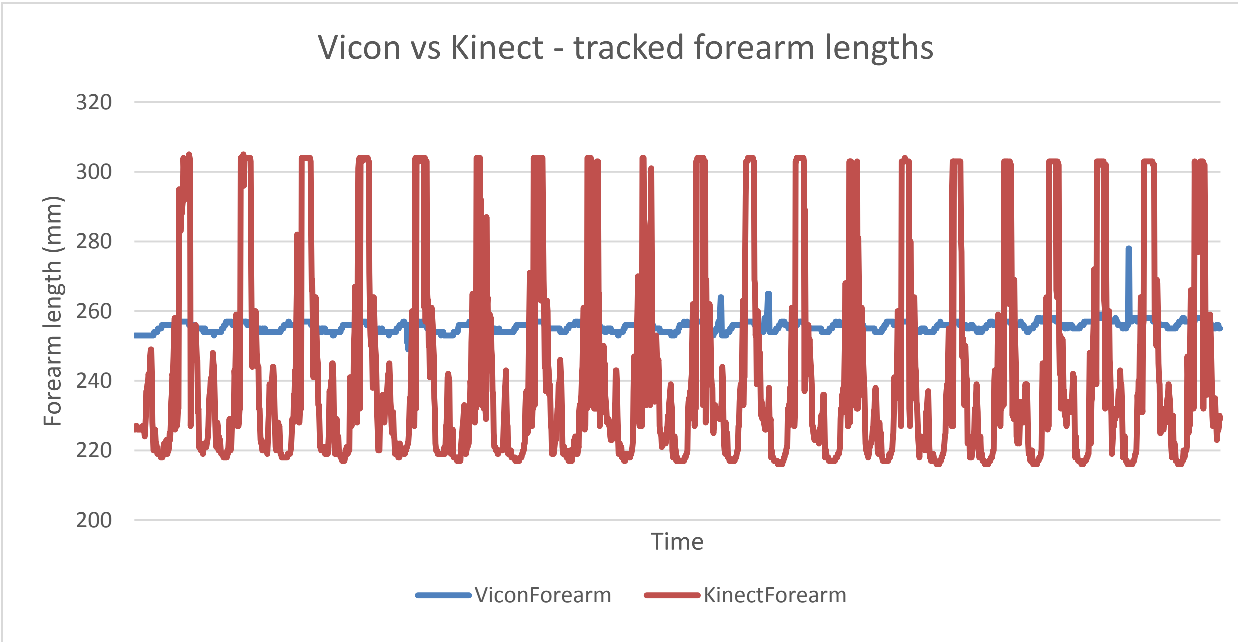


Figure 5.2: Comparing the lengths of forearms tracked by Vicon and Kinect.

alternative with proven capture and tracking accuracy, and has seen prior use in rehabilitation projects due to its accuracy (Chung et al., 2011; Carse et al., Nicolau et al., Nixon, et al., 2013).

The significant problem in Zipples was the Kinect's skeleton placement. The Kinect works by viewing a person's body and placing a multi-joint skeleton over it using computer vision and depth. This is sufficient for its intended use as a gaming device, as the Kinect's estimated skeleton is able to encompass the player's body, and works very well with gross motor movements—for example, dance, as seen in Kinect Dance Central. However, the skeleton placement is less precise when it cannot clearly see all of a person's limbs. For example, if a player was to hold their arm close against their side, the Kinect will try and place the skeleton, but would place the shoulder and arm off further than expected. The colour of a person's clothing and type of clothing also affects the skeleton placement. Often in Zipples, the Kinect misplaced the user's shoulder if they were wearing a baggy or black sweater.

The most significant problem with the Kinect and affected Zipples was inaccuracy caused by joint obscuration (Figure 5.1). If the Kinect could not see a joint, it would still try to place it, but the position of the joint is considerably less accurate. For instance, if a person held their hand out directly in front of the Kinect, their hand obscures the elbow and shoulder joints. When this occurs, the Kinect will try to place the shoulder and elbow, but will misplace them drastically. This results in extremely inconsistent readings of joint positions.

To demonstrate the severity of this problem, I ran an informal comparison between the Kinect and Vicon. This was a quick test of how consistently either system tracked the lengths of my forearm (length between wrist and elbow) and bicep (length between elbow and shoulder). Because the Kinect and Vicons tracked different points for wrist and elbow, I evaluated how consistently either system read the lengths of these limbs. The ideal system would be one where the joint positions are being read correctly at all times, which would result in the forearm and bicep lengths being consistent during movement over time. I did this by wearing the arm tracking braces used in Physio@Home and performing a series of arm movements while being tracked by both the Vicons and the Kinect. I recorded the length of my forearm and bicep as tracked by both systems while performing 20 repetitions of the shoulder abduction and combination exercises used in both Zipples and Physio@Home studies.

The reported lengths of my forearm was much more varied with the Kinect than the Vicons (Figure 5.2). The Kinect produced a standard deviation of roughly 28.4 mm compared to the Vicons' 1.5 mm. As well, the reported length of my bicep was also slightly more varied with the Kinect (Kinect: 16.6 mm, Vicons: 13.4 mm). The inconsistent Kinect readings were due to the depth sensor misplacing the elbow when obscured, thereby adding extra length to the forearm. This early comparison, while not a formal study, should serve to demonstrate that the Kinect produced less stable readings than the Vicons.

The Kinect inaccuracy was a cause for concern, as it resulted in poor placement of visualizations and questionable data collection. Visualizations from Zipples were misleading to follow if they were drawn too far off the body depending on how the Kinect misplaced joints. The inaccurate joint placement also added an additional source of error for the joint-by-joint analysis I wished to perform. Possible solutions while keeping the Kinect were impractical due to performance concerns: applying more of the Kinect's skeleton filtering would slow Zipples down too much for real-time use, and adding a second Kinect would also slow Zipples down and still not have resolved the obscuration. The second-generation Kinect was also not available at the time, but I found in early testing that obscured joints was still a problem.

Therefore, the solution was to forego the Kinect and use a more accurate Vicon motion tracking system for now. This is not an indictment of the Kinect's use in physiotherapy. Quite the opposite, a Kinect-like device is the ideal accessory for an at-home physiotherapy system due to its ease-of-setup and commodity-level cost and availability. I envision over time, tracking will achieve Vicon-like accuracy with commodity-level costs. For the sake of reliable data collection

Figure 5.3: Combo exercise split into separate steps. In total, the exercise consists of 4 steps.

right now, I switched to the Vicons and assumed that I was working with a perfectly reliable sensor to discount tracking problems while designing Physio@Home.

5.1.2 Chapters/Annotation application

The other crucial addition was the notion of 'chapters' for exercises. In Zipples, exercises were recorded as a single continuous movement. While this is not incorrect, it became clear throughout Zipples that exercises are often treated as iterative steps—in the case for a shoulder abduction, the exercise consists of two steps: a movement of the arm upwards, followed by another down. Treating this as a single movement in Zipples caused visualizations to fold into themselves, or show too much of the next step and cause participants to skip to the next step when they really should finish their current. Later interviews with the physiotherapist also noted that breaking exercises into discrete steps was also necessary because each step could have required characteristics—for example, a joint may need to be kept still during a step or arm kept at an angle, as described previously in chapter 3. These qualities were not being modelled in Zipples.

To support these features in Physio@Home, I implemented a tool for splitting a recorded exercise into distinct steps or 'chapters'. The metaphor of 'chapters' in Physio@Home was used due to its similarity to subtitle files adding chapter headers and caption text to common video files. My annotation tool works similarly by allowing a user to seek through the recorded data and mark off segments as chapters. These are then saved as a distinct data file that would also be opened by Physio@Home when loading exercises.

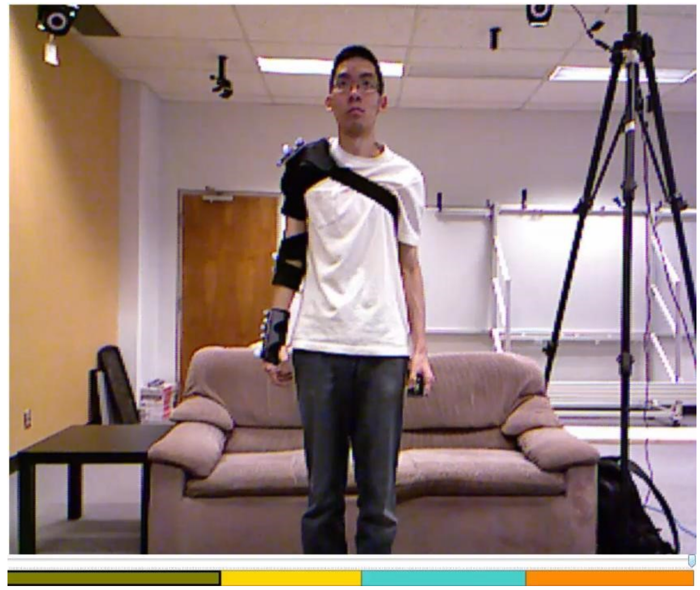


Figure 5.4: Combo exercise seen in Figure 5.3 after being edited in the annotation tool. Coloured segments represent the 4 steps of the exercise.

The tool is currently restricted to splitting an exercise into chapters, but more functionality may be supported in the future. For instance, textual instructions specific to the chapter could be added and displayed, or specific parameters may be highlighted, such as keeping the arm straight or repeating the chapter.

5.1.3 Wedge visualization

I iterated on the design of my guides from Zipples and created a single new visualization to encompass my findings—known within this thesis as 'the Wedge' (Figure 5.5). The Wedge was designed to follow on prior examples of the 2D and 3D Arrows described in Chapter 4. The early findings from the Zipples study were too inconclusive to pick out a single well-performing

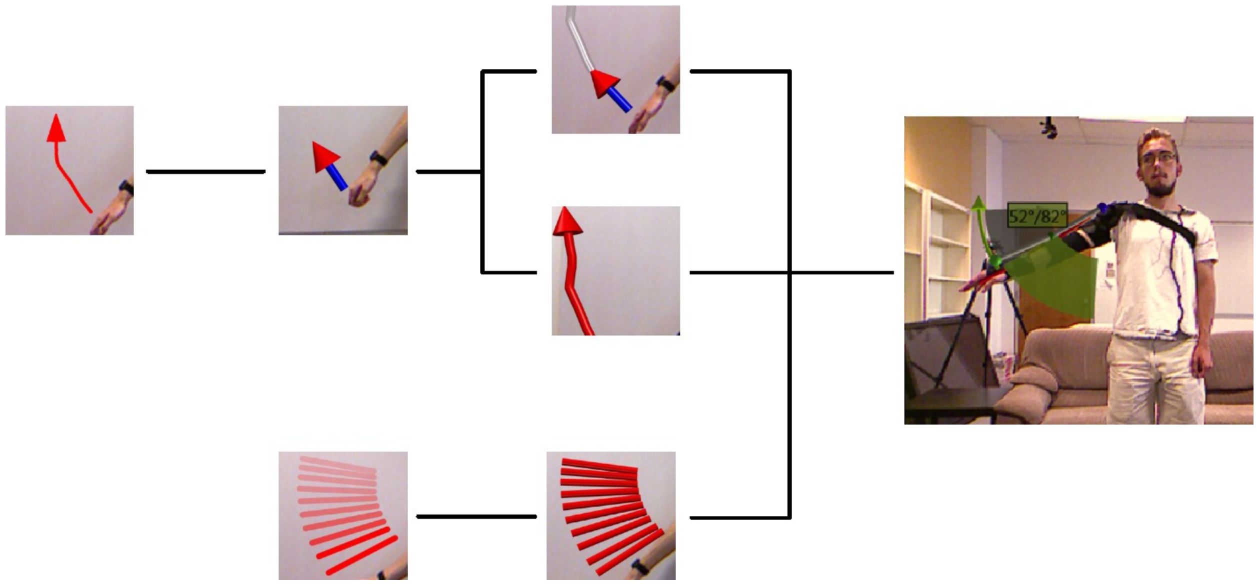
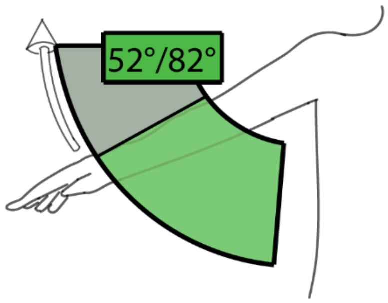


Figure 5.5: Iteration of Zipples' original guides into the Wedge.

visualization, but noted interesting qualities that I chose to iterate with. For instance, the ability of the 2D Arrow and updated 3D Arrow with feed-forward path were equally important. The Arm Lines visualization in both 2D and 3D were also promising in how they showed the plane of movement.

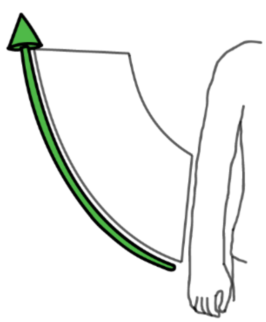
These qualities were combined to make the Wedge. The Wedge consists primarily of an arrow with a long stem to show movement path, but also an arc formed by the movement of the whole arm to show the plane of movement. Taken together, the arrow shows where to move and the arc where to move along. Splitting exercises into chapters, as previously described, also helps to convey movement by only showing the Wedge between smaller sections of the exercise.

The Wedge consists of several distinct parts: the Movement Arc, Directional Arrow, Nearest Arm, and Topdown Angle.

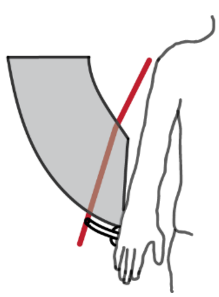


Movement Arc. The central arc shape of the Wedge conveys the plane of movement for each part of an exercise. It is based on the motion of the arm with either the shoulder or elbow as the center of its radius and where the moving arm forms the shape of the arc.

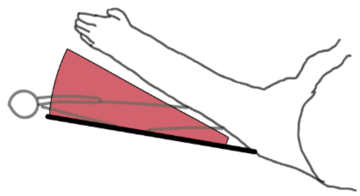
The Movement Arc is divided into two parts: one section for the completed portion in green, and the other for the incomplete remainder of movement. As the patient follows the plane, the green completed section grows to indicate progress, while the grey incomplete section shrinks to show how much of the movement still remains. This conveys both feedback and feedforward, and offers motivation for the user. In addition to the shape and fill of the Arc, I also provided a numeric angle indicator of their current and required arm angles to complete exercise.



Directional Arrow. The Wedge also features an arrow on the outside of the Movement Arc to show the direction the user must move in. Similar to the Movement Arc's feedforward, the Directional Arrow shows where to move to and how much of the movement is left as the stem shrinks with user progress.



Nearest Arm. I draw a red stick figure of the nearest correct arm from the exercise to the user's when they are in the wrong position. This guide provides feedback on the user's movements by letting them know if they are in the incorrect place and where they should be. When they are properly aligned, this guide disappears.



Topdown Angle. Similar to the Nearest Arm, I show a red arc in the top-down view when the user's arm is moving along a vertical plane and is not on the same angle. This arc grows and becomes more visible if the user is further away so their arm may maintain the required angle from their forward direction. This provides corrective feedback on the extent of the movement.

By design, the Wedge and its separate parts encapsulate all movement characteristics except for rate of movement. I envision the latter being conveyed by animating sections of the arc and arrow to imply required movement speed. The Wedge uses simple visual elements to avoid screen clutter, and so that its components do not interfere with each other.

5.1.4 Multiple camera views

A novel feature of Physio@Home was its use of multiple camera views. Zipples, and the similar systems mentioned in Chapter 2, all used a single perspective from a single camera—particularly from the Kinect. This approach is unable to easily show movements in depth. The initial approach to resolving this was to encode depth in the visualization, as was the case with the Dashed Triangles visualization. However, there needed to be more exploration on how to best approach this. Related work had only implemented a single view, but never more than this, and I felt it was a design space that had not yet been explored.

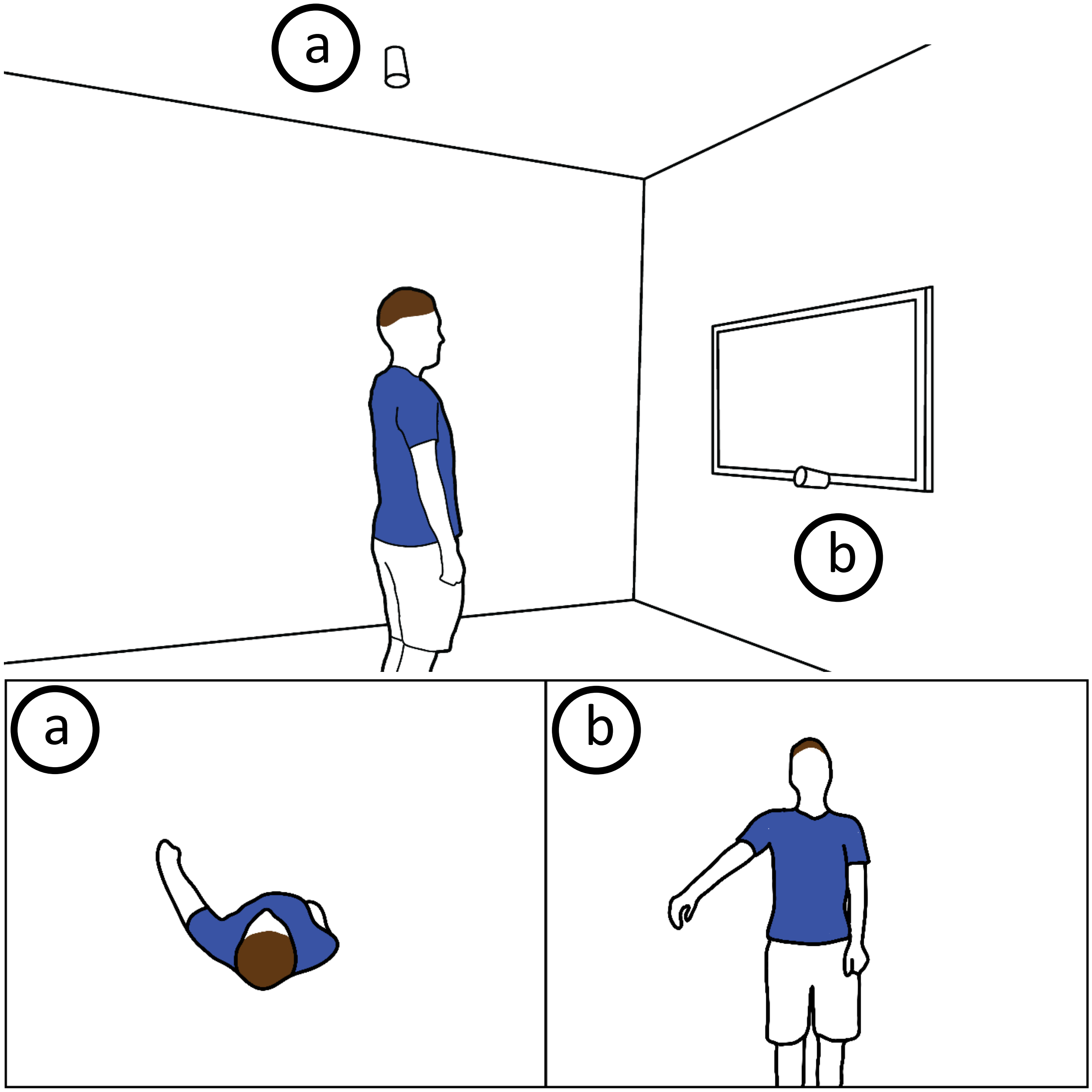


Figure 5.6: Multiple-camera view setup in Physio@Home. (a) Top-down camera and (b) frontal camera, with corresponding perspective of what the patient sees. Note that patient's perspective of (b) is mirrored.

Using multiple cameras was drawn from similar usage in dance instruction DVDs and a commercial physiotherapy application. Some online-based dance instruction programs film dance steps from multiple angles and allow a student to view them individually or in tandem. By doing this, students can see specific parts of a dance from a different angle to better understand posture or foot positioning (Figure 5.8[31]). PTMotions' Program Viewer allows patients to view physiotherapy poses and exercises from different angles (Figure 5.7[32]). This allows them to better view and understand a prescribed exercise that they would not have if limited to only a single perspective.

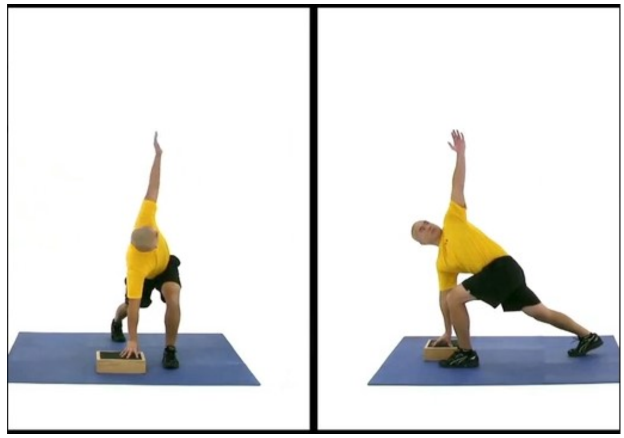


Figure 5.7: PTMotions' Program Viewer.

I build upon this in Physio@Home by offering two camera views. The primary camera is a forward-facing view of the patient's front, which acts like a mirror (Figure 5.6b). The secondary camera view shows a view of the patient from another angle that the primary cannot capture (Figure 5.6a). For instance, the secondary camera could be mounted above the patient to show what their exercise movements look from above, where they may be more

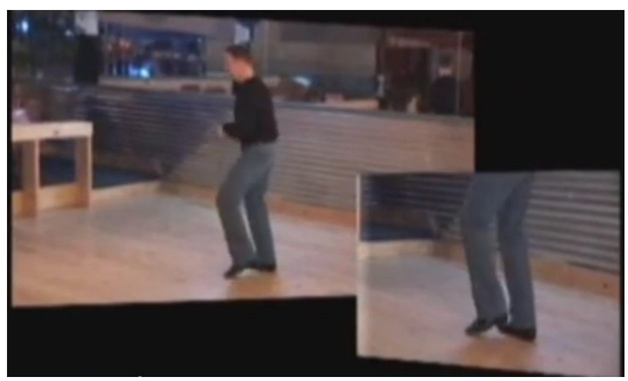


Figure 5.8: Video still from a dance instruction video with multiple camera views.

[31] Captured from https://www.youtube.com/watch?t=18&v=J7ohresVICU
[32] Captured from http://www.ptmotions.com/ptm_tour.html

visible than a front view. It is also easy to imagine a secondary camera mounted behind a patient to assist exercises behind their back.

Unlike the prior examples in PTMotions and dance instruction, however, the use of multiple views in Physio@Home will be in real-time. Patients will be able to see themselves from the front-on and secondary views as they are moving.

5.2 Physio@Home system design

In this section, I describe the implementation of Physio@Home in greater detail. The system layout is displayed in Figure 5.9.

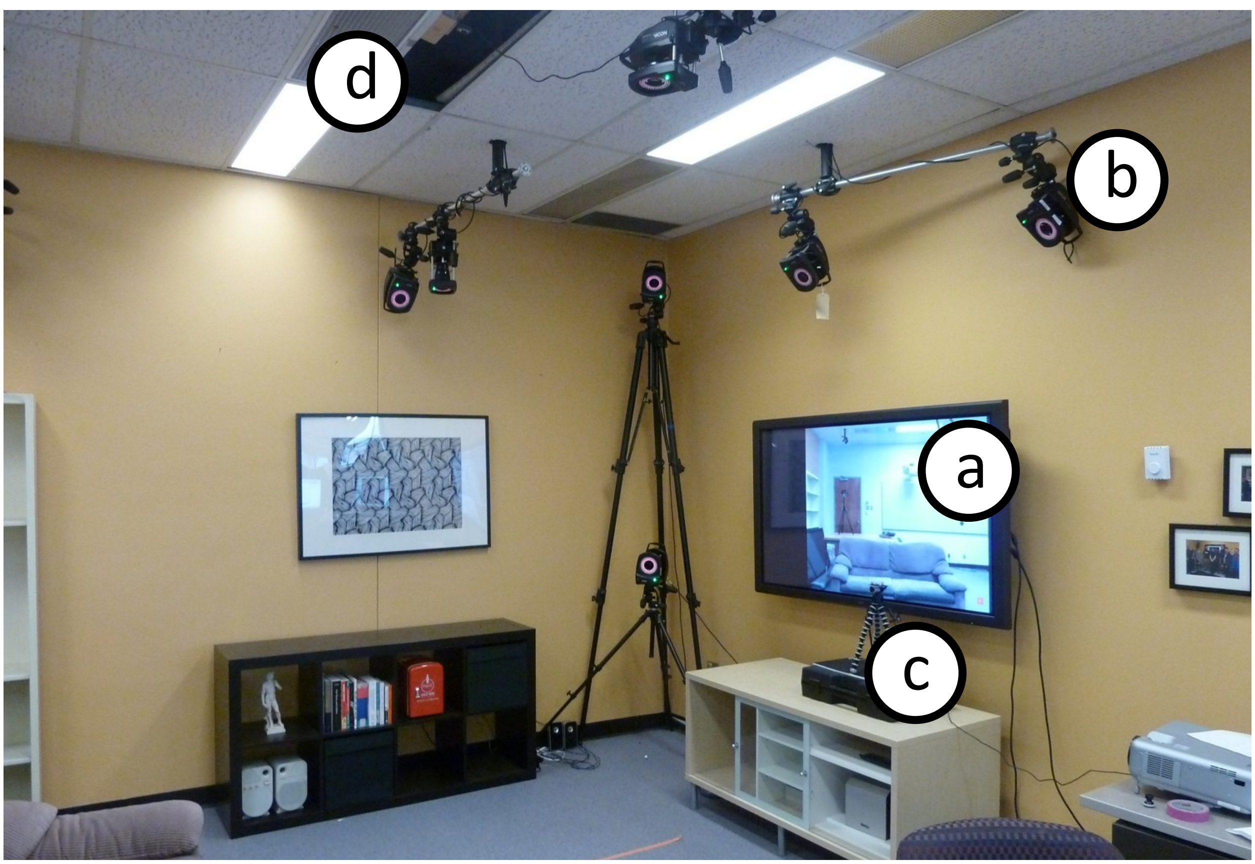


Figure 5.9: Physio@Home prototype setup. (a) Wall display to act as augmented mirror, (b) Vicon motion tracking cameras, (c) front camera, (d) top-down camera.

5.2.1 Tracking

I implemented Physio@Home using Vicon motion tracking cameras, the Proximity Toolkit (Marquardt et al., 2011), WPF, and the Helix3D toolkit. To track joints, users wear markers mounted on shoulder, elbow, and wrist support braces (Figure 5.10). The tracking system provides x, y, z coordinates for each joint in millimeters within the testing space. These coordinates are then used in the 3D viewport to place 3D elements in corresponding positions to the real world.

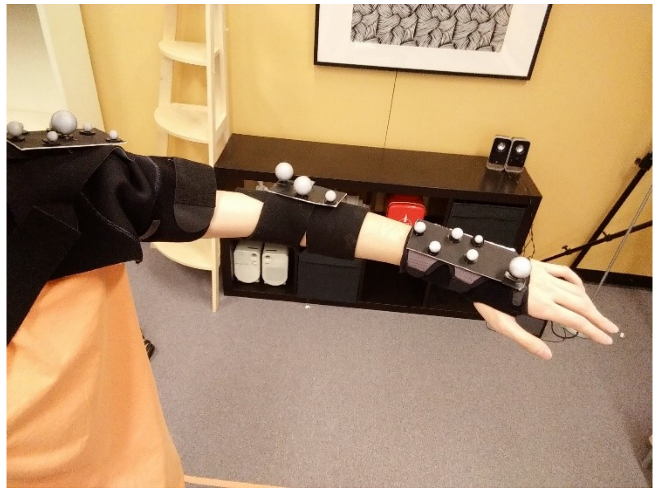


Figure 5.10: Arm-mounted markers for tracking shoulder, elbow, and wrist joints.

5.2.2 Camera calibration

To set the 3D viewport camera, I applied Vicon markers to the corresponding RGB camera. I then used the Proximity Toolkit to retrieve position and orientation and set the 3D camera properties to these values, and manually adjusted the pitch, yaw, and roll of the 3D camera to align its image with the RGB camera. I overlaid the 3D viewport atop the video feed and aligned the Helix 3D and RGB cameras to appear as though they originate from the same location.

Recording and Playback. Physio@Home's recording and playback work similarly to Zipples. Physio@Home records movements captured by both the RGB and Vicon cameras at a rate of 60fps. For each frame, the raw images and x, y, z positions of the shoulder, elbow, and hand markers are captured. Nearest frames are matched using the algorithm described in 4.3.2.

Error metric. I implemented a tool to compare a user and exercise recording and compute average errors between them to show how closely the user was able to follow the exercise. This tool uses the previously described scaling algorithm to scale and transform the exercise to the user's size and position. It then iterates through each recorded user frame; for each user frame, it searches through the scaled exercise frames to find a frame with the least error between elbow and wrist—the shoulder is excluded because the scaling algorithm uses the shoulder as the origin. This error is computed by absolute Euclidean distance in millimeters to focus on how closely participants could follow the exercise. Errors are accumulated and averaged by the number of user frames.

5.3 Guiding movement in Physio@Home

The Wedge visualization was rendered using the Helix3D toolkit. It consists of four visual elements: two pie slice elements that form the entire Movement Arc, one for percentage of chapter completed, and one for the chapter remainder; a pipe for the stem of the Directional Arrow; and, a cone for the Direction Arrow's head.

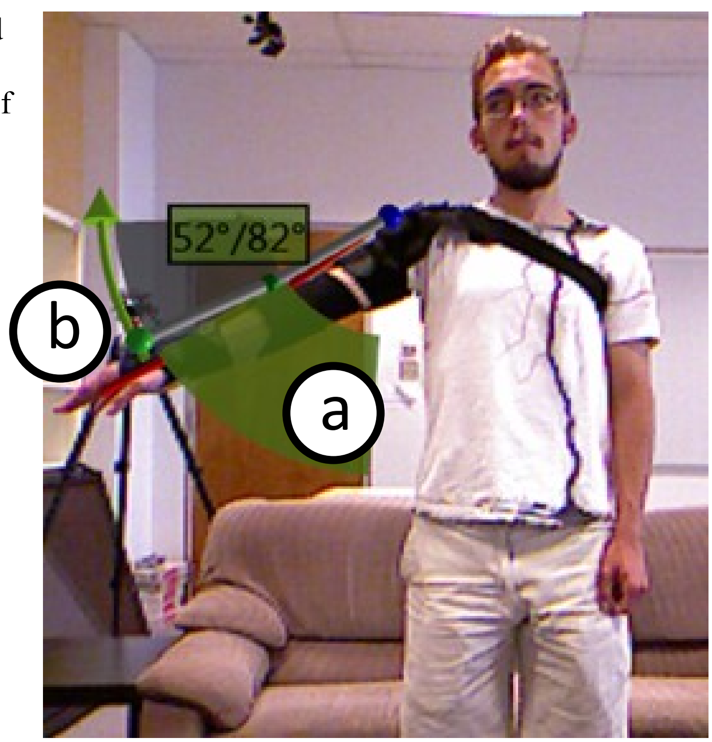


Figure 5.11: Wedge visualization, with components: (a) Movement Arc, (b) Directional Arrow

The first and last frames of the exercise chapter are used to create the start and end points for the Wedge's movement arc. To show percentage of the completed chapter, the user's live arm position is matched by vector to the most similar arm posture from the chapter.

5.3.1 Multiple camera views

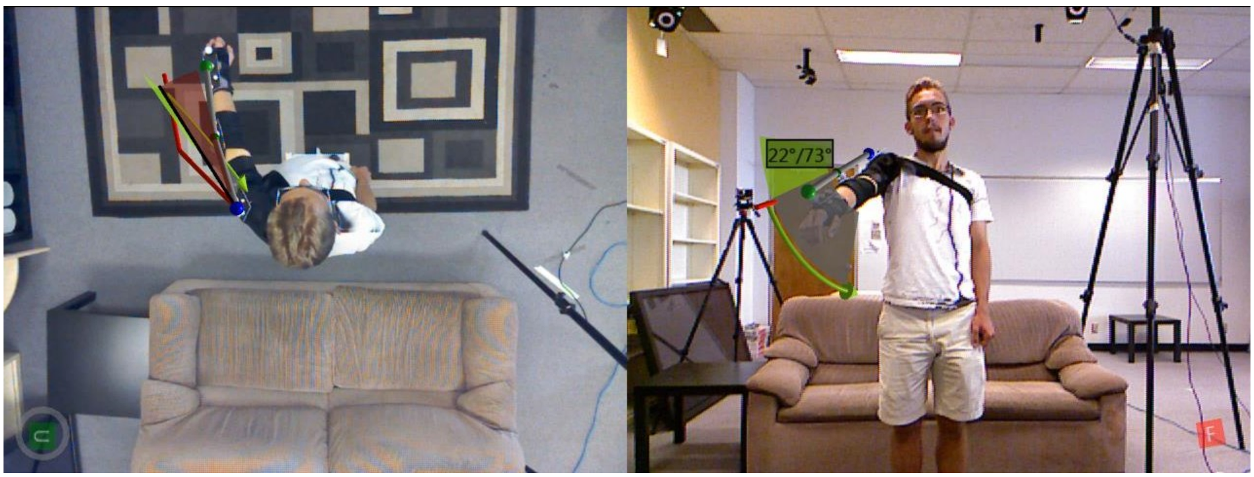


Figure 5.12: Front and top-down views. From the top-down view, the Topdown Arc and Corrective Arm are more visible.

I implemented the multi-view setup using two commercial RGB cameras mounted in front of and above the user. The top perspective was selected as the second view due to the exercises requiring more movements related to the transverse plane. In principle, it is possible to show more camera views; however, I limited this to first understand how a second view would be used.

5.3.2 Scaling

I used the same scaling algorithm described in Chapter 4, section 4.3.2. I transform recorded exercises to account for variations in a recorded participant's arm length and location to compute error. I do this by first computing the length of the participant's bicep and forearm using the absolute Euclidean distances between the x, y, z positions of their shoulder, elbow, and wrist. I then iterate through each pre-recorded frame to compute normalized 3D vectors of the bicep and forearm, and then using the participant's shoulder as an origin, I multiply the bicep vector by the participant's bicep length and add it to their shoulder position to get a new elbow position from the exercise, now scaled to the participant's bicep length. I do the same with the forearm vector to get a scaled wrist position, and repeat over all frames of the recorded exercise until the exercise has been transformed and scaled to the participant.

5.4 Evaluation

My design process produced a rich, but relatively complex, visualization: the Wedge. The Wedge communicates several aspects of movement, and can be augmented by a secondary overhead camera view. I was interested in three specific questions:

- Does the Wedge help people to perform the exercises with increased accuracy?
- If so, are both the Wedge and multiple views necessary, or is one sufficient?
- Does the Wedge and multiple views perform differently for different types of exercises?

To answer these questions, I recruited 16 graduate students from the University of Calgary's Faculty of Graduate Studies through email lists. Each study lasted an hour and participants were paid $20. I used a within-subjects design to evaluate both accuracy and subjective preference with four different combinations of the Wedge and the number of views (Interface condition): *single view with video playback* (VideoSingle), *single view with Wedge visualization* (WedgeSingle), *multiple views with video playback* (VideoMulti), and *multiple views with Wedge* (WedgeMulti). The conditions were presented in a Latin Square ordering to avoid bias.

Participants would complete the exercises while following an on-screen guide (either a video recording of the exercise being demonstrated or the Wedge visualization system). In the video conditions (i.e., the ones that did not use the Wedge visualization), participants would see a main video of themselves (like a mirror), with an inset video of the pre-recorded exercise, allowing them to mimic the exercise. In the Wedge visualization conditions, the visualization (based on the pre-recorded video) is overlaid atop the live video.

5.4.1 Procedure

Participants were introduced to the system with a short demonstration and, after being fitted with markers, completed a trial run of each condition. Participants were allowed to spend as much time as they needed to test and understand the visualization. During this phase, each participant was taught how to interpret the Wedge. Participants were also instructed not to move, turn or sway during the experiment to ensure accurate data collection.

Each participant provided 48 recorded exercise trials: 4 interfaces × 4 exercises × 3 trials. In some cases I recorded additional trials when tracking errors occurred with the Vicon system. The study concluded with a questionnaire and semi-open interview on their subjective preferences and experiences using the different conditions.

5.4.2 Exercises

Participants completed four real physiotherapy exercises[33]. These four exercises help rebuild shoulder mobility after injury (e.g., a dislocated shoulder). The study was designed to examine

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[33] See Appendix

Physio@Home under distinct and progressively more complex exercises to understand any potential limitations.

I focused on exercises relating to the shoulder, because participants can easily make the movements while standing. The shoulder is also a ball-socket joint (unlike, say, the knee) meaning that a wide range of movements and variation from a prescribed motion is possible (i.e., there is more possibility of error and, therefore, need for guidance). In addition to being an extremely common subject of rehab, the shoulder allowed me to control individual differences in physical abilities between participants: a person only needs to be able to stand and move their arm comfortably. For these reasons I felt the representative set of exercises in shoulder rehab would allow the study to go in-depth with a single but potentially useful application of Physio@Home's design, rather than focusing on a general motion feedback system.

Straight. Abduction of arm along the frontal plane up to shoulder level, followed by adduction of arm back to the participant's side. This is a simple frontal plane exercise.

Angled. Abduction of the arm at 45° from the frontal plane, followed by adduction back to the side. This is an angled variation of the *Straight* exercise, where interpreting the angle may be difficult.

Elbow. External rotation of forearm away from the center of the participant's body until 90° from the sagittal plane, followed by an internal rotation back to center. This exercise requires the participant to keep their elbow tucked against their side and is a difficult exercise to understand without depth cues (i.e., with just a frontal view). This is similar to the Rotation exercise from Zipples.

Combo. Abduction of the arm along the frontal plane up to shoulder level, internal rotation of the arm until pointing forward, followed by an external rotation of the arm back to the frontal plane, and adduction of the arm back to the participant's side. This is a more complex exercise than the previous three, involving many components.

5.4.3 Performance measurements

I collected three performance measures: two distance error metrics (one for the hand and one for the elbow), and a measurement of the maximum angle of rotation achieved. I ignored speed as a measure because I was mainly interested in how closely participants can follow an exercise. The two error metrics captures how closely a participant can follow a pre-recorded exercise delivered either by video or the Wedge system: one for the error from the hand and one from the elbow. For the Elbow exercise, I also recorded a separate metric—the maximum angle reached by participants during the external rotation. Because the Elbow exercise relies on a patient rotating outwards to their farthest extent, I was interested in evaluating how clearly the participants could interpret the required angle with the different interface conditions.

5.4.4 Data Analysis

Performance data were analyzed using 4×4 RM-ANOVA, with interface (VideoSingle, VideoMulti, WedgeSingle, WedgeMulti) and exercise (elbow, combo, angled, straight) as factors. Violations to sphericity used Greenhous-Geisser corrections to the degrees of freedom. Post-hoc tests used Bonferroni corrections for multiple comparisons; only significant pairwise differences are reported. Post-hoc analysis was only performed to compare levels of the interface condition, as I was only interested in the performance of the different interfaces overall and within the different exercise conditions, and less interested in differences between different exercises. Subjective responses were analyzed using Friedman's test, and post hoc comparisons were done using the Wilcoxon signed-rank test. Before analysis, outlier trials were removed that were > 3 sd. away from the mean for any given exercise, this resulted in the removal of 24 of 1920 records (1.25%).

5.5 Results

I will first present the performance results—including hand error, elbow error, and maximum rotation—and then present the analysis of subjective response data. I present observations and the responses I received from participants during the semi-structured interviews in the discussion to help explain the results.

5.5.1 Performance Results

Hand Error: Across all exercises, the WedgeMulti had the lowest mean hand error improving error by ~1.7cms over the baseline VideoSingle (see Figure 5, left). While this difference is not large, it is reduced by the poor performance by all conditions for the elbow exercise, as larger difference can be seen in other exercises (e.g., WedgeMulti reduced error by 50% over VideoSingle in the angled exercise); see Figure 6. There was a significant main effect of both interface ($F_{3,45}$=20.15, p<.001) and exercise ($F_{1.77,26.54}$=7.012, p=.005) on hand error. Pairwise

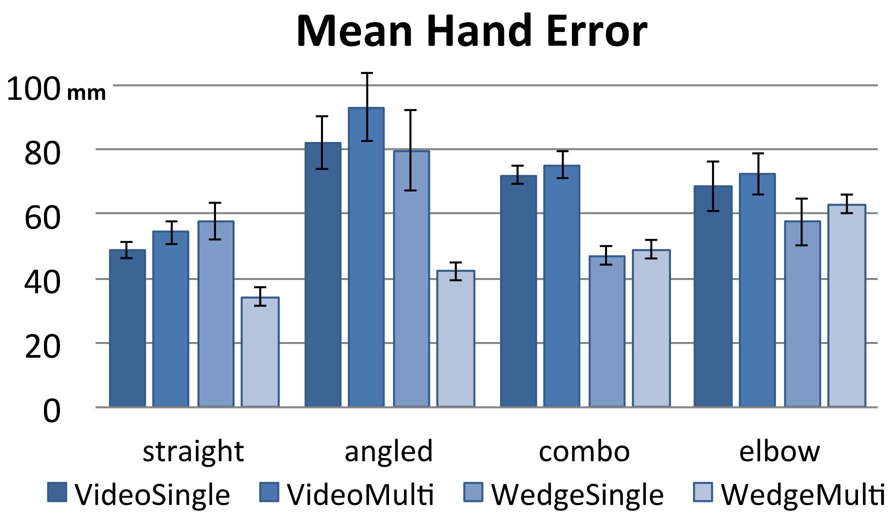

Figure 5.13: Mean hand error in mm (±SEM) for each interface grouped by exercise. Lower is better.

comparisons of interface showed that WedgeMulti had significantly lower hand error than WedgeSingle ($p<.05$), VideoMulti ($p<.001$), and VideoSingle ($p<.001$). Hand error was lower for WedgeSingle than VideoSingle ($p<.05$).

There was a significant interaction effect between interface and exercise ($F_{4.05,60.69}=6.026$, $p<.001$) for hand error. Within all exercises pairwise comparisons showed that WedgeMulti had consistently lower hand error than VideoMulti ($p<.001$), VideoSingle ($p<.001$), and WedgeSingle ($p<.05$, not combo*)*, with the exception of the elbow exercise, where no differences were observed. For combo, WedgeSingle had significantly lower hand error than both VideoMulti ($p<.001$) and VideoSingle ($p<.001$).

Elbow Error: Overall exercises, WedgeMulti had the lowest mean hand error improving error by ~1 cm over the baseline VideoSingle (see Figure 5, right). However, again this number was reduced by performance in the elbow exercise (see Figure 7). There was a significant main effect of interface ($F_{3,45}=9.895$, $p<.001$) on elbow error. However, there was no effect observed for exercise ($F_{1.5,23.01}$=2.073, p>.05) on elbow error. Pairwise comparisons again showed that WedgeMulti had significantly lower elbow error than VideoMulti (p<.005) and VideoSingle (p<.001), but no other pairwise differences were observed. See Figure 7.

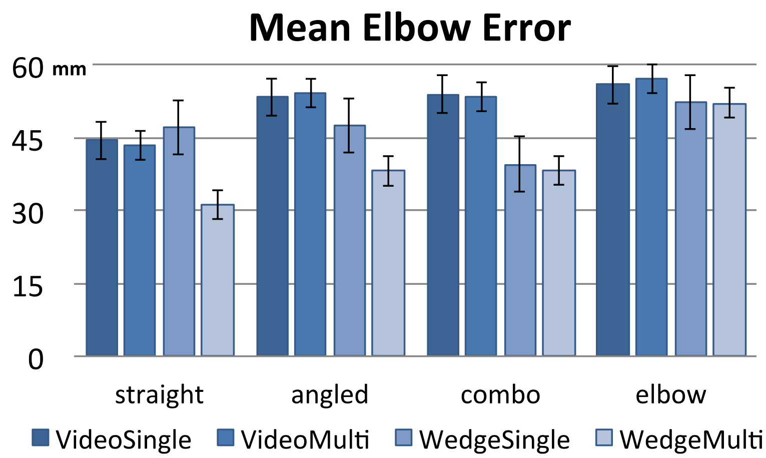

Figure 5.14: Performance by Condition (Left) Mean Hand Error ±SEM (Right) Mean Elbow Error ±SEM. Lower is better.

There was an interaction effect objected between interface and exercise for elbow error ($F_{9,135}$=2.091, p<.05). Pairwise comparisons within the groups show that WedgeMulti had significantly lower elbow error than VideoMulti (p<.05, for combo and straight), VideoSingle (p<.05, for angled, combo and straight), WedgeSingle (p<.05, straight). The only other pairwise

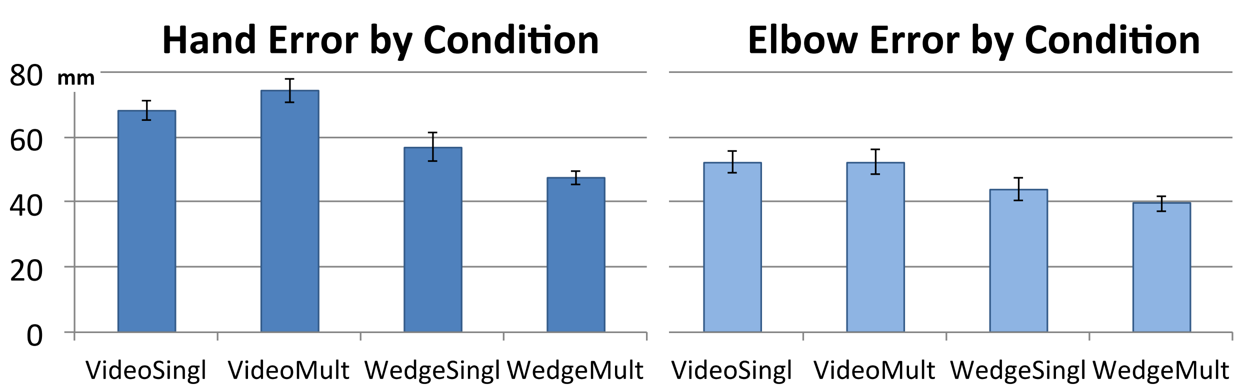

Figure 5.15: Performance by Condition (Left) Mean Hand Error ±SEM (Right) Mean Elbow Error ±SEM. Lower is better.

differences observed was for WedgeSingle, which had significantly lower elbow error than VideoMulti (p<.005) and VideoSingle (p<.05), but just during the combo exercise.

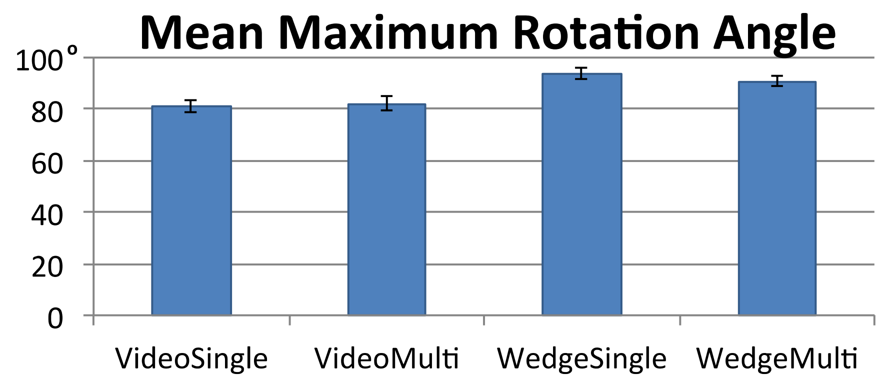

Figure 5.16: Mean max rotation angle ±SEM. Higher is better.

Rotation Angle: Figure 5.16 presents the mean maximum rotation angles obtained by participants. Analysis showed a significant effect of interface on max rotation angle during the elbow exercise ($F_{3,45}$=13.285, p<.001). Pairwise comparison showed that participants made significantly higher rotations with WedgeMulti than VideoSingle (p<.05), and that WedgeSingle had higher rotation than both VideoSingle (p<.005) and VideoMulti (p<.005).

5.5.2 Subjective Response Results

At the end of the experiment participants were asked to rank each condition on two criteria. First, participants ranked the interfaces on how accurate they felt the interface allowed them to be. Second, they also ranked the interfaces based on their subjective preference. The mean ranks can be seen in Figure 9, where 4 is ranked highest, and 1 is ranked lowest. I also asked participants their favorite visualization (video / Wedge) and view (single / multiple).

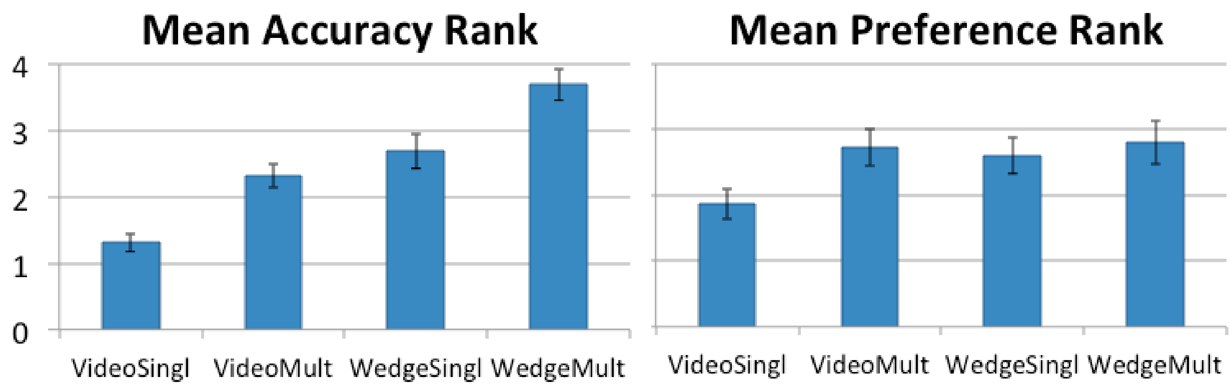

Figure 5.17: Subjective Rankings (Left) Mean Accuracy ±SEM
(Right) Mean Preference ±SEM; 4 is best.

Subjective Accuracy: Analysis found a significant effect of interface on accuracy rankings ($\chi^2(3)=22.754$, $p<.001$). Pairwise comparisons showed participants felt they were more accurate with WedgeMulti than VideoMulti ($z=-2.61$, $p<.01$) and VideoSingle ($z=-3.20$, $p<.001$). Participants also felt they were more accurate with WedgeSingle than VideoSingle ($z=-2.83$, $p<.005$) and with VideoMulti than VideoSingle ($z=-2.97$, $p<.005$).

Subjective Preference: Participants were split on their most preferred methods. The rankings in Figure 9 show no clearly preferred method. There was no effect of interface observed on preference ranking ($\chi^2(3)=5.0$, $p>.05$).

Preferences for Visualization and Views: 14 participants responded to which group of interfaces they preferred, 9 chose the Wedge visualization interfaces (WedgeSingle and WedgeMulti) and 5 chose the simpler video-only interfaces (VideoSingle and VideoMulti). Eleven indicated they preferred using multiple views, while 5 selected a single view.

5.6 Discussion

The results show that both the Wedge visualization and multiple views may be needed in combination to improve guidance. My study highlights four main findings:

- The Wedge visualization with multiple views performed consistently as the most accurate technique
- No technique performed better than any other for the elbow exercise based on my error metrics
- Both Wedge conditions improved the ability to perform the rotation movements found in the elbow exercise
- Despite performing the best and participants feeling that they were most accurate with the Wedge, participants were split on which visualization they prefer.

I will discuss these findings below with observations from the study and participant comments from the semi-structured interview to help explain the results.

5.6.1 Why was the Wedge with multi-view the most accurate?

The Wedge interface with multiple views (front-on and top-down) was the most accurate in terms of both hand and elbow errors (for 3 of 4 exercises). Participants effectively interpreted the information from the Wedge, and multiple views added benefit. The required angle for participants' abduction/adduction movements of the exercises were clearly conveyed by the top-down view available with the multi-view version, while the Wedge's Topdown Angle and Nearest Arm guides provided the necessary information to better allow participants to keep their arm aligned.

Visual guidance from the Wedge resulted in participants stopping as soon as any corrective guides appeared, realigning themselves, and then resuming the movement. These actions ensured they would stay on the correct path at all times. Without corrective guides (in video condition), participants had no direct indication of how far off their movements were, and would continue through the exercise.

5.6.2 Why didn't the Wedge perform better in the Elbow exercise?

The Wedge did not perform better than the other interface conditions for the Elbow exercise due to Physio@Home's current implementation. While the Wedge shows the required vertical angle for the other exercises via its Topdown Angle guide, it does not provide an analogue for the front view. This meant participants did not have sufficient feedback for maintaining their horizontal angle. As a result, the Wedge did not perform any better than video.

I also suspect that the mechanism for tracking the elbow (trackers affixed to participants' forearms closest the elbow) caused problems. During rotation, the markers would sometimes shift position, resulting in a potentially misleading change in the visualization of arm position. Because of this problem and the fact that this exercise is mainly focused on rotation of the forearm, I believed evaluating participant performance for the Elbow exercise is best done by the maximum angle of rotation.

5.6.3 Why did the Wedge help for rotation movements?

While Wedge errors for the Elbow exercise were not much lower than the Video, participants were able to rotate roughly 10 degrees farther during the exercise using either Wedge conditions. Using only the Video conditions, the participant can see that they must rotate outwards during the exercise, but not how far they must go. This often resulted in participants stopping early. Both Wedge conditions showed the fully required extent of the rotation; the Movement Arc in the top-down view showed how much rotation is still required, and the Directional Arrow in both views showed when movement in a direction was needed.

5.6.4 Why did Wedge/single view perform as well as Wedge/multiple views?

The single-view Wedge performed as well as the multi-view Wedge in the combo and elbow exercises. A possible explanation for this may be that most participants experienced visual overload while using the multiple views and were not able to follow the Wedge as closely. Some participants reported that the multiple views was overwhelming and they had to constantly look back and forth between them. Doing so would reduce their ability to interpret both the frontal and top-down Wedges while in motion. This is difficult to analyze because I had no means of tracking eye gaze during the study. However, as indicated by the perceived accuracy rankings, participants at least recognized that having more information from the additional view could still be helpful.

Another likely reason are that the exercises, particularly the combo's movements on the transverse plane, were easier to see and follow with the frontal view than from above.
In the same way that the angled and non-angled shoulder abductions were easier for participants to line up on with the top-down view, it may also be easier to line up transverse movements with the frontal view, and the Wedge's arrow stem already provided sufficient guidance for this. The view from above during these movements was not as necessary and did not provide much benefit.

5.6.5 Why did people not prefer the Wedge?

While the Wedge conditions were rated the most accurate, preferential rankings were split due to their difficulty and complexity. Even though some participants were able to follow movements more accurately by performing short 'micro-corrections' whenever a guide appeared, these corrections required noticeable attention on their part. The guides appear whenever there is the slightest misalignment and do not disappear until it is corrected, leading to comments that the Wedge was "too strict." Still, some participants felt this could be a potential benefit for a physiotherapy patient, as it would force them to follow exercise movements carefully and pay close attention to the feedback.

A related complaint about the Wedge was that its Nearest Arm guide felt misleading. While this guide helped participants see when their movement was incorrect, it did not tell them how to correct themselves. This resulted in several participants trying to align themselves with the Nearest Arm, but finding it difficult to get their arms in the correct position. The five participants preferring Video felt that it was more straightforward. Participants reported being more comfortable following video because it allowed a more fluid movement and felt more fun than the stricter Wedge.

5.6.6 How did physiotherapy patients feel about the Wedge?

Five participants had prior physiotherapy experience. Their feedback was consistent: all rankings indicated that Wedge with multiple views as the most accurate; furthermore, three preferred WedgeMulti, one preferred video, and one liked every technique. Two of these participants also indicated that all techniques could have a role in effective physiotherapy: video provides an easy-to-understand demonstration of the movement that would introduce a patient to a new exercise and help them adjust to a learning curve, while the Wedge would be helpful later in follow-up sessions to understand the finer-grained movement characteristics. This feedback is important as exercises are sometimes painful to perform correctly—the feedback provides reassurance that things are moving forward (P14). Finally, these participants were notably more forgiving of momentary tracking and visualization errors by the Wedge, because it helped overall with accuracy.

5.7 Conclusion

I applied the lessons learned from implementing Zipples and performing its initial study to develop Physio@Home. In Physio@Home, I used a more precise tracking system in place of the Kinect and implemented a new visualization called the Wedge that builds upon my prior designs and makes novel use of multiple cameras. I then ran a new study evaluating the usage of my Wedge and multiple cameras.

In the final and concluding chapter, I will analyze the performance results and conclude on the design of at-home physiotherapy tools and future work.

Chapter Six: CONCLUSIONS

In this chapter, I conclude on my work with at-home physiotherapy systems. In developing both Zipples and Physio@Home, I have answered my thesis questions originally raised in the first chapter. I now reflect on my work to discuss potential areas for future work and my lasting contributions.

I first describe the limitations of Physio@Home—primarily with the study—but also outstanding issues with the system and its intended usage. Following these limitations, I raise topics for future work to address them, and to guide work on similar systems that may build on the work in this research. I then conclude with my contributions and final remarks.

6.1 Limitations

While Physio@Home's laboratory study was successful and the system was more refined than Zipples, it still had several distinct limitations that reduces its impact and completeness. Overall, Physio@Home was limited by its participant pool, tracking difficulties, and study limitations. I will describe them below and discuss their effects on my results.

6.1.1 Participant pool

As with Zipples, my recruited participants were local graduate students rather than on-going physiotherapy patients or seniors. I selected this participant pool due to the early state of the prototype and difficulties recruiting and working with more specialized populations. Notably, there was a risk of injury for current physiotherapy patients, and their reduced motion might not allow them to follow the exercises as closely, thereby affecting my intended focus on accurate movement replication. Specifically with the senior population, I was concerned about time and transportation issues that would affect their availability. I understood these problems in advance of running my study and I chose to use a more readily available graduate student population to gather more results now for future iterations. With this population, I also focused specifically on how best to guide movements that could aid in designing later iterations of Physio@Home that would be used with physiotherapy patients and seniors.

Despite this, my graduate student participant pool was still not the intended user base. These participants were healthy and most had not been seriously injured in the past. Most notably, some of the participants preferred smoother and more fluid movements seen more in dance, and did not have had an appreciation for strict guidance and correction. It is therefore unclear how well their feedback may carry over to physiotherapy patients and seniors. Even though some participants had prior physiotherapy experience and were able to comment positively on the use of the Wedge and multiple cameras, this is still a limited pool to draw upon. Overall, it is not clear how well my current findings will transfer to actual patients undergoing rehabilitation or seniors not familiar with technology.

6.1.2 Tracking and marker limitations

While the Vicon motion capture system was more accurate than the Kinect at tracking consistent joint positions, it still had some drawbacks. The Vicons required the markers to be visible at all times and could not be covered under any circumstances to ensure continued tracking. They also had to be visible at optimum angles so that even if tracked, the Vicons could determine the correct positions and orientations of the marker vectors. For these reasons, the markers had to be on the outside of a person's body, visible at all times, and had to be large enough so that the Vicons could see them and correctly calculate their vectors.

This approach had drawbacks. The visualizations were drawn directly on the marker positions, which were in fact the sides of the participant's arm. This in turn results in the Vicon-tracked joint positions being slightly offset, which in turn offsets the visualizations. During movement, the markers then shift more due to them being mounted on the outside of the arm, further shifting the visualization. The resulting visualization shifting was sometimes misleading or unnatural to see. Sometimes, the visualization may tell a participant to stay still, but the visualization itself was moving due to the marker positions.

This differs from using the Kinect, which used depth-sensing and image processing to place a joint directly inside a user's body. While this is less accurate when joints obscure each other, the positions of joints are kept within a participant's body during movement. The lack of shifting joint positions would result in a visualization being kept in the same positions, if it was being tracked correctly.

Physio@Home was also unable to track the position and orientation of a participant's body. This was due to the markers being present only on their left arm with none elsewhere to provide additional information. For these reasons, Physio@Home also required participants to restrict movements to ensure correct tracking and visualization. These affected how the study was performed, in particular, and are described in detail below.

6.1.3 Study limitations

While I designed Physio@Home with the assumption that it would be used in homes, it was evaluated using a controlled study in the research lab. Naturally, this was done as the Vicon motion tracking system cannot be deployed into homes, and the system is still in too early a state for at-home use. For this reason, the study was also focused entirely on the guidance of an exercise in-progress, and I chose to evaluate movement accuracy to measure it.

Due to the tracking problems discussed in the previous section, however, this was not a realistic example of Physio@Home's intended usage. Participants were specifically instructed to refrain from too much side-to-side movement because the system could not track and correct for this. The participant's orientation was also not tracked and they were instructed to face the display and avoid turning.

Physio@Home was also limited in how it focused on a very narrow and specific problem. I chose to focus on the design of guides that would guide exercise movements and evaluate how these guides may help follow exercises. I had to make the assumption that this system and the technology powering it would already exist and be deployable in homes, and that I would design the guiding mechanisms for it.

Naturally, this focus ignores some other vital aspects of rehabilitation. Participants using Physio@Home are intended to mimic pre-recorded movements as close as possible, but these are not the only relevant physiotherapy exercises. Others include stretching and holding postures, or performing repetitions, which are currently not supported in Physio@Home.

Physio@Home also currently does not support the full rehabilitation process. As described in Chapter 1, the rehabilitation process for a dislocated shoulder will occur over a 12-16 week period, where the patient will have reduced mobility at the beginning and gradually regain it. I ignored this for now due to scoping, but this is a vital part of recovery. Patients will take time to recover and a vital aspect is showing how far they have recovered or how much progress they have made. Currently, Physio@Home assumes they are just exercising by movement with no regard for gradual improvement or mastery over time.

6.2 Future Work

Based on the current state of Physio@Home, I have identified several areas for future work. Future work includes immediate system improvements for Physio@Home and additional implementation beyond it. I will describe these to provide context for where Physio@Home stands at the time of writing this thesis, and to provide readers with possible areas for later work in this field.

6.2.1 Immediate improvements

Some of Physio@Home's present limitations may be resolved by expanding system functionality. To support other exercises, such as stretching and repetitions described earlier, the annotation tool must be expanded. The annotation tool is able to split exercises into chapters and currently has limited functionality for describing what characteristics are important in each. It would be possible to add parameters to the chapters, such as holding a selected chapter for a period of time for a stretching exercise, or specifying a number of times a chapter must be repeated for repetitions.

Improving system functionality may also address problems noted during the study. The visual overload caused by the multiple views may be resolved by keeping a single primary view from the front and showing the secondary view in a picture-in-picture when needed. Alternatively, the primary view may switch to another camera perspective if it provides a better view. A different camera layout and adjustment to the positions of joints tracked by the Vicons may also help with the visualization offsetting. More visual exploration will also be necessary to improve the Wedge. As noted from the previous chapter, the Wedge's Corrective Arm does not provide the necessary corrective details. This may be explored more and other visual factors may be used to address it.

The use of the secondary view may also be explored more. This was limited in Physio@Home strictly to a top-down view for simplification, but this is not the only possible use for it. A secondary view could also be used to provide a viewpoint of an obscured joint while exercising, such as when the patient is stretching behind their back, for instance. Other viewing angles, such as from the side or from a three-quarter perspective, may be used to provide better context. Applications of the second camera in Physio@Home were limited and the top-down view alone does not represent all that can be done with it.

6.2.2 Beyond Physio@Home

Future work beyond Physio@Home is intended to address its functionality with physiotherapy patients and therapists. As mentioned, Physio@Home focuses on a very narrow problem of simply guiding and correcting exercise movement that is valid, but may not be entirely realistic. To address this limitation, future work could focus on the longer-term 12-16 week recovery period. As mentioned from Chapter 5, one physiotherapy patient described all methods are valid and useful during some stage of recovery—this finding should be leveraged in a longer-term rehabilitation system. This could be done by developing a layering or 'scaffolding' technique, where parts of the Wedge are gradually introduced during the rehabilitation period. The patient could be introduced to an exercise by video at the beginning and then gradually given separate parts of the Wedge to train them over time. A simple addition would be to track a patient's performance on exercises over time.

Another area to consider is closer integration with physiotherapists. As is, Physio@Home is a home-based system only, where any activity the patient performs is independent from their work with a physiotherapist. It may be necessary to involve the physiotherapist in systems such as Physio@Home in more ways than modeling exercises. For instance, the system could send detailed performance data from the exercises to the physiotherapist so they can ensure their patient is performing their exercises correctly and intervene where necessary.

Finally, a crucial area for future work would be running more studies. The studies ran on Zipples and Physio@Home were strictly based on how closely a participant could follow an exercise. Other parameters, such as speed, learning, and retention, were not evaluated, and would also be valuable in later work. As well, a long-term trial with physiotherapists and patients with a more polished prototype would be beneficial.

6.3 Contributions

To state my contributions, I must first restate my research goals and thesis questions from the first chapter. I began this thesis with my research question:

> **How do we provide effective and accurate movement guidance and corrective feedback for people doing physiotherapy exercises at home?**

To answer this question, I then posed four thesis questions:

Thesis Question 1: What are the characteristics of at-home physiotherapy exercises, and what implications for visual feedback design do they have?

Thesis Question 2: How can we design a system that provides visual feedback for physiotherapy exercises that make leverage these insights?

Thesis Question 3: How can we evaluate visual and multi-view feedback for movement guidance?

Thesis Question 4: What are the effects of visual feedback and multi-view feedback for movement guidance?

To answer Thesis Question 1, I interviewed a practicing physiotherapist. I asked her what types of exercises she teaches her patients and how she teaches and corrects her patients. From these interviews, I devised a set of movement characteristics common necessary for guidance and corrective feedback, and described these in Chapter 3: plane/range of movement, maintaining position/angle, extent of movement, and rate of movement.

To leverage these insights for answering Thesis Question 2, I implemented two prototype systems: Zipples and Physio@Home, described in Chapters 4 and 5 respectively. Both systems were intended to be used in a patient's home to practice their exercises while away from their physiotherapist. Zipples used a Microsoft Kinect, while Physio@Home used a more accurate Vicon motion tracking system.

To answer Thesis Question 3, I ran studies to evaluate Zipples and Physio@Home. The Zipples study produced qualitative findings and lessons learned that aided Physio@Home's implementation. The results of the Physio@Home study allowed me to present results to answer Thesis Question 4 that supports the usage of my movement characteristics for guiding exercises.

6.4 Final Conclusions

Physiotherapy patients exercising at home do not have the benefit of guidance and feedback, and there is a strong possibility of re-injury with incorrect exercise movements. Zipples and Physio@Home explored the use of a dynamic on-screen visualizations to guide exercise movements, with Physio@Home using a guide called the Wedge and multiple camera views to support depth perception and precision. With Physio@Home, I found that participants performed exercises with the least error using the Wedge and multiple views. From this, I identified several characteristics required for accurate movement guidance, and challenges for exercise guidance systems. Physiotherapy services will continue to be in high demand as the population ages. With increasingly capable and inexpensive motion tracking cameras on their way, I hope that the concepts from this thesis and ideas implemented in both Zipples and Physio@Home will be able to help meet the needs of physiotherapy patients in the future.

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Tseng, C-M., Lai, C-L., Erdenetsogt, D., and Chen, Y-F. (2014) A Microsoft Kinect based virtual rehabilitation system. In the International Symposium on Computer, Consumer and Control *(IS3C 2014)*, 934-937

Uzor, S. & Baillie, L. (2014). Investigating the long-term use of exergames in the home with elderly fallers. In Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (*CHI 2014)*, 2813-2822

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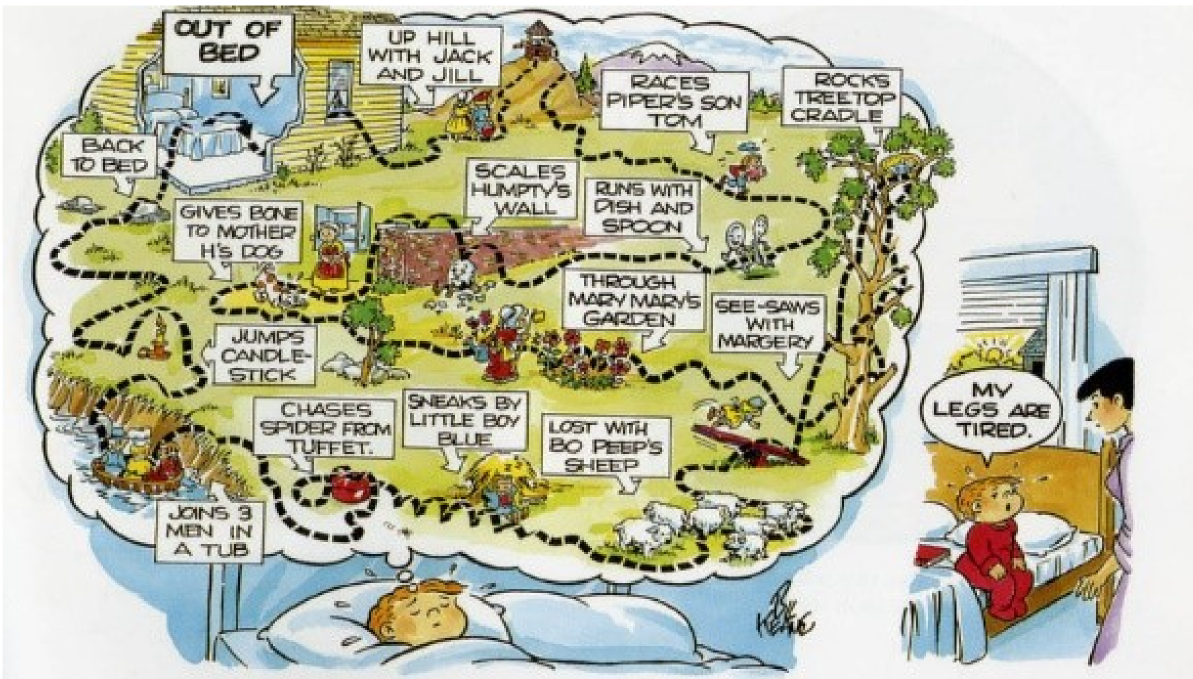
Yeh, S-C., Chang, S-M, Chen, S-Y, & Hwang, W-Y. (2012) A lower limb fracture postoperative-guided interactive rehabilitation training system and its effectiveness analysis. In the IEEE International Conference on e-Health Networking, Applications and Services (Healthcom 2012), 149-54

APPENDIX A: ZIPPLES MATERIALS

A.1. Family Circus Dotted Lines example

(Reproduced from http://www.npr.org/sections/monkeysee/2011/11/11/142218444/bil-keanes-dotted-line-an-appreciation)



A.2. Zipples ethics approval

Conjoint Faculties Research Ethics Board
Research Services Office
Energy Resources Research Building (ERRB)
Suite N140, 3512-33 Street NW
Calgary, Alberta, T2L 2A6
Telephone: (403) 220-3782
Fax: (403) 289-0693
cfreb@ucalgary.ca

UNIVERSITY OF CALGARY

August 12, 2013

Anthony Tang

Dear Anthony Tang :

RE: Video Guides for Physical Movement

Ethics ID: REB13-0656

The above named research protocol has been granted ethical approval by the Conjoint Faculties Research Ethics Board for the University of Calgary. Please make a note of the conditions stated on the Certification. In the event the research is funded, you should notify the sponsor of the research and provide them with a copy for their records. The Conjoint Faculties Research Ethics Board will retain a copy of the clearance on your file.

Please note, a renewal or final report must be filed with the CFREB within 30 days prior to expiry date on your certification. You can complete your renewal or closure request in IRISS.

In closing let me take this opportunity to wish you the best of luck in your research endeavor.

Sincerely, **Date:**

Christopher Sears, PhD, Chair , CFREB August 12, 2013

A.3. Zipples recruitment email

VIDEO GUIDES FOR TEACHING PHYSICAL MOVEMENT

We are researchers from the Interactions Lab in the Department of Computer Science, University of Calgary. We are looking for adults (age: 18+) to participate in a study exploring how different visualizations can aid teaching of physical movements, such as in physiotherapy. Your participation will involve performing simple movements (such as moving your arm in a circle) as guided by video prompts. These motions will be video recorded for analysis.

WHERE: Math Sciences 680, University of Calgary

TIME: Approximately 1hr

REMUNERATION: $20/person

If you are interested in participating, or have any questions, please contact Dr Anthony Tang (tonyt@ucalgary.ca, 403-210-6912).

A.4. Zipples experiment script

Zipples experiment script

Setup

- Set Kinect in front of a display, 4 feet off the ground and seven feet in front of a designated standing location for the participant
- Have 5 post-condition and 1 post-experiment questionnaires ready
- Have pens ready
- Have replays ready: **practice**, **circular motion**, **frontal plane**, and **sequential**
- Ensure 'recordings' folder is empty

Introduction

- Give participant consent form
- Give participant pre-experiment questionnaire
- Explain
- Any questions?
- Start Zipples application

Calibration

  - Instruct participant to stand on marked spot
  - Tell participant to stick arm out in front of them at shoulder-level
  - Start calibration, point out the angled lines
  - Tell participant to move arm backwards while keeping arm at shoulder-level until lines straighten
  - When lines disappear, tell participant to stop and relax their arm and rest for 10s

Testing phase

Participant 1	Directional arrow	Polyline	Directional polyline	Flat arrow	No guide

Participant 2	Polyline	Directional polyline	Flat arrow	No guide	Directional arrow
Participant 3	Directional polyline	Flat arrow	No guide	Directional arrow	Polyline
Participant 4	Flat arrow	No guide	Directional arrow	Polyline	Directional polyline
Participant 5	No guide	Directional arrow	Polyline	Directional polyline	Flat arrow

1. Explain procedure to participant:
   - There are five types of visual guides
   - Participant will be allowed to practice each one before the recording phase five times, or for as long as they require
   - Practice phase will not be recorded
2. Load practice replay and play it once for them to see what the motion looks like
3. Select guide, order to be determined for the participant by the chart above
4. Explain guide to participant and how it works, and let them go through the motion
5. After practice is over, let participant rest arm for 1 minute
6. Load 1 of 3 replays, to be randomly selected, and play it once for the participant to see what the movement looks like
7. Instruct participant that the recording phase will begin. Just before telling them to 'go', begin recording
8. Recording automatically ends when they each the end of the movement
9. Give participant chance to rest/stretch their arm while the replay is being written to file.
10. Repeat step 7-9 four more times – participants will perform five recorded motions for each motion type.

Post-condition questionnaire

1. Give condition questionnaire for participant. Questionnaire asks participant to rate statements on Likert-scale

- “I found this technique frustrating to use”
    - “I was able to follow the motion closely with this technique”
    - “This technique was easy to understand”
    - Etc.
2. Repeat testing phase steps 2-10 for the next guide
    - Re-load practice replay, select next visualization

Post-experiment

1. Give post-experiment questionnaire
2. Thank them for their time and provide compensation
3. Move recorded replays from ‘recordings’ folder to safe location
4. Repeat calibration and testing steps for next participant with visualization order provided by chart

A.5. Zipples consent form

UNIVERSITY OF CALGARY

Name of Researcher, Faculty, Department, Telephone & Email:

Dr. Anthony Tang, Assistant Professor – Department of Computer Science, 403-210-6912, tonyt@ucalgary.ca

Title of Project:

Video Guides for Physical Movement

This consent form, a copy of which has been given to you, is only part of the process of informed consent. If you want more details about something mentioned here, or information not included here, you should feel free to ask. Please take the time to read this carefully and to understand any accompanying information.

The University of Calgary Conjoint Faculties Research Ethics Board has approved this research study.

Purpose of the Study:

The purpose of this study is to understand how different visual hints (visualizations overalayed atop videos of you) can help in guiding physical motions. You are here because you heard about this study based on a poster, email, forum post, social media post, or word-of-mouth, and you volunteered to participate.

What Will I Be Asked To Do?

You will be asked to watch and perform a set of simple motions based on pre-recorded videos of a guide. After watching a video, you will be shown a visualization overlayed atop yourself, the guide, or both. You will then be asked to mimic the same motion that the guide performed. These tasks may involve moving your arm in a circle, a square, etc. We are mainly interested in understanding how well the different visualizations work (in terms of being understandable and usable).

Note: we are *not* evaluating you. Instead, we are evaluating how these different conditions work, and whether they work well. Thus, please relax and simply enjoy yourself while you complete these tasks.

You will also be asked to fill out a brief questionnaire, and participate in a brief interview about your experiences. This study will be video-taped.

Your participation is entirely voluntary. You may refuse to participate altogether, or may withdraw from the study at any time without penalty by stating your wish to withdraw to the researchers.

This study should take approximately 1 hour. You will receive a remuneration in the form of cash or a gift card (value $20) for your participation; you will receive this remuneration even if you choose to withdraw from the study.

What Type of Personal Information Will Be Collected?

Should you agree to participate, you will be asked to provide your gender, age and academic major or occupation in a questionnaire. Providing this information is optional.

We will also be collecting video data. The main purpose for collecting the video is analysis of the exploration session and the interview content. However, with your permission, we might want to use clips or stills of the video in presentations or other electronic media, but this can only happen with your consent. Please, indicate below if you grant us permission to use video clips or still pictures from this interview. Any clips or stills of the video will **not** be associated with your name or contact information. If consent is given to present *identifiable* video clips and/or photographs (see table below), then no anonymity can be provided and you will be clearly recognizable as a participant in this study. Please note that once photographed or videotaped images are displayed in any public forum, the researchers will have no control over any future use by others who may copy these images and repost them in other formats or contexts, including possibly on the internet

There are several options for you to consider if you decide to take part in this research. You can choose all, some or none of them.

Please put a check mark on the corresponding line(s) that grants us your permission to:

I agree to let identifiable video clips or stills from the study to be used for presentation of the research results.	YES __	NO __
I agree to let my conversation during the study be directly quoted, anonymously, in presentation of the research results.	YES __	NO __

Please note that once photographed or videotaped images are displayed in any public forum, the researchers will have no control over any future use by others who may copy these images and repost them in other formats or contexts, including possibly on the internet.

Are there Risks or Benefits if I Participate?

There are no known harms associated with your participation in this research beyond what you would experience in every day life. You will be asked to perform some basic physical movement that is not designed to be stressful; however, if you experience discomfort, please indicate this to the experimenter. You will not be penalized for doing so. We expect no direct benefit to participants. At the end of the session, you will be able to ask questions about our research.

What Happens to the Information I Provide?

You are free to withdraw from this study at any point. If this occurs, we will immediately stop collecting data from you, ensuring that only data for which you have given consent is used.

All data received from this study will be kept indefinitely in a secure location. The investigator indicated on this form will have access to the raw data, as will future investigators or research assistants on this project. While the exact composition of this team will change over time, the primary investigator will remain on the project.

In any reports created based on this study, you will be represented anonymously, using a pseudonym or participant number (e.g. Participant 4). With your permission (as indicated in the table above) we may use quotes from your interview or video stills of your session in our published results; these will not be associated with your name, contact information, pseudonym, or participant number. No personal or confidential information will be published. Please note that once videotaped images are displayed in any public forum, the researchers will have no control over any future use by others who may copy these images and repost them in other formats or contexts, including possibly on the internet.

Please also note that absolute anonymity cannot be guaranteed in a group setting, as the researchers will be unable to control what is said by individuals outside of the session.

Signatures (written consent)

Your signature on this form indicates that you 1) understand to your satisfaction the information provided to you about your participation in this research project, and 2) agree to participate as a research subject.

In no way does this waive your legal rights nor release the investigators, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from this research project at any time. You should feel free to ask for clarification or new information throughout your participation.

Participant's Name: (please print) ______________________________

Participant's Signature ______________________________ Date: ______________

Researcher's Name: (please print) Richard Tang

Researcher's Signature: ______________________________ Date: Sept. 5, 2013

Questions/Concerns

If you have any further questions or want clarification regarding this research and/or your participation, please contact:

Anthony Tang
Professor - Department of Computer Science
University of Calgary
Phone: 403-210-9499, tonyt@ucalgary.ca

If you have any concerns about the way you've been treated as a participant, please contact the Senior Ethics Resource Officer, Research Services Office, University of Calgary at (403) 220-3782; email rburrows@ucalgary.ca.

A copy of this consent form has been given to you to keep for your records and reference. The investigator has kept a copy of the consent form.

A.6. Zipples demographics questions

1. What is your age?
2. What is your gender?
3. What is your occupation?
4. Have you experienced physiotherapy (or other activities where you were to learn physical movements) in the past? Describe these experiences?
5. Given the different visualizations, which did you enjoy the most? Why?
6. Which condition provided you with the most efficient means to complete the task you were given? Why was it more efficient to use this condition?
7. How do these conditions differ in terms of their ability to support the tasks you were given?

A.7. Zipples post-condition questionnaires

Post Technique Questionnaire – Zipples Study

Technique Name _______________ **Participant ID**____________

Please rate your level of agreement with each of the following statements about the guide you just used.

Using this guide I could *see my current location*:

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

Using this guide I could *see where I needed to move my arm* next:

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

Using this guide I could *see how far forward and backwards* I needed to be:

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

I could follow the movements *accurately* using this guide:

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

I found this guide *easy* to use:

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

I could complete the movements *quickly* using this guide:

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

I found this guide was *helpful* to complete the movements:

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

I found using this guide *frustrating, annoying, or stressful*.

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

I found this guide easy to *learn*.

Strongly Disagree	Disagree	Slightly Disagree	Neutral	Slightly Agree	Agree	Strongly Agree

Do you have any other comments about the guide that you just used?

A.8. Zipples post-study questionnaire

Post-Experiment Questionnaire – Zipples Study

Participant ID: ________

Please circle your preferred guide for each of the following dimensions. If you are unclear about the names of the guide, please ask the experimenter:

The guide I was most *accurate* with was:

2D arrow	**3d arrow**	**No guide**	**Dashed triangles**	**Arm lines**

The guide that I found *easiest to learn* was:

2D arrow	**3d arrow**	**No guide**	**Dashed triangles**	**Arm lines**

The guide I found *easiest to use* was:

2D arrow	**3d arrow**	**No guide**	**Dashed triangles**	**Arm lines**

The guide I found most *helpful* was:

2D arrow	**3d arrow**	**No guide**	**Dashed triangles**	**Arm lines**

The guide I *preferred* most was:

2D arrow	**3d arrow**	**No guide**	**Dashed triangles**	**Arm lines**

Do you have any comments about the guides you used in the experiment, or comments about why you answered the way you did to the above questions?

How do these guides differ in terms of their ability to support the movements you were given?

____

____

____

____

____

____

Have you experienced physiotherapy and were you prescribed exercises in the past? Describe these experiences (e.g. ,what were the exercise for, did they work, did you do them)?

____

____

____

____

____

____

Have you ever participated in a sport or activity (e.g., dance) that has required you to learn physical movement? Please briefly describe the activities and your level of experience with them.

____

____

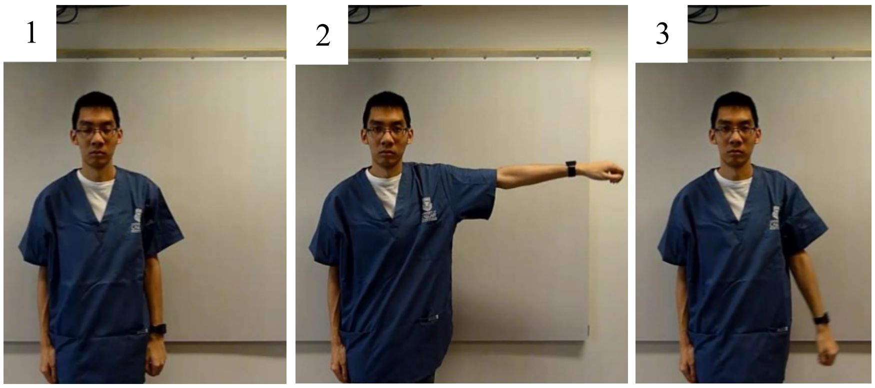
____

____

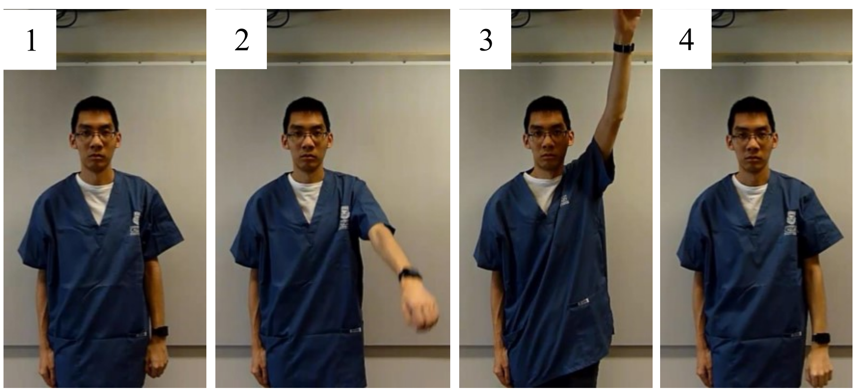
____

A.9. Zipples exercise images

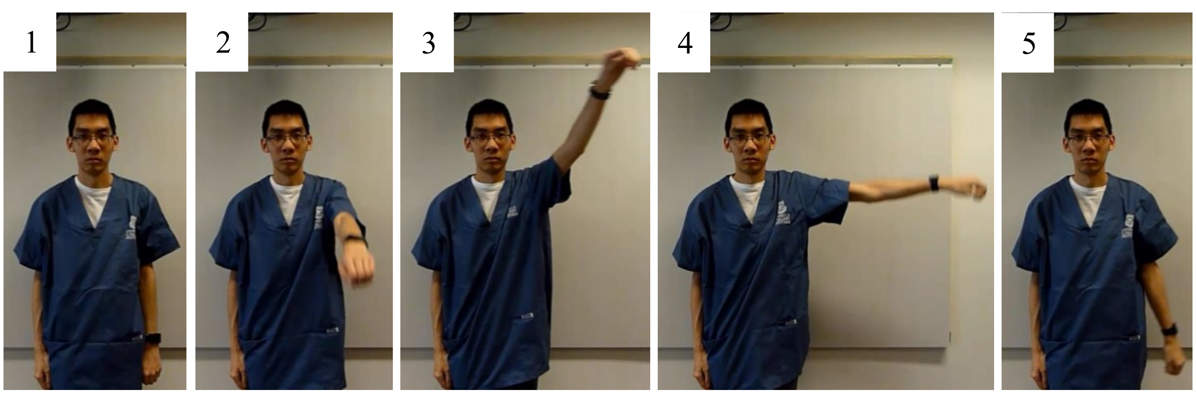
A.9.1. Up-down



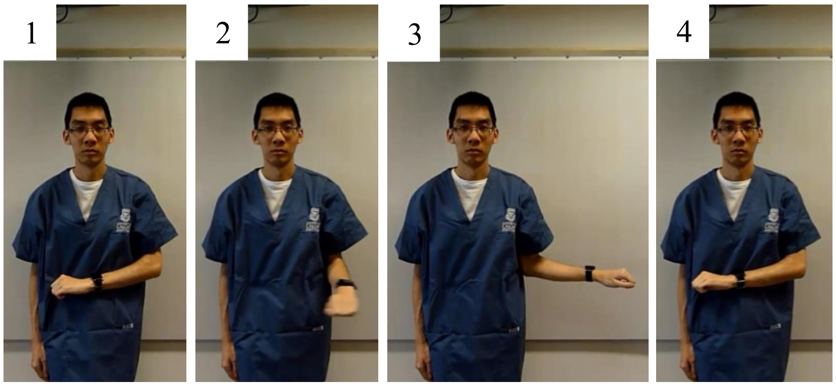
A.9.2. Vertical up-down



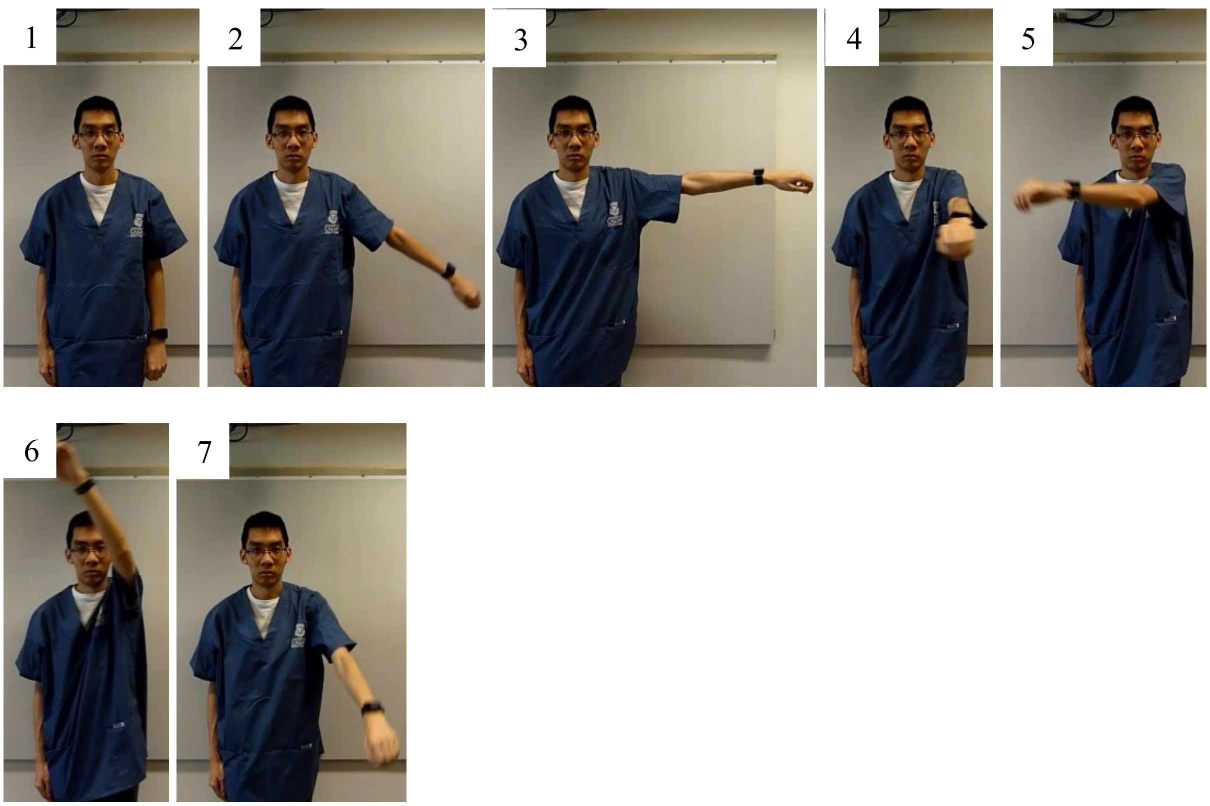
A.9.3. Circular



A.9.4. Rotation



A.9.5. Figure-8



A.10. Zipples questionnaire results

Strongly disagree:	1
Disagree:	2
Slightly disagree	3
Neutral	4
Slightly agree	5
Agree	6
Strongly agree	7

	p0	p1	p2	p3	p4	p5	p6	p7	p8	p9
Could see current location	7	7	7	6	7	7	6	7	4	7
Could see where to move next	6	7	6	5	7	5	5	7	6	7
Could see how far forward/back needed	2	7	5	7	7	2	6	6	4	6
Could follow accurately	5	7	7	6	7	3	6	6	6	7
Easy to use	6	7	7	6	7	6	6	6	7	6
Could complete movement quickly	4	7	7	7	7	4	6	6	6	7
Was helpful	6	7	6	6	7	5	6	6	6	7
Was frustrating, annoying, stressful	2	1	2	1	1	1	2	1	2	1
Easy to learn	6	7	6	6	7	6	6	6	6	7
Could see current location	7	1	1	4	4	2	4	6	6	6
Could see where to move next	1	6	2	4	3	1	5	6	1	6
Could see how far forward/back needed	1	1	5	6	3	1	3	6	1	5
Could follow accurately	1	6	2	4	3	2	6	6	4	6
Easy to use	2	7	3	5	4	6	6	6	6	5
Could complete movement quickly	4	7	6	5	5	4	6	3	6	5
Was helpful	1	7	3	4	4	2	6	6	4	5
Was frustrating, annoying, stressful	4	1	6	1	4	4	5	4	4	4
Easy to learn	4	5	6	4	4	6	6	4	5	4
Could see current location	7	7	6	7	7	7	6	7	6	7
Could see where to move next	7	7	7	6	7	7	6	7	7	7
Could see how far forward/back needed	6	7	5	7	4	7	6	6	7	7
Could follow accurately	6	7	7	7	6	7	6	7	6	7
Easy to use	6	7	7	7	6	7	6	7	2	6
Could complete movement quickly	4	7	6	7	7	7	7	7	4	6
Was helpful	6	7	6	6	7	7	7	7	6	7
Was frustrating, annoying, stressful	2	1	2	1	2	1	2	1	5	2
Easy to learn	6	7	7	7	7	7	6	7	4	7
Could see current location	7	7	6	6	7	7	6	7	4	7
Could see where to move next	5	7	4	6	7	6	6	3	6	7

Could see how far forward/back needed	6	7	6	7	7	1	3	1	3	6
Could follow accurately	4	7	3	7	7	5	5	5	6	6
Easy to use	6	7	4	7	7	6	5	5	6	6
Could complete movement quickly	6	7	3	7	7	4	5	3	5	7
Was helpful	5	7	5	7	7	5	6	5	5	6
Was frustrating, annoying, stressful	2	1	5	1	1	3	5	5	4	2
Easy to learn	6	7	5	7	7	3	5	5	4	6
Could see current location	7	7	5	7	7	7	5	6	4	7
Could see where to move next	7	7	5	7	6	7	6	6	3	6
Could see how far forward/back needed	6	7	4	7	5	7	6	7	2	7
Could follow accurately	7	7	5	7	6	6	6	6	5	6
Easy to use	7	7	5	7	6	7	6	7	3	7
Could complete movement quickly	6	7	5	7	6	7	6	7	5	7
Was helpful	7	7	6	7	6	7	6	6	4	7
Was frustrating, annoying, stressful	2	1	3	1	2	1	4	1	5	1
Easy to learn	6	7	6	7	6	7	4	6	4	7

	I was most accurate with:	I found easiest to learn:	I found easiest to use:	Most helpful	Preferred
p0	2D Arrow	2D Arrow	Arm Lines	Arm Lines	Arm Lines
p1	3D Arrow Dashed	3D Arrow	3D Arrow	3D Arrow Dashed	3D Arrow Dashed
p2	Triangles	2D Arrow Dashed	2D Arrow Dashed	Triangles	Triangles
p3	Arm Lines	Triangles	Triangles	Arm Lines	Arm Lines
p4	2D Arrow	2D Arrow Dashed	2D Arrow	2D Arrow	Arm Lines
p5	Arm Lines Dashed	Triangles Dashed	Arm Lines Dashed	Arm Lines Dashed	Arm Lines Dashed
p6	Triangles Dashed	Triangles	Triangles	Triangles Dashed	Triangles
p7	Triangles	2D Arrow	2D Arrow	Triangles Dashed	2D Arrow
p8	2D Arrow Dashed	2D Arrow	2D Arrow	Triangles	2D Arrow Dashed
p9	Triangles	2D Arrow	Arm Lines	2D Arrow	Triangles

APPENDIX B: PHYSIO@HOME MATERIALS

B.1. Physio@Home/Zipples ethics extension

UNIVERSITY OF CALGARY

Conjoint Faculties Research Ethics Board
Research Services Office
3rd Floor Mackimmie Library Tower (MLT 300)
2500 University Drive, NW
Calgary AB T2N 1N4
Telephone: (403) 220-3782
Fax: (403) 289-0693

CERTIFICATION OF INSTITUTIONAL ETHICS REVIEW

This is to certify that the Conjoint Faculties Research Ethics Board at the University of Calgary has examined the following research proposal and found the proposed research involving human participants to be in accordance with University of Calgary Guidelines and the *Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans* 2010 (TCPS 2). This form and accompanying letter constitute the Certification of Institutional Ethics Review.

Ethics ID:	REB13-0656_REN1
Principal Investigator:	Anthony Tang
Co-Investigator(s):	There are no items to display
Student Co-Investigator(s):	Richard Tang
Study Title:	Video Guides for Physical Movement
Sponsor (if applicable):	1021604 / Natural Sciences and Engineering Research Council 1021292 / University of Calgary 1023958 / University of Calgary

Effective: August 12, 2014 **Expires:** August 31, 2015

<u>Restrictions:</u>

This Certification is subject to the following conditions:

1. Approval is granted only for the project and purposes described in the application.
2. Any modification to the authorized study must be submitted to the Chair, Conjoint Faculties Research Ethics Board for approval.
3. An annual report must be submitted within 30 days from expiry date of this Certification, and should provide the expected completion date for the study.
4. A final report must be sent to the Board when the project is complete or terminated.

Christopher R. Sears, PhD, Chair , CFREB

Date:
July 10, 2014

B.2. Physio@Home recruitment email

We are researchers from the Interactions Lab in the Department of Computer Science, University of Calgary. We are looking for adults (age: 18+) to participate in a study exploring how different visualizations can aid teaching of physical movements, such as in physiotherapy.

WHERE: Math Sciences 680, University of Calgary
TIME: 1hr, link for available times
REMUNERATION: $20/person

If you are interested in participating and have not participated in our previous study last year, or have any questions, please contact Richard Tang (tanr@ucalgary.ca, 587-436-9229)

B.3. Physio@Home consent form

Name of Researcher, Faculty, Department, Telephone & Email:

Dr. Anthony Tang, Assistant Professor – Department of Computer Science, 403-210-6912, tonyt@ucalgary.ca

Title of Project:

Video Guides for Physical Movement

This consent form, a copy of which has been given to you, is only part of the process of informed consent. If you want more details about something mentioned here, or information not included here, you should feel free to ask. Please take the time to read this carefully and to understand any accompanying information.

The University of Calgary Conjoint Faculties Research Ethics Board has approved this research study.

Purpose of the Study:

The purpose of this study is to understand how different visual hints (visualizations overlaid atop videos of you) can help in guiding physical motions. You are here because you heard about this study based on a poster, email, forum post, social media post, or word-of-mouth, and you volunteered to participate.

What Will I Be Asked To Do?

You will be asked to watch and perform a set of simple motions based on pre-recorded videos of a guide. After watching a video, you will be shown a visualization overlaid atop yourself, the guide, or both. You will then be asked to mimic the same motion that the guide performed. These tasks may involve moving your arm in a circle, a square, etc. We are mainly interested in understanding how well the different visualizations work (in terms of being understandable and usable).

Note: we are *not* evaluating you. Instead, we are evaluating how these different conditions work, and whether they work well. Thus, please relax and simply enjoy yourself while you complete these tasks.

You will also be asked to fill out a brief questionnaire, and participate in a brief interview about your experiences. This study will be video-taped.

Your participation is entirely voluntary. You may refuse to participate altogether, or may withdraw from the study at any time without penalty by stating your wish to withdraw to the researchers.

This study should take approximately 1 hour. You will receive a remuneration in the form of cash or a gift card (value $20) for your participation; you will receive this remuneration even if you choose to withdraw from the study.

What Type of Personal Information Will Be Collected?

Should you agree to participate, you will be asked to provide your gender, age and academic major or occupation in a questionnaire. Providing this information is optional.

We will also be collecting video data. The main purpose for collecting the video is analysis of the exploration session and the interview content. However, with your permission, we might want to use clips or stills of the video in presentations or other electronic media, but this can only happen with your consent. Please, indicate below if you grant us permission to use video clips or still pictures from this interview. Any clips or stills of the video will **not** be associated with your name or contact information. If consent is given to present *identifiable* video clips and/or photographs (see table below), then no anonymity can be provided and you will be clearly recognizable as a participant in this study. Please note that once photographed or videotaped images are displayed in any public forum, the researchers will have no control over any future use by others who may copy these images and repost them in other formats or contexts, including possibly on the internet

There are several options for you to consider if you decide to take part in this research. You can choose all, some or none of them.

Please put a check mark on the corresponding line(s) that grants us your permission to:

I agree to let identifiable video clips or stills from the study to be used for presentation of the research results.	YES __	NO __
I agree to let my conversation during the study be directly quoted, anonymously, in presentation of the research results.	YES __	NO __

Please note that once photographed or videotaped images are displayed in any public forum, the researchers will have no control over any future use by others who may copy these images and repost them in other formats or contexts, including possibly on the internet.

Are there Risks or Benefits if I Participate?

There are no known harms associated with your participation in this research beyond what you would experience in every day life. You will be asked to perform some basic physical movement that is not designed to be stressful; however, if you experience discomfort, please indicate this to the experimenter. You will not be penalized for doing so. We expect no direct benefit to participants. At the end of the session, you will be able to ask questions about our research.

What Happens to the Information I Provide?

You are free to withdraw from this study at any point. If this occurs, we will immediately stop collecting data from you, ensuring that only data for which you have given consent is used.

All data received from this study will be kept indefinitely in a secure location. The investigator indicated on this form will have access to the raw data, as will future investigators or research assistants on this project. While the exact composition of this team will change over time, the primary investigator will remain on the project.

In any reports created based on this study, you will be represented anonymously, using a pseudonym or participant number (e.g. Participant 4). With your permission (as indicated in the table above) we may use quotes from your interview or video stills of your session in our published results; these will not be associated with your name, contact information, pseudonym, or participant number. No personal or confidential information will be published. Please note that once videotaped images are displayed in any public forum, the researchers will have no control over any future use by others who may copy these images and repost them in other formats or contexts, including possibly on the internet.

Please also note that absolute anonymity cannot be guaranteed in a group setting, as the researchers will be unable to control what is said by individuals outside of the session.

Signatures (written consent)

Your signature on this form indicates that you 1) understand to your satisfaction the information provided to you about your participation in this research project, and 2) agree to participate as a research subject.

In no way does this waive your legal rights nor release the investigators, sponsors, or involved institutions from their legal and professional responsibilities. You are free to withdraw from this research project at any time. You should feel free to ask for clarification or new information throughout your participation.

Participant's Name: (please print) ____

Participant's Signature ____Date: ______________

Researcher's Name: (please print) ____

Researcher's Signature: ______________________________________Date: _______________

Questions/Concerns

If you have any further questions or want clarification regarding this research and/or your participation, please contact:

Anthony Tang
Professor - Department of Computer Science

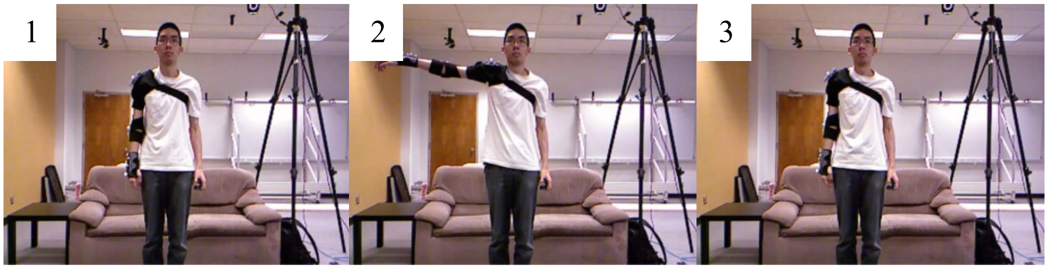
University of Calgary
Phone: 403-210-9499, tonyt@ucalgary.ca

If you have any concerns about the way you've been treated as a participant, please contact the Research Ethics Analyst, Research Services Office, University of Calgary at (403) 210-9863; email cfreb@ucalgary.ca.

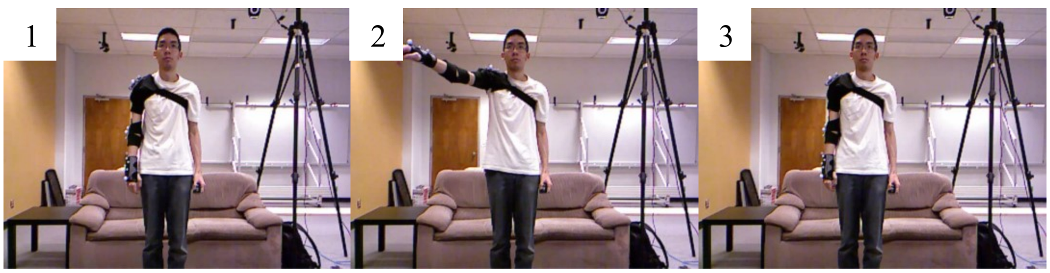
A copy of this consent form has been given to you to keep for your records and reference. The investigator has kept a copy of the consent form.

B.4. Physio@Home exercise images

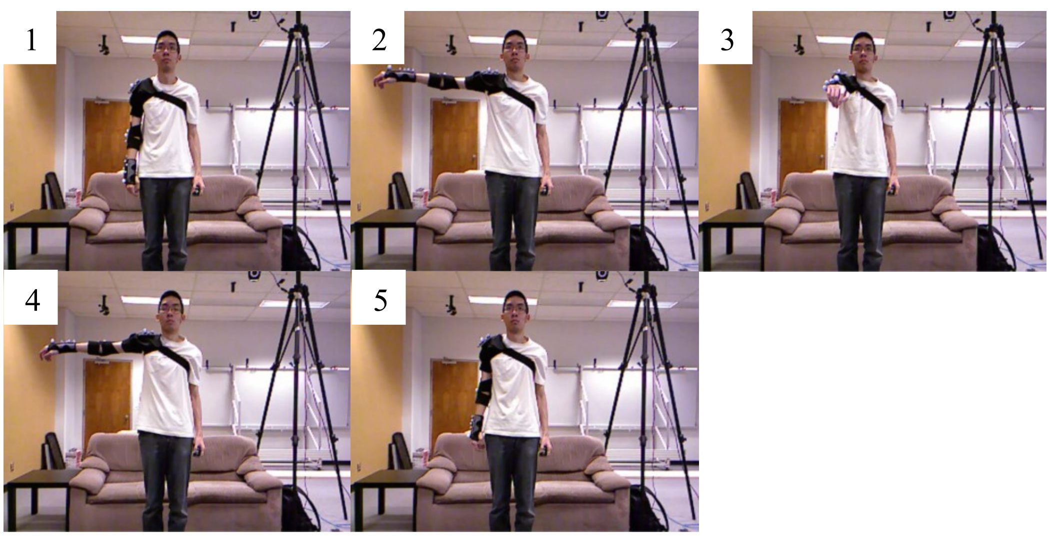
B.4.1. Up-down



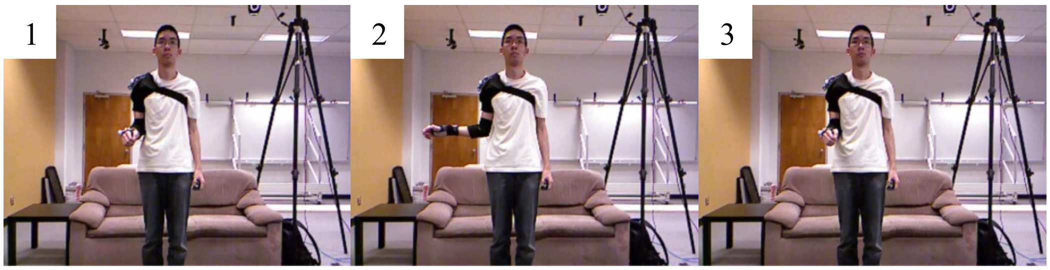
B.4.2. Angled



B.4.3. Combo



B.4.4. Elbow



B.5. Physio@Home demographics questionnaire

Participant ID: ________

Sex: male___ female ___

Handedness: right ___ left___ ambidextrous___

Age: ______

Highest level of education completed: ___________________________________

Occupation: ____
(if you are a student or researcher please mention your major or discipline)

To the best of your knowledge do you have normal or corrected to normal vision?
___ Yes ___ No

If "No", please describe your vision ability: __________________________________

____

Do you have any health conditions or injuries that may make it difficult for you to move your body or arms?
___ Yes ___ No

If "Yes", please describe your situation with regards to movement:
____

Have you experienced physiotherapy and were you prescribed exercises in the past? Describe these experiences (e.g. ,what were the exercise for, did they work, did you do them)?

Have you ever participated in a sport or activity (e.g., dance) that has required you to learn physical movement? Please briefly describe the activities and your level of experience with them.

B.6. Physio@Home post-study questionnaire

Participant ID: ___________

Please select which of the two you preferred using and describe why:

Video	Wedge

Please select which of the two you preferred using and describe why:

Single view	Multi view

Rank the following conditions:

A. **Single view, with Video**
B. **Multi view, with Video**
C. **Single view, with Wedge**
D. **Multi view, with Wedge**

With regards to accuracy:

With regards to personal preference:

B.7. Physio@Home questionnaire results

A. SingleView, with Video
B. MultiView, with Video
C. SingleView, with Wedge
D. MultiView, with Wedge

	Video or Wedge	Single or multiview	Rank by accuracy				Rank by preference			
p0										
p1	Wedge	Single	D	C	A	B	C	D	A	B
p2	Video	Multi	D	C	B	A	B	D	A	C
p3	Wedge	Multi	D	B	C	A	D	B	C	A
p4	Video	Multi	D	B	A	C	B	A	C	D
p5	Wedge	Multi	D	C	B	A	D	B	C	A
p6	Wedge	Multi					D	C	B	A
p7	Video	Multi					B	A	C	D
p8	Video	Multi	D	B	A	C	B	D		C
p9	Wedge	Single	D	C	B	A	C	A	D	B
p10	Video	Multi	C	B	A	D	B	A	C	D
p11	Wedge	Multi	D	C	B	A	D	C	B	A
p12	both	Single	C	D	B	A	C	A	B	D
p13	Wedge	Multi	D	B	C	A	D	B	C	A
p14	Wedge	Multi	D	C	B	A	D	C	B	A
p15	Wedge	Single	D	C	B	A	C	D	B	A