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THE DESIGN AND IMPLEMENTATION OF A KINECT-BASED
REHABILITATION EXERCISE MONITORING AND GUIDANCE SYSTEM

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May 2009

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at the

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HAI FENG

ABSTRACT

In preventive and rehabilitative healthcare, physical exercise is a powerful intervention. However, a program may require in the range of thousands of practice repetitions, and many people do not adhere to the program or perform their home exercises incorrectly, making the exercise ineffective, or even dangerous. This thesis research aims to develop a Kinect-based system for rehabilitation exercises monitoring and guidance. In the first step, a feasibility study was carried out on using Kinect for realtime monitoring of rehabilitation exercises while a multi-camera motion tracking system was used to establish the ground truth. In the second step, a Unity-based system was developed to provide realtime monitoring and guidance to patients. The Unity framework was chosen because it enables us to use virtual reality techniques to demonstrate detailed movements to the patient, and to facilitate examination of the quality and quantity of the patient sessions by the clinician. The avatar-based rendering of motion also preserves the privacy of the patients, which is essential for healthcare systems.

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CHAPTER I

INTRODUCTION AND BACKGROUND

1.1 Motivation of This Research

In rehabilitative health care, patients are generally needed to perform lots of supplemental exercises. To achieve faster and full recovery [1], patients are always asked to do thousands of practice repetitions. Furthermore, the rehabilitation exercises must be independently customized to address and record for the patient's particular pathology and limits by a clinician, additionally the other morbidities and additional debilitations. It is important for a patient to perform individual activities correctly as recommended and in the number of repetitions and durations as prescribed [2, 3]. Due to the large amount of repetitions required, it is inevitable for patients to be asked to perform the prescribed exercises at home on a daily basis.

The present state-of-the-practice to facilitate patients' at-home exercises is to use written instructions, exercise recording videos or logs and simple repetition counting devices. Unfortunately, this kind of practice is not adequate for patients since:

1. For patients, written instructions are not easy to follow.
2. Patients do not receive any feedback when they are doing the recommended exercises.

Thus, not only might patients fail to perform the exercise correctly, patients could be too baffled and disheartened to keep completing the recommended exercises because of the absence of interest, instructions and feedback. What is worse, there is no accountability on the patient's side since the clinician has no chance to know whether a patient has completed the recommended exercises accurately and with the established number of repetitions.

The main problem of state-of-the-practice is the absence of tracking and feedback during home exercises. The utilization of a simple counting device aims to check the exercise reiterations. However, this kind of simple, economically accessible devices cannot capture all the detailed requirements but the most basic, such as counting steps or recording overall terms of movements [4], furthermore, as revealed by its name, a simple counting device cannot fully capture the quality of the exercises performed at home.

1.2 Motion Tracking with Microsoft Kinect

1.2.1 Motivation of choosing Microsoft Kinect

To address these problems, new technologies based on the Virtual Reality (VR) have been used. VR-based technologies use motion-tracking sensors to capture patients' movement and give patients realtime feedback.

Motion tracking is the process of recording the movement of object or people. It has been used in military, entertainment, sport and media applications, and for validation of computer vision and robots. [5]. In film making and video game development, such systems often involve the recording of human motions and mirror the human motions in the form of 2D or 3D avatars.

In this thesis, motion tracking system was developed to serve as a realtime exercise tutor at home. Our system offers the following features:

1. Patients can quickly get the feedback from the system. Any results can be recorded and reflected directly.
2. Both the coach avatar and patient's avatar can be seen on the screen.
3. The speed of activity can be modified, the height of coach avatar can be modified, even the coach avatar can be modified into a cartoon character to provide the maximum convenience and fun for patients.

In our system, we choose to use Microsoft Kinect for motion sensing due to its low cost and relative high accuracy.

1.2.2 Microsoft Kinect

Microsoft Kinect was first released in 2010 as an addition to the Xbox 360 game console. It is equipped with an RGB camera, an infrared emitter, a depth sensor, and a microphone array. With the official Microsoft Software Development Kit (SDK) or third party toolkits, the 3D positions of skeleton joints can be obtained in streams of skeletal frames in realtime.

Kinect does not require any marker to track the user's skeletal joints. For each tracked user, there are up to 20 joints recorded with 3-dimensional position data, including head, shoulder center, left/right shoulder, left/right elbow, left/right wrist, left/right hand, spine, hip center, left/right hip, left/right knee, left/right ankle, left/right foot as shown in Figure 1.

The Kinect depth camera consists of an infrared laser project combined with a monochrome CMOS sensor, which captures video data in 3D (Figure 2.) under any ambient light conditions [6, 7]. The sensing range of the depth sensor is adjustable, and Kinect software is capable of automatically calibrating the sensor based on gameplay and the player's physical environment, accommodating for the presence of future or other obstacles [8].

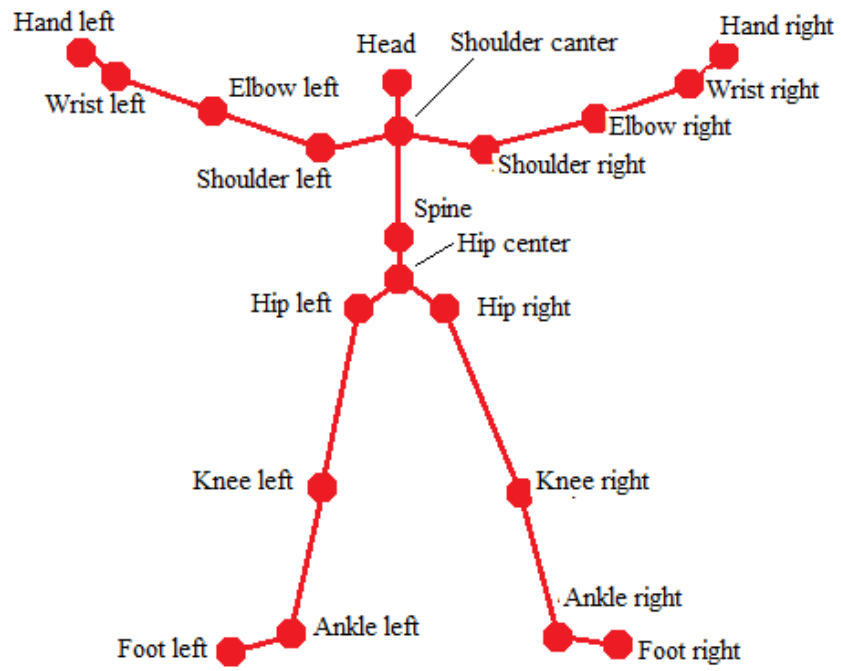


Figure 1. Microsoft Kinect skeleton joint-positions.

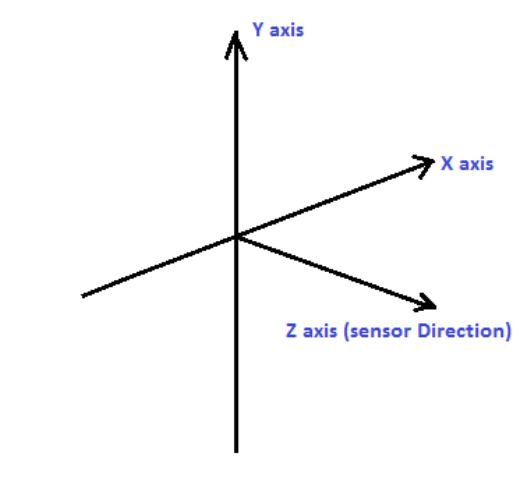


Figure 2. Microsoft Kinect 3D reference system.

1.2.3 Justification of the feasibility study on Kinect

In this thesis research, we studied the feasibility of using Kinect to evaluate the quality of three rehabilitation exercises, namely, Can-Turn, Bowling and Hip-Abduction. As shown in section 1.4.1, several studies have been done to validate the accuracy of the Kinect sensor for motion tracking. However, such studies mostly used static poses or movement, in this case, the function of the Kinect is not fully used. The three exercises we have chosen involve the movement in both frontal plane and the sagittal plane, as well as subtle rotation movements. Furthermore, unlike other studies, which focus on the absolute angle measurement and joint position comparison with a reference motion capturing system, we aim to establish the feasibility of using Kinect to assess the quality of an exercise based on predefined correctness rules. As such, consistency of Kinect motion measurement is more important than the absolute values, i.e. Systematic errors in measurement would not prevent the use of Kinect for correctness assessment if such errors are properly compensated. Finally, our study also aims to establish the boundary of the Kinect's capability. For example, we will show that the subtle rotation movement in can-turn cannot be properly assessed with Kinect.

1.3 Gesture and Human Activity Recognition

Gesture and activity recognition are the most basic foundations for human motion tracking. The gesture generally refers to the use of one or two hands, or feet and possibly body poses, to show some specific meaning, such as 'Okay' and 'Rock & Roll'. An

activity typically consists of a sequence of full body movements that the person performs, such as running, jumping and opening door, etc.

The ways to deal with human movement tracking can be generally defined into two classes: (1) template based and (2) rule based. In the template based, the succession of movements for a gesture or an activity is initially recorded, which is then utilized as a model to be contrasted and the watched gesture or activity either directly, or is utilized to train a model for the gesture, and the prepared model is then used to arrange the observed gesture or activity. The methods utilized to train the model vary significantly, from simple ones such as obtaining average joint angles at a set of feature points [9], to particle filters [10], to finite state machines [11], and to sophisticated statistical methods such as hidden Markov models [12], and neural networks [13]. The main advantage of the template-based approach is that either no model is required, or the model parameters can be fitted consequently utilizing exemplar-model. But, the feedback given by the template based approach regularly contains restricted information, for example, just downright process data in regards to the gesture or activity observed, which doesn't match the goal of rehabilitation exercise.

For the rule-based approach, it doesn't require specific exemplars and the downright-trained models. Instead, a gesture or an activity is defined and created based on a set of dynamic rules, which is the key of the activity. Using this kind of approach has several advantages over template-based approach:

- 1) It doesn't require large amount of computation for rule based approach doesn't require every single detail matching. Thus, it is suitable for realtime

motion evaluation, which is fundamental for rehabilitation exercise monitoring.

- 2) The rules used in the rule-based approach are independent of each individual's form and weight. Hence, this approach diminishes the intricate and computational expense, which makes the rule-based approach more attractive for rehabilitation exercise tracking.
- 3) It can provide realtime feedback with much more special instruction regarding how the motion digresses from the predesigned gesture or activity. This is critical for rehabilitation exercise tracking. For example, it is valuable to inform a patient when s/he is doing bowling and the bowling arm is bending to the sagittal plane, instead of simply telling the patient that s/he is doing incorrect.

Granted that this kind of approach is more suitable in rehabilitation exercise than template-based approach, it still have few limitations:

1. Rules have to be defined very carefully by experts and expressed in an implementable form. For every rule can map to general issue but is not suitable for every issue, whose details will be different. For example a rule is suitable for male but might not suit for female, it needs to be modified to match female's issue. This would incur additional financial cost to a human motion tracking system.

2. For some complicate gesture or activities, it may require a very precise define. But, fortunately, general rehabilitation exercises are not complicated and easy to design.

1.4 Related Work

1.4.1 Validation of Kinect for Exercise Monitoring

In [14], a passive marker-based reference system called iotracker was used to evaluate the accuracy of the Kinect sensor. In their experiment, only two values were compared, the vertical distance between right hand and right shoulder in reaching motion, and the foot position. The results for both systems have a few centimeters different which are very close. And the difference was caused by the different joint definition in two systems.

In [15], the accuracy of the Kinect measurement of several joint angles was compared by the marker-based multicamera system called Vicon. This experiment involved the movement of knee, hip and shoulder separately within anatomical planes. These exercises discovered that mean error in the joint angles as measured by Kinect ranged between 5 to 13 degrees.

In [16], a marker-based system called Vicon was used as a reference system. This experiment calculated the angles between the specific joint (shoulder, elbow, hip, and knee) and plane (frontal plane and sagittal plane). During the motion analyze, they found

the maximum angle range between Kinect sensor and Vicon system are 11 degrees. The discrepancy was likely caused by the inaccurate estimation of joint center by Kinect.

1.4.2 Rehabilitation Exercise Monitoring

MotionMA [17] is a system designed to provide feedbacks to the user regarding the quality of the exercise. This system is closely related to our project. In this approach, a model is derived from the recorded motion data of a demonstration by an expert. The interface has its own function to judge the user's motion. However, the system can only capture the violations of static poses.

Sun et al. [18] also provide a system to facilitate in-home exercise assessment. The procedure is rather similar to that of MotionMA. The specific statistical algorithms are used to compare the motion difference and the assessment can be done off-line instead of realtime. But this system's initial results are limited to what can be performed within three categories: excellent, good and bad. So in our system we could provide more vivid feedback to the users.

In [19] and [20], the rules for gait retraining are expressed in terms of the trunk flexion angle, trunk lean angle, and the distance that a set of joints for postural control traverse. In [21], the knee angle and the ankle are used to assess the quality of sit-to-stand and squat, and the shoulder angle is used to access the shoulder abduction. In [22], the rules are expressed in terms of the knee angle in the robotic system for knee rehabilitation.

CHAPTER II

FEASIBILITY STUDY

To evaluate the feasibility of adopting Kinect sensor for rehabilitation exercises monitoring, we compared the motion data acquired from Kinect to those obtained simultaneously by an expensive eight-camera marker-based motion capture system (MBS). The results from MBS were utilized to establish the ground truth for the study. The data acquisition software for Kinect was programmed in C++ programming language using Microsoft Kinect Software Development Kit version 1.5.

We experimented a total of three common rehabilitation exercises: can-turn, bowling and hip-abduction. In the following, we first describe the overview and the rules, and then we provide the feasibility results and analysis for each of the three exercises.

In addition, for each of the exercises, the correct movements are defined in terms of three sets of rules: (1) dynamic rules, (2) static rules and (3) invariance rules, as explained in the following:

- **Dynamic Rules:** Each rule consists of a number of monotonic segments [23] of a key body segments. A monotonic segment is characterized as a portion of movement in which the key measurements for the movement are either non-expanding or non-diminishing. For instance, if a joint angle is the key metric for some movement, during a monotonic segment, the angle may diminish consistently from some most maximum value to some minimum value. Hence, there are two elements in every rule: (1) each monotonic segment requires a range of value, for example, we expect that for the hip abduction exercise the hip angle should vary within the boundary of 0 to 50 degrees; (2) when the segments moves in the range of the boundary, the value must change monotonically (i.e., either increasing or decreasing), and we can also set up an error bound for preventing rapid rise or slow decrease.
- **Static rules:** Some exercises only include stationary poses. It is also possible for some body fragments to keep stable at the predesigned position while other parts are moving. In this situation, static rules are required. In general, a guideline for a static pose can be expressed in terms of the desired angle for a specific joint, or the position of a body section regarding the frontal, sagittal plane. It is also possible to depict the relationship between different joints or distance between different joints.
- **Invariance rules:** An invariance rule defines the requirement that must be satisfied during each entire cycle of the exercise. The rule is typically defined in terms of the relative angle between the moving body segment and the frontal plane, sagittal plane.

The frontal plane and the sagittal are necessary in the determination of body movements, such as the angle of relative distance. In this case, no matter what exercise is used to do the feasibility study, the two basic planes are determined in the first step.

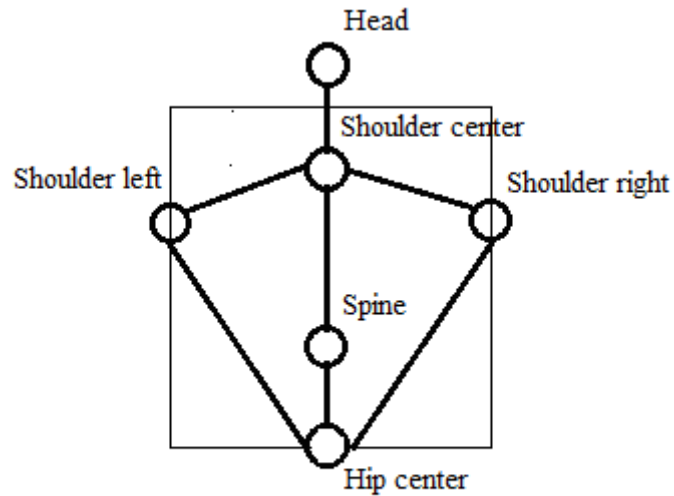


Figure 3. Frontal plane and relative joints.

As shown in Figure 3, the frontal plane is determined by the following three joints, the left shoulder, the right shoulder and the hip center.

A vector can be determined by two points, so the vector of Hip-Center to Shoulder-Left is established by left shoulder to hip center, the vector of Hip-Center to Shoulder-Right is established by right shoulder to hip center.

Once the frontal plane is determined, we can determine the sagittal plane, as show in figure 4, the sagittal plane can be defined by using vector cross and other two joints: the hip center and the shoulder center.

So the sagittal plane can be determined by using vector cross and vector which is established by shoulder center to hip center.

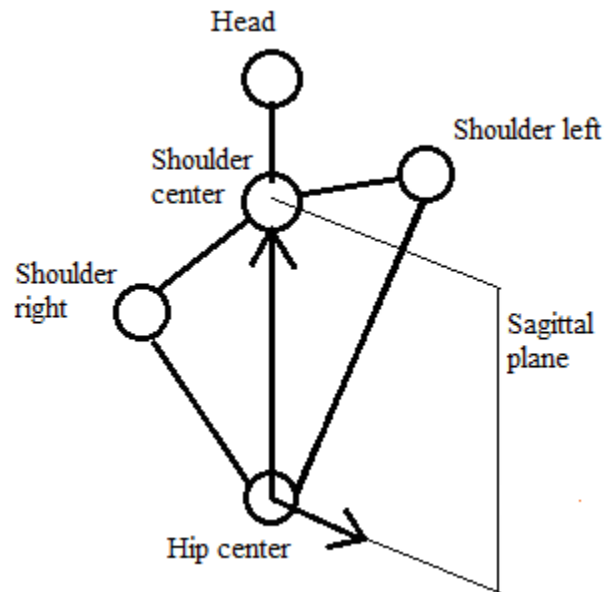


Figure 4. Sagittal plane and relative joints.

2.1 Feasibility Study for Can-Turn

The Can-Turn exercise is regularly done to fortify the supraspinatus muscle, particularly after rotator sleeve damage. In the Can-Turn movement, the patient is required to move his or her arm straight forward such that it is in parallel with the transverse plane and stay in the stance while performing the Can-Turn exercise. In this exercise, we assume that the right arm is used as the Can-Turn arm.

We can divide this coherent action into several detailed steps:

Step 1, face to Kinect camera.

Step 2, make the body in the T-pose, which make whole body stand straight against ground and both arms are stretched on both sides of the body, looks like the initial “T”.

Step 3, move down the can-turn arm firstly, and then extend Can-turn (right) arm forward and make sure the angle between right arm and torso is 90 degrees.

Step 4, right arm keep straight, and make the action of dumping can to the sagittal plane for three times.

Step 5, complete the action, make hands naturally hang on either side of the body, stand straight against the ground.

But, the current version of Kinect cannot recognize the movement of rotation which is facing to the camera. In that case Kinect is impossible to track the rotation movement. What can be evaluated by Kinect are the arm positions.

The following rules are defined for Can-Turn exercise:

- Static rule: The Can-Turn arm extends forward during the process of exercise.

The angle between the can-turn arm and the torso should keep changing during the movement proceed.

- Invariance rule: The can-turn activity should insure that can-turn arm must keep straight. The main arm and forearm should keep in the degree of 180.

2.1.1 Movement of can-turn arm

In this experiment, the can-turn arm and the torso can be presented by the vector of can-turn arm (right wrist to right shoulder) and the vector from hip center to shoulder center. In this case, the static rule angle can be calculated by those two vectors. If patient could follow the rule strictly, in this experiment, we can make a prediction that after the can-turn exercise has begun, the angle should stay at 90 degrees.

This is one of the necessary conditions in can-turn experiment, but this could not be the sufficient condition.

To avoid the joint of elbow retain during the experiment and cause noise in the experiment result. We choose wrist to replace elbow and build up the can-turn arm with right shoulder.

In this condition, after we determine the movement and the related vectors, the angle between the right arm and torso is shown in the figure below:

Figure 5 shows the movement of the can-turn arm. The curve represents the angle between the right arm and the frontal plane and reflects the static rule within 14 seconds. X axis represents the time and the Y axis represents the angle.

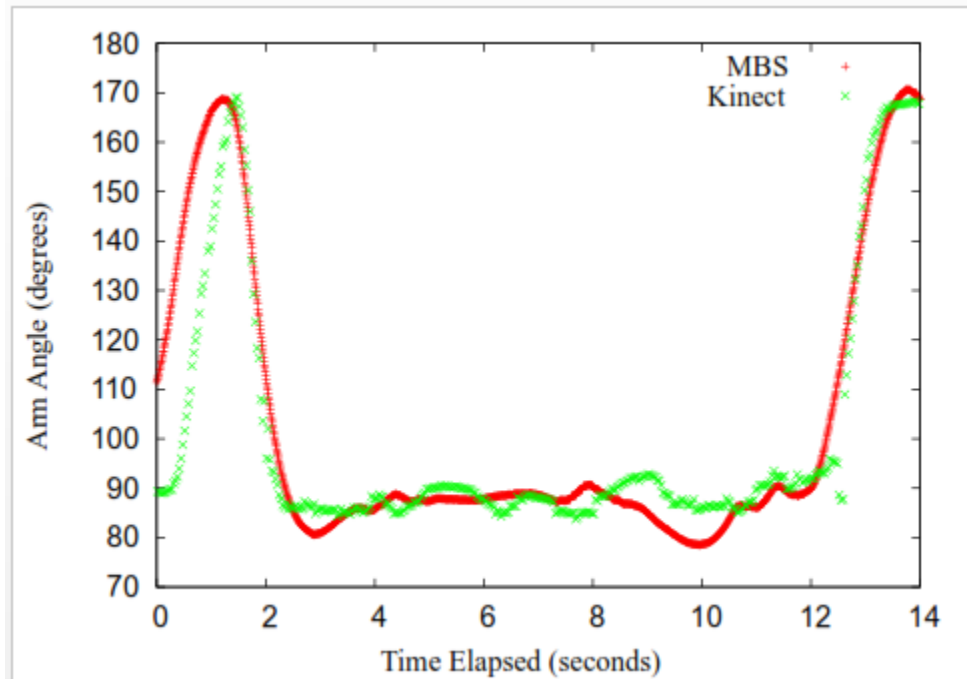


Figure 5. Arm angle in the can-turn activity.

From the Figure 5, we can easily figure out the movement of right arm. According to the rules, the arm is carried out the movement in four steps:

1. To reach the position of can-turn, the can-turn arm firstly put the arm down to the side of the body from the T-pose. This processing have the goal to make arms hang to each sides of the body and keep the irrelevant left arm in a position that cannot effects the balance of body. From the figure, the corresponding data is 0-1.5 second period till the angle increase to peak value.
2. Other irrelevant joint keep stable, extend the right arm forward to the can-turn position. In the figure, we can find the corresponding point: form the timeline of 1.5 to the timeline around 2.5. The value of degrees decreases from 180 to 90 again. But the position of arm is not in the initial position.

3. Once right arm move in the can-turn position, experiment action starts. This process is presented in the timeline between 2.5 to 10. During this period, the right arm keeps pointing forward to the Kinect camera and repeats the motion of the can-turn for three times.
4. At the end, the arm is moved back to the side of the torso.

For both motion capture systems (Kinect and MBS), once the movement of can-turn begin, the angles keep in the range of 90 degrees and have little floating, hover around 10 degrees. In this motion, both systems have no significant difference in the experimental value. For both curves, not only the peak value or the stable phase, the difference doesn't exceed beyond 5 degrees.

2.1.2 The angle of the can-turn elbow

The invariance rule regarding the elbow angle was defined by two vectors of the right arm. One vector from right shoulder to the right elbow (main arm), one from right elbow to right wrist (forearm). According to the invariance rule, the angle between those two vectors should keep in the degrees of 180.

Figure 6 shows the angle of the can-turn elbow. The curve represents the angle between the main arm and the forearm and reflects the invariance rule within 14 seconds. X axis represents the time and the Y axis represents the angle.

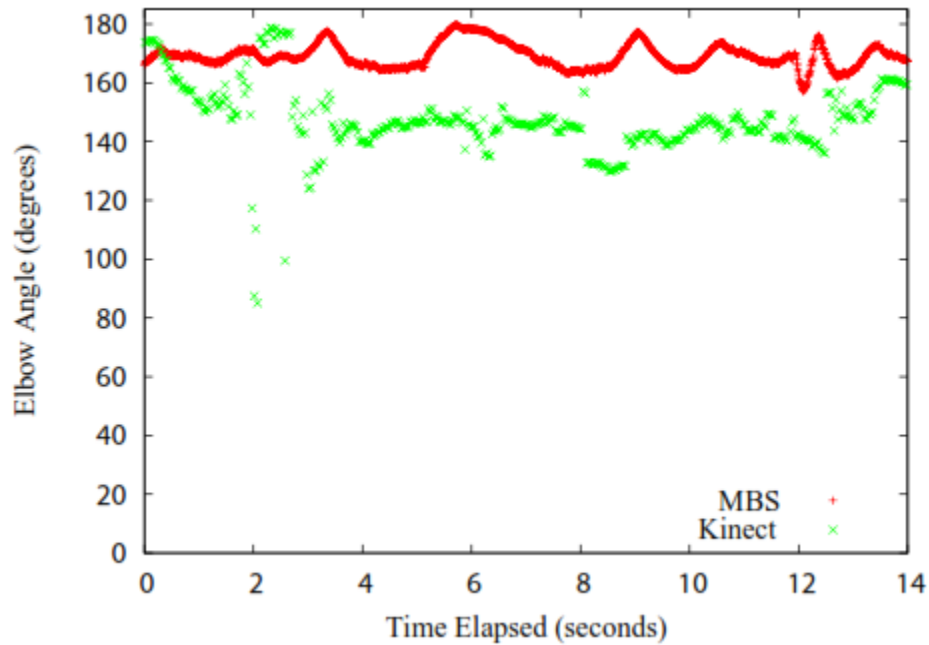


Figure 6. Elbow angle between main arm and forearm.

The elbow angles which are presented by both systems are shown in the Figure 6. For the curve of MBS, we can easily figure out that the elbow angle was maintained at the degree of 170, floating in 10 degrees during the whole process. Because of the hardware advantage, each single joint can be identified by the eight-camera marker-based motion capture system including right shoulder, right elbow and right wrist. Plus, in the monitoring of MBS, there is no occluded joint for eight cameras can capture the action in 360 degrees.

But for the curve of Kinect, apparently, we cannot use this system to assess this rule unless we setup a huge error bound. Because when the can-turn motion is doing, according to the motion step 1, the right arm is facing directly to the Kinect camera and the elbow joint is partially occluded when the arm is pointing forward to the Kinect. In

the Kinect curve, there is lots of noise apparent in the timeline of 2 to 3. The range of fluctuate is up to 45 degrees.

2.2 Feasibility Study for Bowling

In this exercise, right arm is the Bowling arm.

The Bowling exercise is designed for a patient to practice straight plane shoulder flexion. It can be used in individuals post stroke who need to learn to isolate shoulder flexion from elbow flexion, as this exercise requires shoulder flexion with elbow extension. It can also be used to work on progressively greater amounts of anti-gravity shoulder flexion.

As the steps shown in can-turn exercise, we can also divide the coherent Bowling process into several steps:

Step 1, face to the Kinect camera.

Step 2, stand straight against the ground and use the T-pose as the initial pose.

Step 3, swing the right arm backward first and then moves forward until the right arm is pointing straight forward, this process exercise twice.

Step 4, complete the action, moving back to initial pose.

The following correctness rules are used for a typical patient:

- **Dynamic rule:** In this experiment, we can set up the frontal plane as reference vector, all the following angles should be based on the horizontal plane. Firstly, the bowling arm swing backward to the degree of -50 with respect to the reference plane. Each motion of bowling starts at the degree of -50 located at the back of the torso. Then swing the right arm forward until the arm is pointing forward about 90 degrees with the frontal plane. So in this experiment, the boundary value should keep between -50 and 90 with respect to the reference plane.
- **Invariance rule:** Sagittal plane is the reference vector. The bowling arm should keep in the sagittal plane. In this case, the angle between right arm and the sagittal plane should be 0 degree.

2.2.1 Movement of the bowling arm

Firstly we should determine the experiment vectors. As the instructions about the dynamic rules, the reference plane is the frontal plane (which is mentioned at the beginning of the chapter II). Plus we have to determine the right arm vector which is represented by the joint of right shoulder and right elbow. By using the reference plane and right arm vector , we can calculate the angle of the bowling arm.

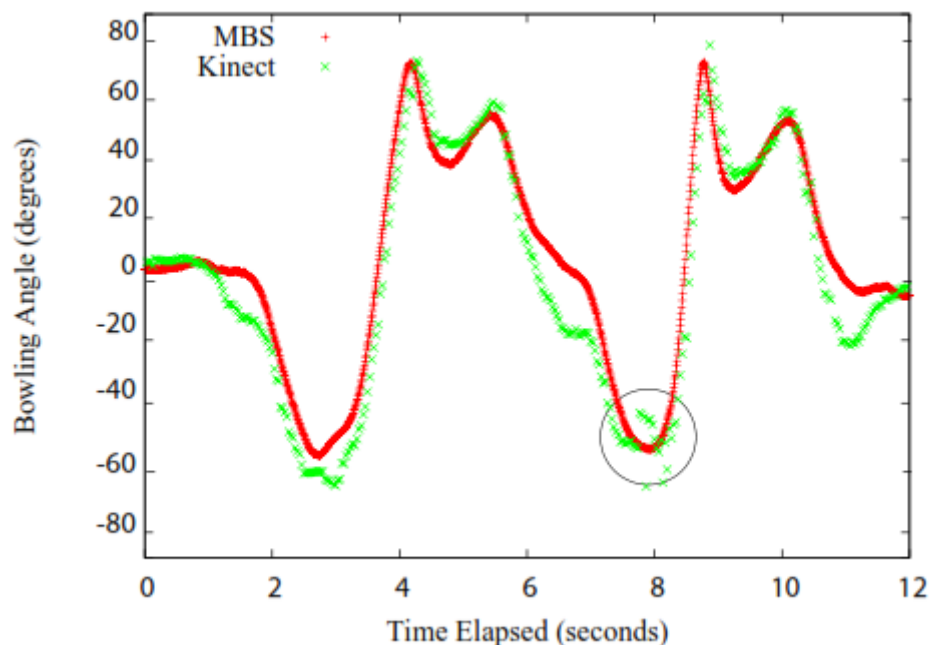


Figure 7. Bowling angle with the frontal plane reference.

Figure 7 shows the measurement result for the bowling angle between the right arm and the frontal plane within 12 seconds (with a highlighted noise). The curve reflects the dynamic rule. From the figure, we can see the trace of the curve. Bowling arm motion repeated twice from the initial pose and back to initial pose. According to the dynamic rule represent, we can also separate the whole curve into three steps.

1. The arm moves back from the initial position during the timeline of 0 to 2.5. This motion is used to give bowling arm a potential power for swing forward. So a degree of backward is necessary.
2. Then the bowling arm swing forward to the front of the trunk within 2 seconds (2.5 to 4 in the timeline) and then swing back to the position again where can provide the potential power (4 to 8 in the timeline). After that, start the second iteration (8 to 9).

3. Finish the motion and put the right arm back to the initial position.

In these three steps, the curve measured by Kinect and the MBS curve don't have huge difference. The biggest discrepancy occurred when arm move back to the side of the trunk (on the timeline of 11, about 10 degrees), but this point doesn't include in the dynamic rule. In this case, we don't have negative impact to the experiment. We can also notice that there were a set of noise during the second backward period which is highlighted (on the timeline of 8). For those two issues, we can set up the error bound within 5 degrees.

Even though the motion capture process is under the supervisory of the expert and visually indicated that the motion was doing correct, we can still find that there are two peaks on each iteration when the right arm is swinging forward. To accommodate this instability, a very large error bound need to be used. Plus, when the right arm swinging forward the peak angle which we expect the degrees of 90 was not even close to this value in both motion capture systems. For this problem, we can set up a 75 degrees as the maximum boundary value instead of 90 degrees. For the minimum boundary value, according to the figure, -50 is an ideal value.

2.2.2 Bowling arm motion within sagittal plane

As we mentioned in the invariance rule, the right arm should move within the sagittal plane. The vector of right arm should be used in this section as well. For the

reference vector, a shoulder line can be chosen which is built up by the right shoulder and the non-bowling left shoulder. As we predicted, when the bowling motion begin the angle between reference vector and bowling arm should keep in the degrees of 90. In this case, we can get the necessary condition of the invariance rule.

Figure 8 shows the measurement result of the shoulder angle between the shoulder line and the right arm. The curve reflects the invariance rule.

At the beginning and the end of the motion, the angle for both curves are close to 180 degrees, that is because of the initial T-pose: the arms are in the position of sideways of the body straightly, so the angle between shoulder line and the bowling arm represent the angle of 180 degrees. During the bowling motion, the angle decreased to 120 and floating about 10 degrees. The angle which measured by Kinect and MBS are different from what we expect (90 degrees). So in actual invariance rule, we should set up a more reasonable value of 120 degrees instead of 90 degrees of the shoulder angle. In other word, the bowling arm should keep a degree of 30 against the sagittal plane. Plus, as shown in the figure, both curve have large fluctuations during the bowling action, in this case, the error bound should be set up in a large range of 30.

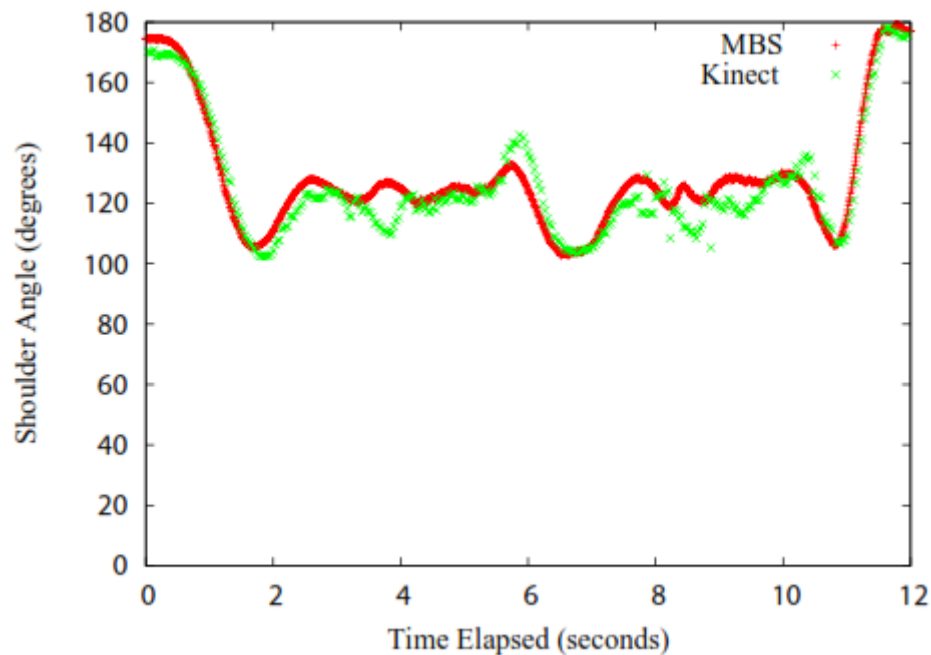


Figure 8. The shoulder angle of the bowling exercise.

2.3 Feasibility Study for Hip-Abduction

For the Hip-Abduction exercise, we use right leg as the abduction leg, and the primary steps include the following:

Step 1, face to the Kinect camera.

Step 2, use the “T” pose as the initial pose.

Step 3, make the abducting leg moves from the initial position respect to the stable leg to a specific degree, then back to initial position. This process exercise three times.

Step 4, once abduction activity finish, whole body go back to “T” pose.

Once the steps are decided, the primaty rules can also be determined:

- Dynamic rule: Firstly we should set up the initial angle which depends on the angle between left leg and right leg at the very beginning. We expect that the initial angle between two legs is 0. Then the abducting leg moves from 0 degree to beyond 50 degrees. Plus, when right leg move back, the angle go back to the initial degree. In this case, we can set up the boundary between 0 and 50.
- Invariance rule: During the hip abduction process, the right leg and left leg should keep straight all the time at the joint of the knee. Plus the abducting leg must moves within the frontal plane.

2.3.1 Movement of the abducting leg

The angle between two legs is determined by the vector of left hip to left knee and the vector of right hip to right knee. By using dot product, we can calculate the angle.

From the Figure 9, we can see that there were 3 hip abducting iterations occurred in the process. At the beginning, the curve of the Kinect starts at the degrees of 6 and start to increase at the timeline of 1. After 1 second increasing, the right leg shift up to the first peak value of 47 degrees. Then the right leg moves back and the minimum value is smaller than the initial angle, which is decrease to 0 degree at the time of 3.5. On the second and third time of hip abduction, the angle between two legs which are measured

by Kinect are 58 and 57 degrees, and the minimum value between these two iterations is 0.

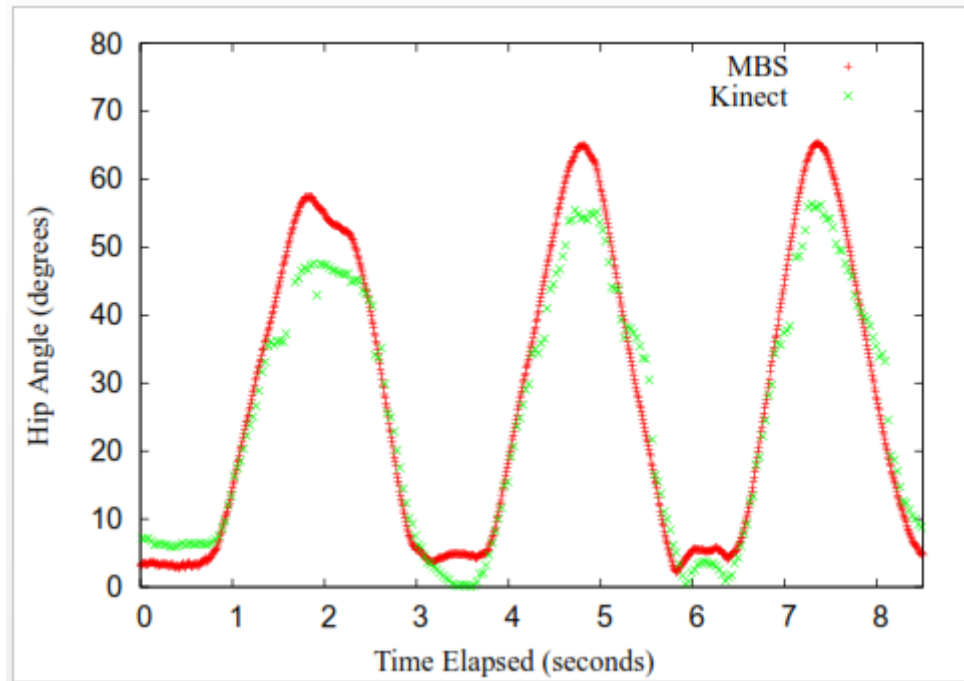


Figure 9. Hip angle for 3 iterations of hip abduction.

For MBS, as we can see from the curve, at the beginning of the motion MBS measured the initial value is 3 degrees. The value is much more larger than Kinect data (59 vs. 48, 65 vs. 58 and 66 vs. 59) for the maximum angle. On the other hand, for those two minimum MBS values are significantly larger than the values of Kinect (5 vs. 0 and 3 vs. 0)

Hence, at the very beginning Kinect has a value of 6, there are two monotonic segments for each iteration, with the boundary values of 6 degree and 58 degree. The range for a hip abduction motion is about 52 degrees with the error bound for maximum value of 9 degrees or larger and with the error bound for minimum value of 5 degrees.

2.3.2 The positions of two legs

To access the invariance rule, the bend of two legs are need to be calculated. We used the vectors of ankle to knee and knee to hip for each side.

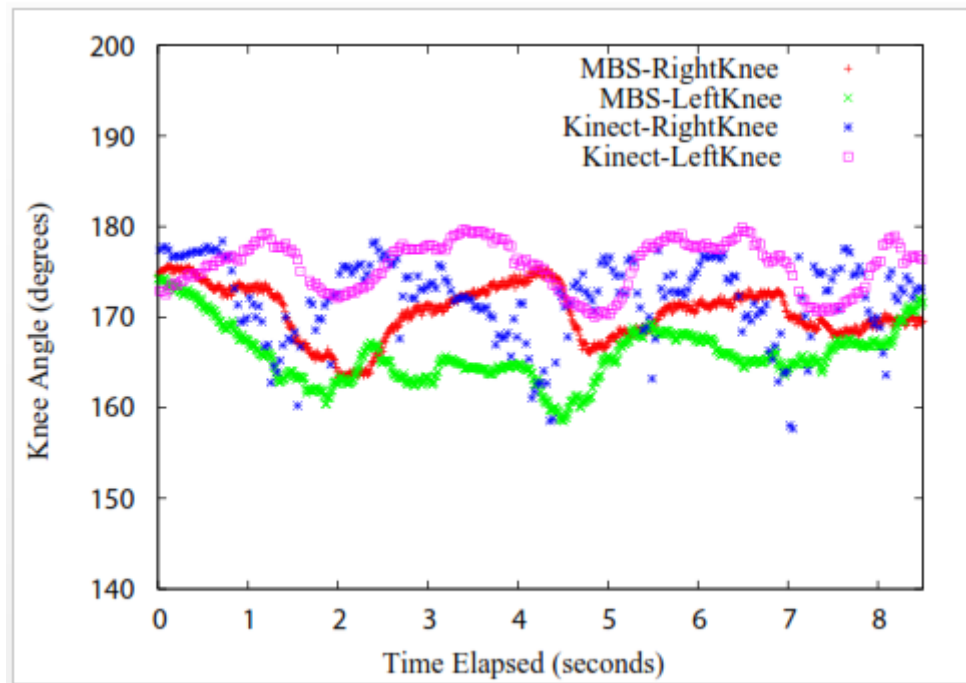


Figure 10. Both knee angles represent by Kinect and MBS.

Figure 10 summarizes the results of the knee angles for both legs using Kinect and MBS in 8 seconds, which reflects the invariance rule.

As we can see, for both legs and for both motion capture systems, all those four curves have varying degrees of float. The range between the maximum value and the minimum value is 20 degrees. Based on the invariance rule, the angle should keep in the degrees of 180. But in this case, the error bound should be based on the curve of the

figure 10. So we should set up a large range of error bound about 20 degrees. Hence, in the experiment of hip abduction, Kinect could perform as well as MBS system.

For the other invariance rule: the abducting leg should keep in the frontal plane.

We can calculate the angle between the frontal plane and the vector of the right leg.

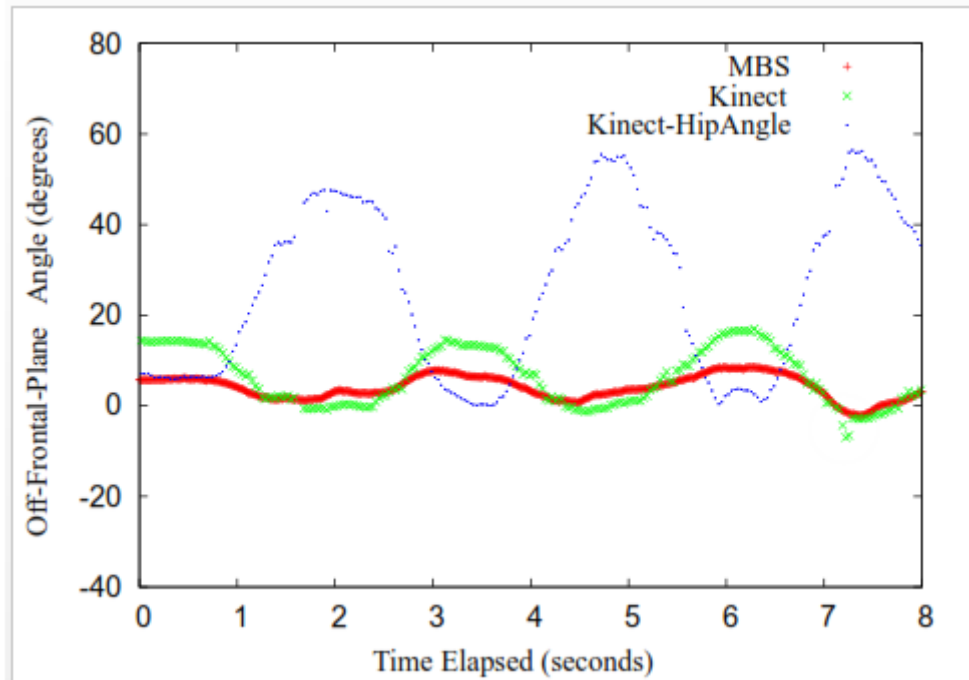


Figure 11. The angle between the right leg and the frontal plane.

Figure 11 shows the angle between the right leg and the frontal plane.

The MBS measures a very stable curve, the range of the offset angle keeps in the range of 0 to 5.

In order to facilitate the understanding to the Figure 11, we added the curve of Kinect-hip-angle in the Figure 11 for the comparison in the timeline. As the curve shows, at the initial position, the angle of the offset from frontal plane is 15 degrees, over time

the right leg shift up from initial position and the hip angle is increasing, meanwhile the offset angle is getting decreased to the angle of 0. It is interesting we can see from the curves that once hip angle rises, offset angle falls. The range of the offset angle is significantly floats between 0 and 15 degrees.

To accommodate the large range during the abduction motion, we can use the 0 degree as the initial angle and it is necessary to use a large error bound of 15 degrees or larger.

2.4 Conclusion

In this section, we present a feasibility study of using Microsoft Kinect to assess the quality of the tracking sensor performance using three common rehabilitation exercise, namely, can-turn, bowling and hip abduction.

Instead of using the template-based approach, in this experiment, we choose the rule-based approach to evaluate the feasibility of using Kinect for rehabilitation exercise monitoring with automated patient feedback.

Based on the rule, we can easily build up the steps for each exercise and set up the dynamic, invariance and static rule. The definition of the correctness rule provides a concrete context in determining if the Kinect is capturing the motion in a correct way and if the Kinect can provide a set of correct value. In this case, we can find a correct rule.

An 8-angle-camera motion capture system was used to evaluate the experiment value of Kinect. From the comparison, we could decide on the error bound that we have

to set up for each exercise. The correctness rule and appropriate error bound values are critical to using Kinect effectively. This would greatly facilitate in-home rehabilitation exercise with improved effectiveness using a low-cost Kinect sensor motion capture system.

Meanwhile, for the next section, correctness rules and the error bound are used in the tutor system in chapter III to assess the quality of rehabilitation exercises and give feedback to patients in realtime.

CHAPTER III

SYSTEM DESIGN AND IMPLEMENTATION

As can be seen from the experiment results presented in chapter II, a Kinect-based system can be used to evaluate the quality of rehabilitation exercises. In this chapter, we describe the design and implementation of a rehabilitation exercise monitoring and guidance system based on Kinect. The system demonstrates the correct way of doing an exercise via a 3D avatar on one side of the screen. On the other side of the screen, another avatar is shown that reflects the actual patient's activity with the relevant realtime feedback.

3.1 Primary Objectives of the System

Our rehabilitation tracking system is designed to meet the following patient's and clinic's requirements:

1. Provide an intuitive, simple interface on the screen for each exercise.

2. In the interface, there should be a view for patient. This view includes one avatar demonstrating the correct way of doing exercise (referred to as the coach) and another avatar reflecting the patient's movement in realtime (referred to as the patient).
3. The correctness rules for each exercise should be expressed in an easy to understand way, for example, the boundaries could be indicated in terms of visual targets on the screen.
4. Those targets can provide feedback to the patient regarding the quality and quantity of the exercise repetitions.
5. We should not only display feedback, we should also record joints' data. In the feasibility section, we know that Kinect have its own three-dimensional data. These data should be saved in a file so that the patient and clinician can review them.
6. Since the system is implemented for a 3-dimensional environment. Two 360-degree view cameras (one for coach and one for patient) should be used in the system with the function of zoom in and zoom out to show the details of each exercise.
7. The system must not display images of the demonstrator or the patient, to conform to the privacy policy for human trial study and also to maximize the comfort level of the patients.

3.2 Overview of the System

This system is implemented as a Unity project with the ZigFu plugin [24]. The plugin provides a simplified interface to access the Kinect Application Programming Interfaces (APIs) within the Unity framework. The C# programming language is used to implement the system.

To satisfy Objective 1, we decide to use a game engine called Unity 3D. By using this game development framework, both the guidance-avatar and the patient-avatar can display on the screen of the system, as shown in Figure 12.

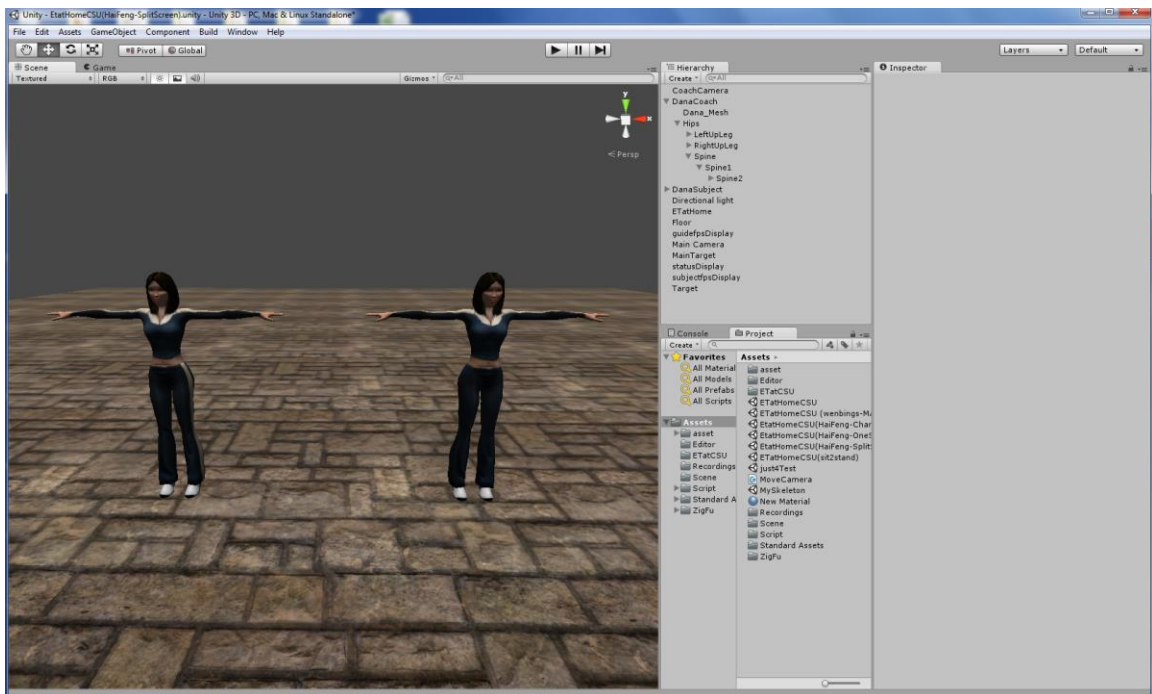


Figure 12. The interface of our system in Unity 3D.

Figure 12 shows the interface of the Unity 3D main editor window, which has 6 major panels including: (1) Project Browser: You can access and manage the assets that

belong to your project. (2) Hierarchy: This panel contains every Object in the current scene. (3) Toolbar: Toolbar provides basic controls, for example, drag, select, zoom in, zoom out, play and pause. (4) Inspector: This panel displays detailed information about current GameObject and you can modify the functionality of the GameObject in here. (5) Scene View: In this view you can modify the whole environments of GameObjects. In our system, we can select and modify the coach, the patient and cameras. (6) Game View: This view representative your design.

As we can see from the game engine interface, in the view of Scene there are two 3D avatars. The left one is the coach avatar, and the other one is patient avatar. The coach avatar's role is to demonstrate the correct way of doing an exercise. This avatar is placed on the left side of the scene view and the game view. The movement of coach avatar is controlled by a script using the motion data collected. The patient avatar is located on the right side of the scene. This avatar mirrors the patient's action in realtime. For the convenience of clinician and patients, the best way to test the standard action is via the 360-degree view. This design is used to satisfy both objective 2 and objective 7.

To satisfy Objective 3, we didn't simply put some written instructions on the interface to make patients follow the written files. The animation target is chosen to replace the old fashioned instructions. In this system, we use target spheres to indicate the boundaries of an exercise, as defined in the correctness rules, as shown in Figure 13. In order to achieve the correct action, the patient has to follow the exercise rule and reach the target(s).

Additionally, another function of the target is to show the repetition count to satisfy objective 4. Once the designated joint and target sphere have a collision, the digital counter on the sphere will be incremented by one.

For Objective 5, the system records the patient's motion data in "comma separated values" (csv) files, which are readable with Microsoft Excel or a text editor. During the experiment, once we open the recording trigger, all the joints position will be recorded in a csv document, until the end of the recording. An example list of csv files are shown in Figure 14.



Figure 13. The frontal view of the target with repetition count.















 1396109177.csv	3/29/2014 12:06 PM	Microsoft Office E...	1,397 KB
 1396109401.csv	3/29/2014 12:10 PM	Microsoft Office E...	1,501 KB
 1396109434.csv	3/29/2014 12:10 PM	Microsoft Office E...	76 KB
 1396109437.csv	3/29/2014 12:10 PM	Microsoft Office E...	50 KB
 1396109440.csv	3/29/2014 12:10 PM	Microsoft Office E...	52 KB
 1396109442.csv	3/29/2014 12:10 PM	Microsoft Office E...	122 KB
 1396109445.csv	3/29/2014 12:11 PM	Microsoft Office E...	1,236 KB
 1396109473.csv	3/29/2014 12:11 PM	Microsoft Office E...	404 KB
 1396109484.csv	3/29/2014 12:11 PM	Microsoft Office E...	53 KB
 1399314027.csv	5/5/2014 2:20 PM	Microsoft Office E...	4 KB
 1399319360.csv	5/5/2014 3:49 PM	Microsoft Office E...	20 KB
 1399319396.csv	5/5/2014 3:50 PM	Microsoft Office E...	135 KB
 1399319400.csv	5/5/2014 3:50 PM	Microsoft Office E...	52 KB
 1399319403.csv	5/5/2014 3:50 PM	Microsoft Office E...	67 KB

Figure 14. Snapshot of the log files.

As we can see in the Figure 14, all the experiment data will be recorded. Once the motion capture begins, the patient can use the right hand to touch his/her head to start or stop the recording.

In Figure 12, we can see that the scene view is displayed from the point of view of the main camera. To satisfy objective 6, we setup a new camera called the coach camera, as shown in Figure 15. The coach camera focuses on the coach avatar and the main camera centers at the patient avatar.

Each camera has its own function. The coach camera is used to allow the patient to have more ways of seeing all the details of the coach exercise in 360 degrees view. For patient camera, the camera provides greater convenience to patients and clinicians.

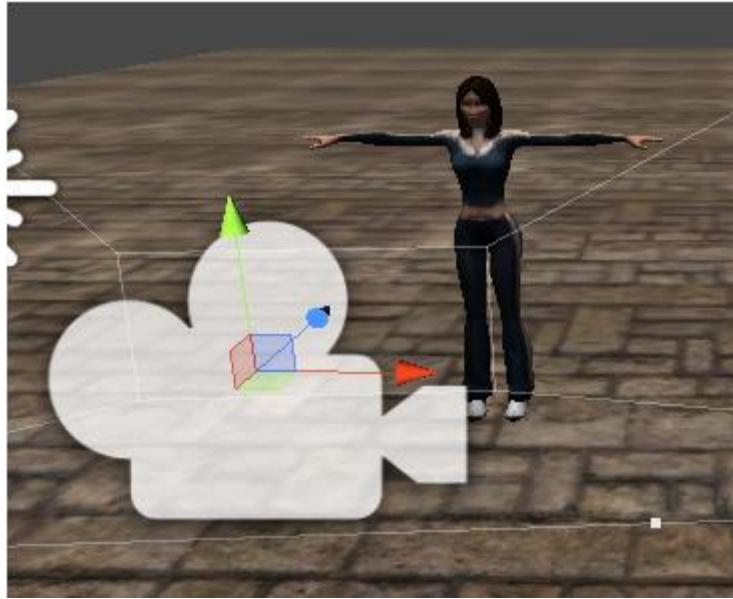


Figure 15. The coach camera.

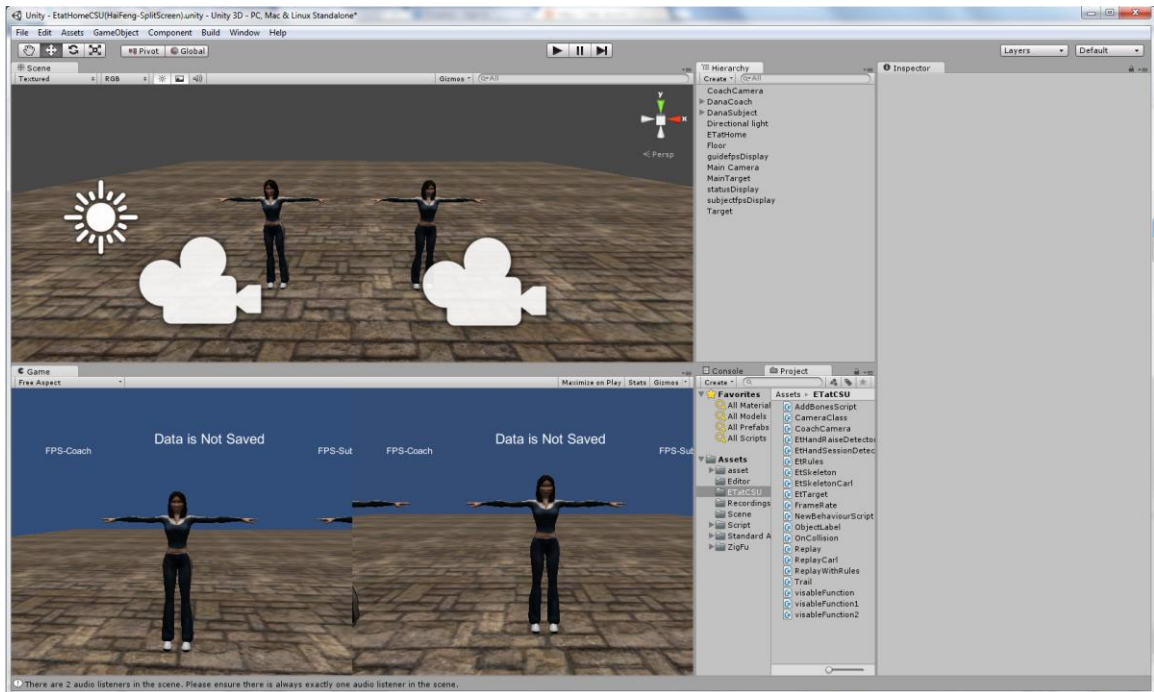


Figure 16. The entire scene after we satisfy all the requirements.

Figure 16 illustrates the basic environment for the monitoring and guidance system design. In this design scene, the primary components are two predesigned game avatars, rule-based targets, which are invisible in scene view and cameras for each avatar. Other components include the floor, the light and so on, which build up the whole scene with primary components. After the overview is designed, the correct rules for exercise should be the next task need to design.

3.3 Correctness Rules Design

Correctness Rules is used for the design of the rehabilitation exercise. According to the rule-based approach as we have discussed in Chapter II, the following are specified for each rehabilitation exercise:

- Key joints: For each movement, we need to determine the key joints first. All the rules are designed based on the key joints.
- Movement rule: this rule includes all the feasibility rules together: dynamic rule, static rule and invariance rule. In order to distinguish the feasibility study and system design. In this section:
 - a. We use Target rule to achieve the function of dynamic rule, the main role of the target rule is constraint the motion of the key joints to avoid the key joint move out of the boundary value during the rehabilitation exercise.
 - b. Relative angle rule in the guidance system is used to realize the specific angle of specific joints in exercise with an error bound.

- c. The Moving angle rule is for the purpose of set up the angle between the specific vector and the reference plane with an error bound as well.

These rules can be programmed in XML files and can be loaded in the precise exercise in realtime. In the following, we present the correctness rules for bowling and hip abduction.

3.3.1 Correctness rules for bowling

All the parameters used in the correctness rules are based on the feasibility study results.

- Target Rule:

```
<Target>  
  <AnchorJoint>"RightShoulder"</AnchorJoint>  
  <TargetJoint>"RightWrist"</TargetJoint>  
  <TargetAngleXY>75</TargetAngleXY>  
  <TargetAngleZ>50</TargetAngleZ>  
  <ShowTarget>2</ShowTarget>  
</Target>
```

Figure 17. Target Rule based on the feasibility study for the bowling exercise.

This rule (shown in Figure 17) specifies the target position for each key joint. First, we determine the key joints are right shoulder and right wrist. In this case, all the angles we can calculate are based on the vectors formed by those two joints. In this rule, the anchor joint is right shoulder and the target joint is right wrist, which means right wrist movement all based on the right shoulder.

According to the dynamic boundary of the bowling, we determined the boundary of the bowling arm angle is -50 to 75. In this case, the TargetAngleXY in this correctness rule means the angle point upward to the camera against the frontal plane. The TargetAngleZ was formed by the angle which pointing away from the camera against the frontal plane.

ShowTarget is the information that informs the system whether or not targets should be placed at the target places. The value of two means two target should be created and placed on the target position.

- RelativeAngle rule:

```
<RelativeAngle>  
  <CenterJoint>"RightElbow"</CenterJoint>  
  <UpstreamJoint>"RightShoulder"  
    </UpstreamJoint>  
  <DownstreamJoint>"RightWrist"  
    </DownstreamJoint>  
  <TargetAngle>180</TargetAngle>  
  <ErrorBound>10</ErrorBound>  
</RelativeAngle>
```

Figure 18. RelativeAngle Rule based on the feasibility study for the bowling exercise.

According to the feasibility study, this rule (Figure 18) is used to detect whether or not the bowling arm is bent. This rule is not mentioned in the Chapter II but in the system design we put this rule into correctness rules. For bowling, the bowling arm bend generally express that the angle between the forearm and mainarm is not 180 degrees.

As shown in Figure 18. CenterJoint and UpstreamJoint form the vector of right shoulder to right elbow, CenterJoint and DownstreamJoint form the vector of right elbow to right wrist. And the TargetAngle that should be formed between those two vectors. The ErrorBound is used to indicate the tolerated variance to the ideal target angle.

- MovingAngle Rule

```
<MovingAngle>  
  <AnchorJoint>"RightShoulder"</AnchorJoint>  
  <TargetJoint>"RightWrist"</TargetJoint>  
  <TargetAngleX>30</TargetAngleX>  
  <ErrorBound>10</ErrorBound>  
</MovingAngle>
```

Figure 19. MovingAngle Rule based on the feasibility study for the bowling exercise.

This rule represents the invariance rule of feasibility study. In Figure 19, the rule shows that the right arm must move within sagittal plane with an angle of 30 with a tolerated error of 10 degrees.

Figure 20 shows a partial visual display of the correct rules as we have defined previously. A correct rehabilitation bowling exercise is based on the target, relative angle and moving angle rules, which have two targets, the target positions and the invisible error bound.



Figure 20. The frontal view and sagittal view of the bowling targets.

3.3.2 Correctness rules for hip abduction

- Target Rules

```

<Target>
  <AnchorJoint>"RightHip"</AnchorJoint>
  <TargetJoint>"RightKnee"</TargetJoint>
  <TargetAngleX>50</TargetAngleX>
  <ShowTarget>1</ShowTarget>
</Target>

```

Figure 21. Target Rule based on feasibility study for Hip abduction.

According to Figure 21, the target is determined by right hip and right knee. The TargetAngleX used the feasibility dynamic rule value in Chapter II, which is the boundary value between the left leg and right leg. Plus, for this exercise, there is only one target position so the value of ShowTaget is 1.

- RelativeAngle Rule

```
<RelativeAngle>  
  <CenterJoint>"RightKnee"</CenterJoint>  
  <UpstreamJoint>"RightHip"  
    </UpstreamJoint>  
  <DownstreamJoint>"RightAnkle"  
    </DownstreamJoint>  
  <TargetAngle>180</TargetAngle>  
  <ErrorBound>20</ErrorBound>  
</RelativeAngle>
```

Figure 22. The RelativeAnlge Rule based on feasibility study for Hip abduction.

The relative rule in hip abduction indicates that the desirable angle should be formed between the vector of right knee to right hip and the vector of right ankle to right knee. The angle between the two vectors should be 180 degrees and according to the error bound we set in figure 10. We decided to use the value of 20 for relative angle error bound.

- MovingAnlge Rule

Based on the invariance rule of hip abduction, the right leg should keep moving within the frontal plane. The TargetAnlgeZ determines the angle between the

right leg and frontal plane. The ErrorBound also refers to the tolerance value of Figure 11.

```
<MovingAngle>  
<AnchorJoint>"RightHip"</AnchorJoint>  
<TargetJoint>"RightKnee"</TargetJoint>  
<TargetAngleZ>0</TargetAngleZ>  
<ErrorBound>20</ErrorBound>  
</MovingAngle>
```

Figure 23. The MovingAngle Rule based on feasibility study for Hip abduction.



Figure 24. The frontal view of the Hip abduction target.

As shown in figure 24, the target is located at the right side of the mirrored right leg. If the patient follows the correct rules, there should be a collision between right foot and the target sphere.

3.4 Implementation of the Monitoring and Guidance System

A patient can use this guidance system to assist his/her rehabilitation exercise.

Figure 25 shows all the elements in an example running scene:

- 1) The coach avatar is doing the bowling exercise as a visual guidance and the patient is following the motion of the coach avatar.
- 2) The system allows both two cameras focus on each avatar in 360-degree view.
- 3) The recording file is already been saved frame-by-frame with the file name 141209669 which include joints position and the calculated relative angle.
- 4) The target objects indicate the correct rules of the movement with a counter that changes color temporarily and add one when the patient obey all the correct motion and reach the target.



Figure 25. A snapshot of our system running in live exercise (including save file, targets, counter and two cameras) for the Bowling.

CHAPTER IV

CONCLUSION AND FUTURE WORK

4.1 Conclusion

In this thesis, we presented a Kinect based rehabilitation exercise system. The major contributions of this thesis include:

- 1) We carried out a feasibility study using Kinect as the motion tracking device for rehabilitation exercises. We chose three most basic rehabilitation exercises in our study, namely, can turn, bowling and hip abduction. An MBS motion tracking system is utilized to evaluate the performance of the Kinect system. This is essential to establish a correct error bound.
- 2) We used a rule-based approach to instead of template-based approach on gesture and activity recognition. For the rule-based approach doesn't need the recoding of whole set of activity or train the model to demonstrate the whole set movements from A to Z. Rule-based approach is less complicate than template-based approach.

The advance of the rule-based approach is we just need to define or set up a series of rules include dynamic, static and invariance rule.

- 3) We developed a Kinect-based motion tracking system. This system provides a low-cost effective solution to enable patients to carry out rehabilitation exercises at home. Our system can be operated to demonstrate the exercise and record the patient session frame-by-frame with a 360-degree view.

4.2 Future work

It is shown that by using an ideal set of correctness rules, we can implement the Kinect-Based monitoring and guidance system to address the specific problem. This system can perform realtime assessment of motion and provide specific feedback to the patients. However, because of the limitation of the Kinect' performance and the selection of the correctness rules, we expect to do more future work as below:

- 1) For the correctness rules of the can-turn motion, it is hard to access the invariance rule because of the huge error bound and noise. In the future, for this common motion, we plan to select ideal rules to access and implement it in the Kinect based system. The correctness rules should follow those requirements:
 - The angle or the distance between specific segments or plane has to avoid jitters or noise.
 - From the result curves, it is necessary to represent the information that how many iterations are taken in this section.

- Make sure during the implementation process, the Kinect sensor can also recognize the can-turn iteration.
- 2) We plan to analysis more feasibility study of common exercises, figure out the correctness rules of those motions and implement in Kinect-based system. For example:
- Toe touch: it is the most common exercise which can help to improve patients' flexibility. Toe touch stretches the shoulders, back and leg muscles especially when the patients do this exercise in standing pose. In this exercise, we expect that the knee angle should keep in 180 degrees. The angle between arm and torso and the angle between leg and torso will be critical for the feasibility.
 - Sit to stand: it is used to help people to be more independent standing up. In this exercise, the angle between leg and torso should be critical in choosing the correctness rules and implementing the Kinect-based system. The angle or the offset distance of knees should also be very important.

When more and more feasibility study motions can access the correctness rule and can be present in Kinect-Based system, we expect that there are many regular patterns in choosing rules.

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