Low-Cost 3D Vision Based System for Post-Stroke Arm Rehabilitation using RGB-D Camera

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Abstract. In this paper, a low-cost markerless system based on RGB-D sensor was developed for rehabilitation purposes. The purpose of this system is to provide the physical therapist with the adequate data to characterize the arm motion in post-stroke rehabilitation, athletic injuries recovery or other possible human arm motion recording and analysis issues. The proposed system uses the Microsoft Kinect sensor to determine the motion of the patient arm. The 3D position of the joints ($shoulder, elbow$ and $wrist$) and the centers of mass of arm segments ($upper$ and $forearm$) are estimated during the motion. The system then calculates the velocities and energies expenditure by each segment of the arm. More data are estimated by the system such as the angles of each joint ($shoulder$ and $elbow$) and the angular velocities of the arm segments, where these data are useful to help the therapist with a full overview in the analysis about the patient motion. With the help of these data, the therapist has the analysis of the arm, and comparing with the previous analysis of the patient arm motion, a relative performance can be estimated, allowing a quantitative evaluation of the recovery of the patient over series of exercises. Furthermore, as a part of the work, 3D Virtual Reality System (VRS) was developed. This 3D VRS can be a beneficial environment for learning a motor task and it is important in terms of the motion motivation, since it presented to the patient as a rewarded computer game.

Keywords: Markerless Motion Capture, Kinect Sensor, Virtual Reality, Arm Rehabilitation.

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1 Introduction

Stroke is one of the most important causes of disablement among elderly people, where more than 17.3 million people suffer stroke worldwide. Stroke effects usually cause paralysis or in sometimes weakness of one side of the body, which in most cases, this paralysis affects the arm or leg of the patient. Evidences show that additional early exercise maybe beneficial. Rehabilitation is the term that describes the process of the treatment or recovery from a physical injury or a disease. This process aims to enable the patients to reach and maintain their optimal physical, psychological, intellectual, sensory and social functional levels.

Rehabilitation involves a variety of medical cases such as athletic and other sports-related injuries, post-accident rehabilitation. In Addition, it provides disabled people with the tools they need to attain independence and self-determination.

Physical therapy helps to regain the skills and functionalities of the human extremities that are lost due to athletic injuries, stroke attack or any pathological cause.

Robotic systems are very efficient in rehabilitation and several technologies are adopted for enhancing the motion of the patient's limbs, and providing analysis and quantitative recovery evaluation tools that aid the therapists. Rehabilitation systems can be classified into three main categories based onto the technologies used in each:

- Mechanical-based systems.
- Inertial Measurement-based systems.
- Vision-based systems.

Nevertheless, fusion among them often takes place for achieving better system performance.

In this paper, low-cost vision-based system using the Microsoft Kinect sensor is presented to facilitate post-stroke rehabilitation monitoring and assessment as shown in Figure 1. This system is able to obtain the positions, angles, and velocities of the arm joints $(shoulder, elbow$ and $wrist)$ in the 3D space as well as the positions, velocities of centers of mass of the $upper$ and $forearms$. In addition, a 3D game is associated to the system in order to enhance the rehabilitation process and motivating the patient for performing the exercise.

The remainder of this paper is organized as follows; section 2 introduces the state-of-the-art work related to vision-based rehabilitation systems and technologies, followed by brief explanation of the hardware used in the system in section 3. Section 4 shows the anatomy of the human arm indicating the arm kinematics and the geometric and inertial characteristics. The proposed rehabilitation system is presented in section 5. Section 6 describes the Virtual Reality System and the Game Scenarios and levels, then section 7 discusses the experimental results. Finally, in section 8 conclusion is summarized.

Figure 1: System Overview (Lab Layout); Up: Patient Interface, Down Therapist Interface

2 Related Work

In Vision-Based Systems, the rehabilitation process is based on the optical sensors, or by using cameras for either 2D or 3D spaces.

An exoskeleton supporting robot for the rehabilitation was developed in [3], this robot works under a computer program that takes the commands from the relevant physiotherapist to control the robotic exoskeleton arm.

A mechanical system depending on dissipating the energy exerted by the trainee or the patient was proposed by [7]. However, since their system does not have any type of actuation, the weight of the robot might present difficulties, for both old and young patients.

Lanfermann *et al.* [12] developed a wireless network that combines data acquired by two inertial measurement units. Their system adds the computation of posture that is familiar to physiotherapists. Then, all data is displayed on a graphical interface.

In [4], a vision camera was incorporated with fiber optic-based flex sensors mounted on the hand in the form of a glove. This rehabilitation system calculates the 2D position of color patches mounted on both the forearm and the upper arm. After that, the software calculates the joint angles between the color patches.

White *et al.* [24] presented a software application with a virtual environment for the physical therapy. This VR System simulates the daily activities.

A positioning system using a high-resolution stereo-vision camera and a 40-inch TV set was built by [25]. The patient has to be holding a cylindrical tube object while moving throughout the exercise. Then, the system calculates the 3D position of a predetermined marker shape fixed on top of this cylindrical object.

Low-tech and inexpensive virtual reality technique of motion capturing was developed by [18]. In this system, the movement of a body part is recorded by a camera and projected in the virtual environment on a computer or television screen. By these movements, the virtual objects on the screen can be manipulated.

Attygalle *et al.* [2] used the Nintendo Wii-mote gaming device as an infrared camera. Each Wii-mote has an IR camera system that can track up to six moving infrared active markers.

The sophisticated tools and technologies that can be offered at a doctor's office are generally too expensive to have in a home, but the Kinect is low in cost and readily available. At-home rehabilitation software written for use with the Kinect could track patient's movements, giving them feedback about what to do differently.

Schönauer *et al.* [19] presented an implementation of a system providing multi-modal input; of a full body motion capture system, Microsoft Kinect and biosignal acquisition devices to a game engine. In addition, serious game scenarios have been designed.

Labelle [11] presented an evaluation of using the Kinect sensor for the joint tracking in the clinical and home rehabilitation. In her study, two Kinect's SDKs were compared, and it mentioned that the Kinect has shown potential for use in Stroke rehabilitation and the data estimated and the capabilities of the sensor are very promising.

3 The Hardware

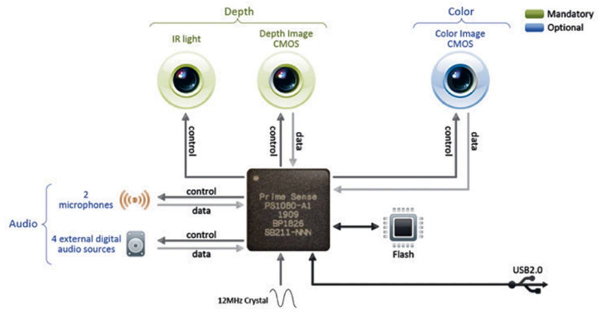

Figure 2: Kinect Sensor Diagram [15]

The Kinect sensor as shown in Figure 2 is a peripheral device developed by Microsoft for use with their $Xbox360$ gaming platform [14]. Using its depth, image, and audio sensors, the device allows users to control games using just their bodies. Instead of playing video games using conventional hand-held controllers, players can stand in front of the Kinect and be the controller themselves. The Kinect enables this by following users movements by tracking and identifying their joints. Positions of a player's joints in the 3D space are obtained from the sensor data and are used to follow the motion of the player. Although the Kinect was developed as a gaming tool, this study considered its potential in the realm of stroke therapy. The joint-tracking capability could enhance therapeutic diagnostics considerably. Doctors could use software developed with the Kinect to assess the performance of their patients and to track their improvement. By examining the movement of a patient's joints, therapy professionals would be able to pinpoint areas where the patient's movement needed improvement.

The Kinect contains a color camera of (640×480) resolution. It also contains an active-sensing depth camera using a structured light approach, which sends depth images of (320×240) pixels 30 times a second (although it appears that not every pixel is sampled on every frame) [23].

The Kinect sensor has a practical ranging limit of 1.2-3.5 m distance. The area required to play Kinect is roughly 6 m^2, although the sensor can maintain tracking through an extended range of approximately 0.7-6 m. The sensor has an angular field of view of 57^o horizontally and 43^o vertically, while the motorized pivot is capable of tilting the sensor up to 28^o either up or down. The horizontal field of the Kinect at the minimum viewing distance of ~ 0.8 m is therefore ~ 87 cm, and the vertical field is ~ 63 cm, resulting in a resolution of just over 1.3 mm per pixel.

For this research, one of the biggest advantages of the Microsoft SDK [15] was joint tracking without calibration. The system can track the human skeleton without pre-calibration phase. Because any calibration requiring a patient to hold a specific pose could be problematic for many stroke rehabilitation patients.

4 Human Arm Anatomy

4.1 Human Arm Kinematics Model

A definition of the arm and hand mechanism is required prior to the development of the mathematical model. Lenarčič defines the arm as a 4 segment's serial mechanism involving the shoulder girdle, the upper arm, the forearm and the hand [13]. Due to its high complexity and high number of degrees of freedom, the hand movement is studied separately. The hand and the wrist are replaced with a rigid segment with two degrees of freedom at the wrist.

A model of 8 DoFs and three segments, namely the upper arm, the forearm and the hand was proposed by [5]. Grams suggests an arm model that consists of 4 segments with 10 DoFs [9], where the shoulder girdle and glenohumeral joint possess 3 DoFs each, whereas the elbow and the wrist has a total of 4 DoFs. The Human arm Skeleton Structure is shown in Figure 3.

The most common model of the human arm is 7 DoFs as shown in Figure 4 consisting of the shoulder ball-and-socket joint with rotation axes for abduction-adduction (q_1), flexion-extension (q_2), and internal-external rotation (q_3) of the upper arm, the elbow double-hinge joint with rotation axes for flexion-

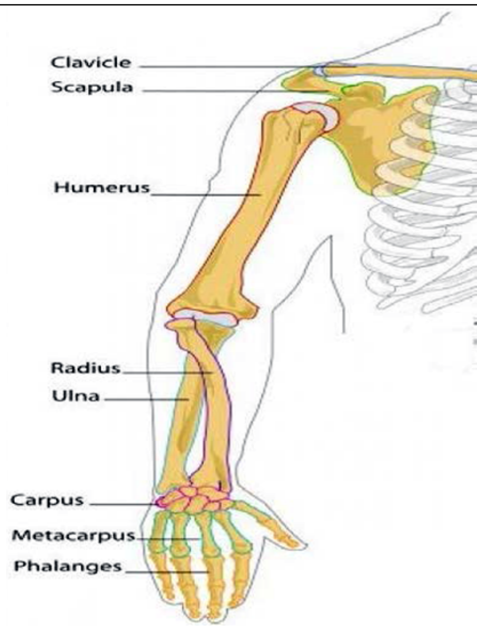

Figure 3: Skeleton Structure of the Human Arm

extension (q_4), and pronation-supination (q_5) of the forearm and the wrist double-hinge joint with rotation axes for ulnar-radial deviation (q_6), and flexion-extension (q_7) of the hand, which are shown in Table 1.

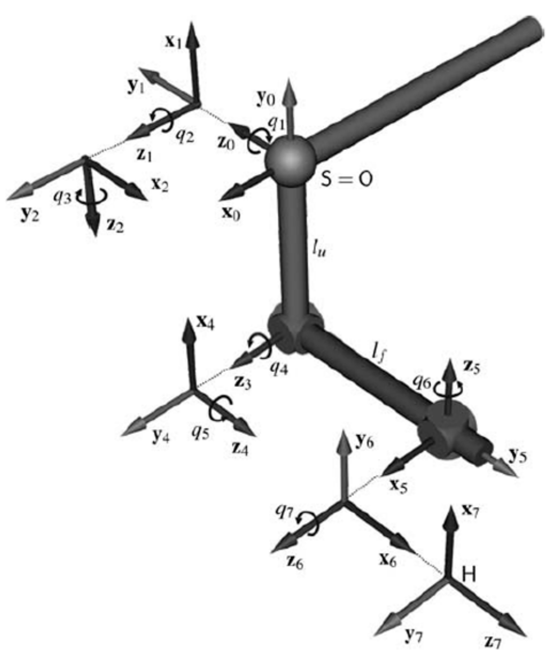

Figure 4: Simplified human arm kinematics using 7 DoFs

Table 1: WEIGHT OF BODY SEGMENTS

Point	Joint	Functionality
q_1	Shoulder	abduction-adduction
q_2	Shoulder	flexion-extension
q_3	Shoulder	internal-external rotation
q_4	Elbow	flexion-extension
q_5	Elbow	pronation-supination
q_6	Wrist	ulnar-radial deviation
q_7	Wrist	flexion-extension

In this work, the human arm motion is considered as a combination of the shoulder and the elbow motion. The shoulder motion is composed of elementary motions in the $glenohumeral$, $scapulothoracic$, $sternoclavicular$, and $acromioclavicular$ joint [22]. The elbow joint is understood as a uniaxial joint connecting the $ulna$ with the $humerus$ and the $radius$ with the $humerus$. These two joints allow the elbow flexion and extension [13] and are modeled as a single rotation as shown in Figure 5.

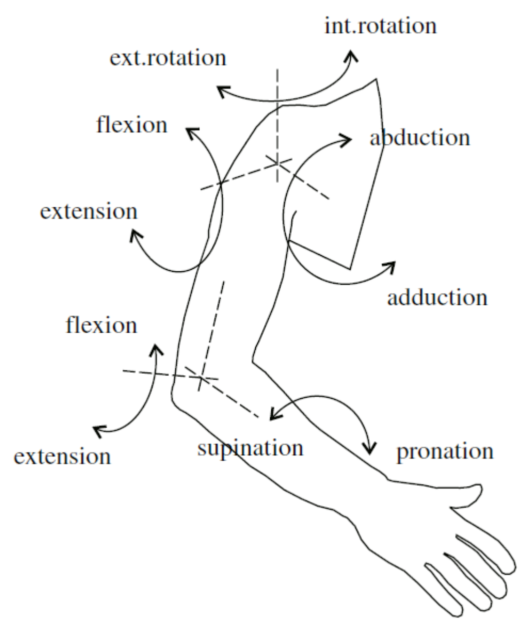

Figure 5: Shoulder-Elbow movement

4.2 The Geometric and Inertial Characteristics of the Human Arm

Different approaches of calculation characteristics of the human body segments in terms of weight, volume, and centers of mass have been demonstrated by numerous investigators. These approaches have been developed and used in wide variety of techniques and applications. In 1983, Zatsiorsky obtained by means of a gamma-ray scanning technique, the relative body segment masses, center of mass (CM) positions, and radii of gyration for samples of college-aged Caucasian males and females. In addition, the parameters B_0, B_1 and B_2 was determined of each body segment [20],[21]. The equation of estimating the mass of the body segments is given as follow:

$$m_i = B_0 + B_1 \times m + B_2 \times \nu \tag{1}$$

where, $m(kg)$ is the total mass of body, $\nu(cm)$ is the height of the body and the parameters B_0, B_1 and B_2 are explained in Table 2.

Table 2: B_0, B_1 AND B_2 PARAMETERS OF THE MASS OF BODY SEGMENTS [20],[21]

Cadaver	B_0	B_1	B_2
Head + Neck	1.2960	0.01710	0.01430
Upper Arm	**0.2500**	**0.03012**	**-0.00270**
Forearm	**0.3185**	**0.01445**	**-0.00114**
Hand	**-0.1165**	**0.00360**	**0.00175**
Leg	-0.0829	0.00770	0.00730
Shank	-1.5920	0.03616	0.01210
Thigh	-2.6490	0.14630	0.01370
Trunk	…	…	…
Upper part of the Trunk	8.2144	0.1862	-0.05480
Middle part of the Trunk	7.1810	0.2234	-0.06630
Lower part of the Trunk	-7.4980	0.0976	0.04896

Focusing on the upper arm and forearm segment, and considering the mass of the forearm and the hand as one rigid segment, so the mass for each one can be calculated as follow:

$$m_{upper} = (0.25) + (0.03012 \times m) + ((-0.0027) \times \nu) \tag{2}$$

$$m_{fore} = (0.3185 + 0.01445 \times m + (-0.00114) \times \nu) + ((-0.1165) + (0.0036 \times m) + (0.00175 \times \nu)) \tag{3}$$

5 System Structure

The proposed Human Arm Tracker System consists of three parts: $Patient - Interface$, $SkeletonTracker$, and $Therapist - Interface$. Figure 6 shows the diagram of the system structure. Generally the patient is sitting in front of the Patient-Interface (Virtual Reality System) and the Kinect sensors. The patient is trying to perform the exercises that are shown in the screen. During this motion, the Kinect sensors detect the arm joints and send the positions to the $SkeletonTracker$ application which in turn performs calculations to estimate more data that helps the therapist in the analysis process. The $SkeletonTracker$ also sends this data to a temporary file over UDP packets.

On the other hand, the $Therapist - Interface$ controls all other applications and takes a copy of the patient data from the temporary file to a permanent database. The $Therapist - Interface$ allows the therapist to monitor the motion of the arm and the data got during the exercise.

In addition, the therapist can search for all the data of the patient in his history file and estimates the performance of the arm during the motion in terms of velocities and energies. The three part of the system will be explained in details in the following subsections.

5.1 Patient Interface

This framework includes a 3D game as interactive exercise to motivate the patient and to estimate the arm data from it. In this game, the patient controls a character appears in the screen using the Kinect sensor, and the patient should follow a moving target which is located on a table in front of the character.

5.2 SkeletonTracker

This part is considered as the core of our rehabilitation system, which is able to track the human arm and estimates the 3D joint positions ($shoulder, elbow$ and $wrist$). Figure 7 shows the human arm joints and segments obtained by the $SkeletonTracker$ application.

5.3 Therapist Interface (Main interface)

This part gives the therapist full monitoring of the patient motion; furthermore it allows the therapist to control all the other applications. Generally this part consists of three forms: New User, Existing User, and Search form. A diagram of the main tasks of the Therapist-Interface is shown in Figure 8.

1. **New/Existing User Form:** In this form, the therapist enters manually the patient personal data before performing the exercise. In "New User form", the therapist enters the full data of the patient $(Name, Age, Weight, Height, Gender, Date)$ in addition to the Level of the Exercise. Whilst in the "Existing User form", just the Date and the Level of the exercise are entered. All these information are saved in the patient record. Figure 9 shows the New User Form.

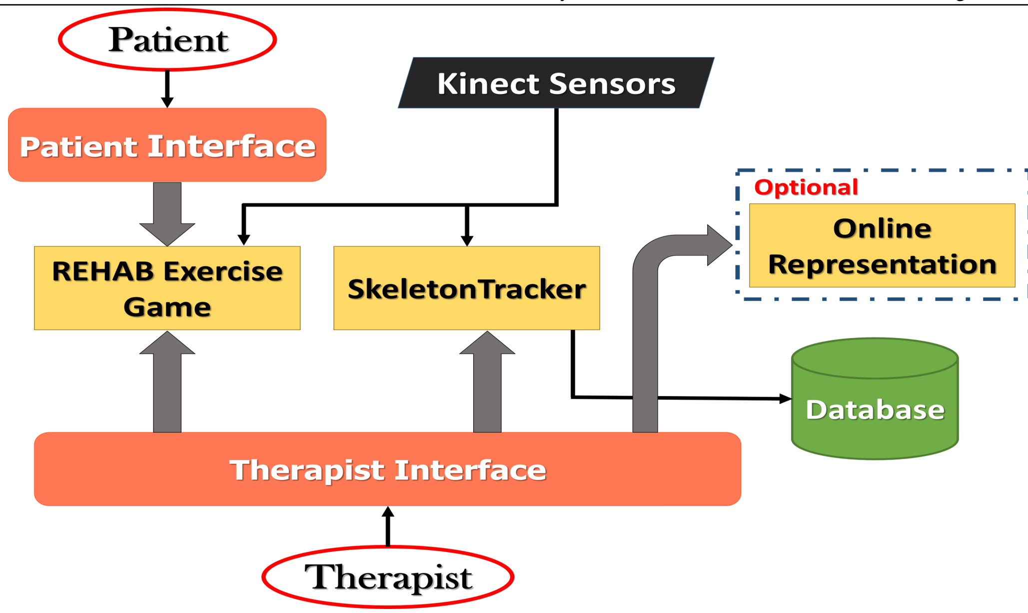

Figure 6: System Diagram

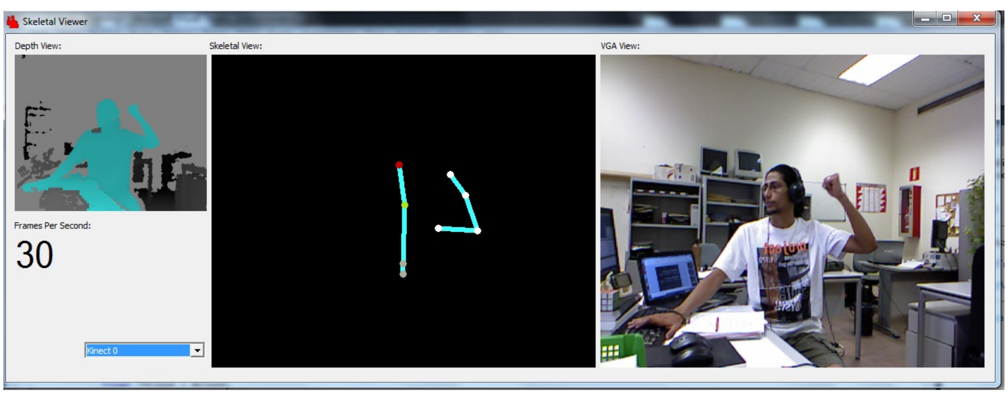

Figure 7: $SkeletonTracker$ Form

In addition to that the data of the arm are copied from the temporary file ($.csv$) into the patient record in the main database.

2. **Search Form:** This form allows the therapist to query about the patient data from his record file. The therapist is basically allowed to search according to the patient record number, and the therapist has also the ability to filter his search either by date or the Level of the exercise. Moreover the therapist can estimate the average velocity and the average energy of each segment of the arm of the selected search.

   In this form also, it is possible to print a report showing the patient personal information and the data estimated during the motion such as the instant velocities and instant energies, with a final summary of the arm data. Figure 10 shows the Search Form.

6 Virtual Reality (REHAB Game)

More prosaically, $VirtualReality$ can be described as a computer technology which allows to create detailed a realistic 2D or 3D environments of particular real life or imaginary situations.

This technology is currently being explored for its potential benefit as a therapeutic intervention for re-

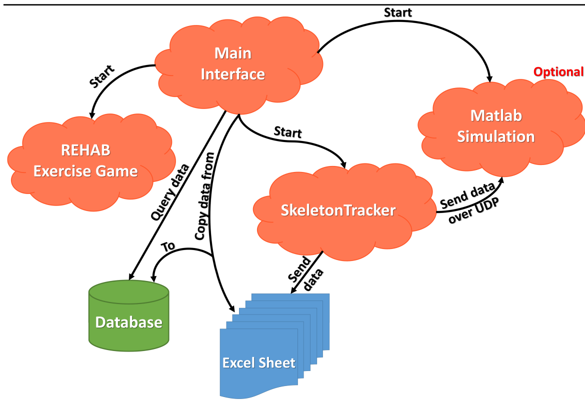

Figure 8: The tasks of the $Therapist-Interface$ (Main-Interface)

Figure 9: New User form

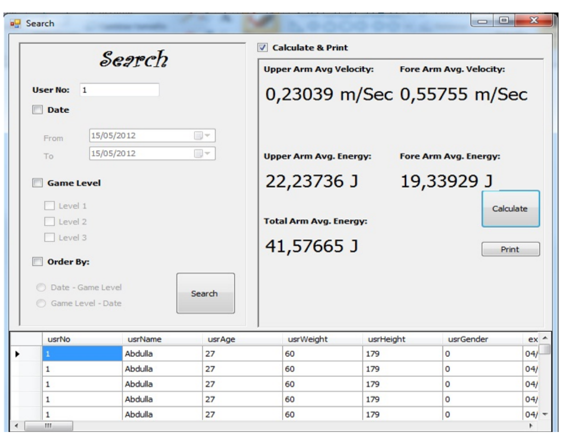

Figure 10: Search form

training coordinated movement patterns.

6.1 Virtual Reality and Rehabilitation

The use of a virtual reality technology is used in a wide range for the training of motor tasks. It is currently being explored in several areas of rehabilitation. Virtual reality training has been used for children with Cerebral Palsy to enhance spatial awareness [16] and to successfully teach these children to operate motorized wheelchairs [8].

In addition virtual reality based rehabilitation systems have several advantages. Similar to computer games VR rehab exercises can be made to be engaging, which is important in terms of the patient motivation [17].

6.2 Unity 3D Game Engine

Unity 3D is a fully integrated development engine that provides rich out-of-the-box functionality to create games and other interactive 3D content. Unity is used to assemble assets into scenes and environments; add physics; simultaneously play test and edit the game and publish to different platforms (PC, Web, iOS, Android, Wii, PS3 and Xbox 360) [6].

6.3 Game Description

REHAB game is a 3D simulation game attached to the $SkeletalTracker$ application, which is able to detect the motion of the patient arm in 3D space. This simulation gives the patient a comfortable and familiar sense that encourages him to improve his efforts, and also it is useful in case of rehabilitation for children where can provide an interesting time during the exercises.

REHAB game has one scenario which simulates an environment of a kitchen, where the human character "$Sara$" can only move her upper limbs. This scenario divided into three levels of difficulty, we create just one scenario not to confuse the patient and make him familiar and confident in each level, while each level provide more difficulty than the previous one. This difficulty aims to improve the patient's motion performance.

For each level the patient should put a "Cup" attached to the character hand on a moving colorful "$Target$". When the "Cup" collides or touches the "$Target$", it moves to a different position and the patient needs again to touch it again, and so on. The game has no time calculation, it ends when all the targets are collided.

6.4 Aims of the game levels

The First level allows the patient a free arm motion, mostly it is a vertical motion to follow **ten** targets -one each time- located in a fixed position. Figure 11 (Up) shows the first level scene. This task focuses on improving the strength of the shoulder joint.

The Second level gives the patient more space of motion. The patient needs to follow **twenty** targets -

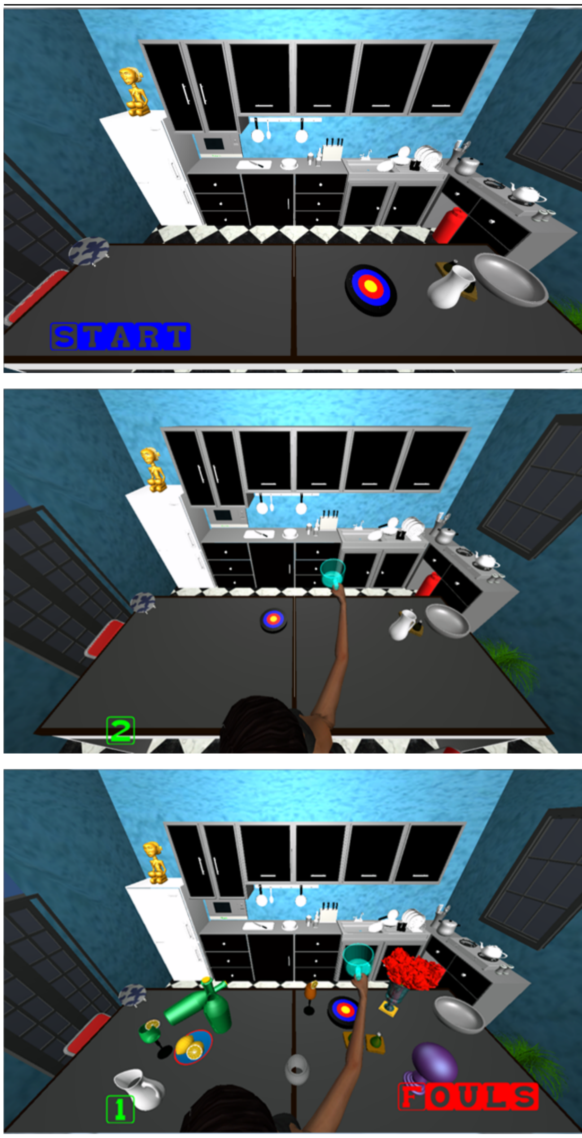

Figure 11: REHAB game: (Up) First Level, (Middle) Second Level, (Down) Third Level

one each time- which it has a random position as shown in Figure 11 (Middle). In this level we focus on the strength of both shoulder and elbow joints.

The Third level is almost similar in concept of motion to the Second level. In which, the patient should follow the 20 targets. But in this level some obstacles were added in the motion space in order to increase the complexity.

While the patient is following the targets, he should avoid touching the obstacles. In this level there is a "$Count$" and "$Foul$" screens, where the "$Fouls$" refers to the number of obstacles collided and the "$Count$" is the number of target followed. Finally, the "$score$" is obtained by subtracting the number of "$Fouls$" from the total number of "$Counts$". This is shown in Figure 11 (Down).

7 Experimental Results

The proposed system explained in the previous sections has been tested and verified with data gathered from experiments performed on 120 volunteers. All experiments were performed using Intel core i7-2600 at 3.4 GHz processor, and 8 GB of memory and AMD Radeon graphics card with 3.5 GB of memory.

Each one performed the three levels of the game in different positions with or without additional weight. Table 3 shows the information (Gender, Weight, and Height) of some of the patients who performed the experiments.

Table 3: PATIENTS INFORMATION

Patient No.	Gender	Age	Weight (Kg)	Height (cm)
1	M	27	64	170
2	F	28	51	164
3	M	29	60	169
4	M	28	62	171
5	M	24	68	180
6	M	28	66	178
7	M	33	69	175
8	M	30	64	184
9	F	27	80	175
10	F	35	58	170

The following figures show various graphs representing the data of patient motion during performing the exercise of Level 3.

7.1 Elbow and Wrist joints positions

Focusing on the human arm, the 3D joint position (x, y, z) can be represented as follows:

$$\begin{aligned} Shoulderjointposition &= (Sh_x, Sh_y, Sh_z) \\ Elbowjointposition &= (El_x, El_y, El_z) \\ Wristjointposition &= (Wt_x, Wt_y, Wt_z) \end{aligned} \tag{4}$$

Figure 12 shows the joints positions in 3D space while motion.

7.2 Centers of Mass Positions

From these joints positions, the position of the center of mass of each arm segment can be calculated as follows:

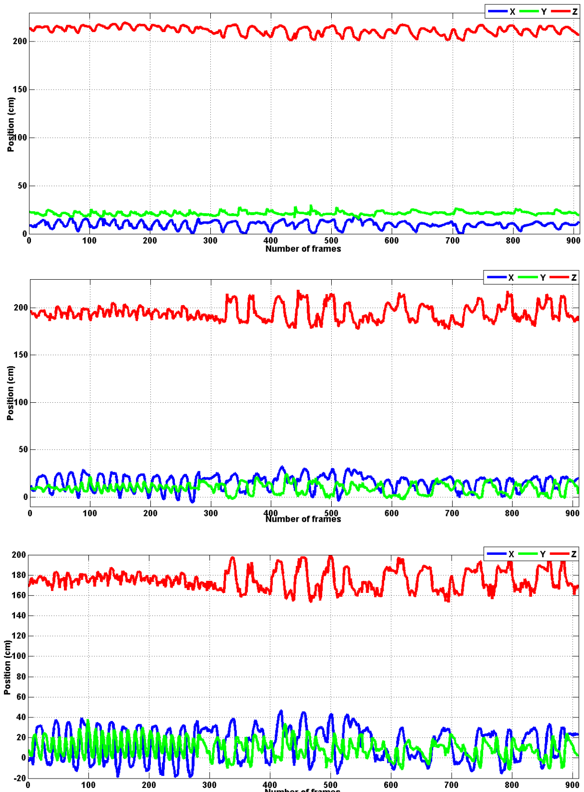

Figure 12: Joints Positions: (Up) Shoulder positions, (Middle) Elbow positions, (Down) Wrist positions - (Blue: x position), (Green: y position), (Red: z position)

1. The position of the center of mass of the upper arm Cu is given as(Cu_x, Cu_y, Cu_z), where

$$\begin{aligned} Cu_x &= \tfrac{Sh_x+El_x}{2} \\ Cu_y &= \tfrac{Sh_y+El_y}{2} \\ Cu_z &= \tfrac{Sh_z+El_z}{2} \end{aligned} \tag{5}$$

2. The position of center of mass of the forearm Cf has some considerations; because of the elimination of the Kinect in detection of the hand, the system cannot calculate the real center of mass of the forearm.

   With the help of previous Anatomy studies [1] [10], and by considering that the hand and the forearm as one rigid segment, a 7 cm was added to the x position of wrist joint, therefor a relative position of Cf will be (Cf_x, Cf_y, Cf_z), where:

$$\begin{aligned} Cf_x &= \tfrac{El_x+Wt_x+7}{2} \\ Cf_y &= \tfrac{El_y+Wt_y}{2} \\ Cf_x &= \tfrac{El_z+Wt_z}{2} \end{aligned} \tag{6}$$

In Figure 13 the 3D positions of the centers of mass for upper and forearm are shown.

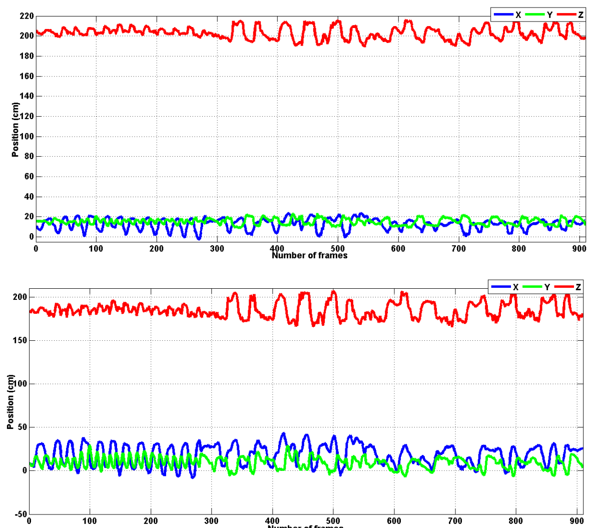

Figure 13: center of mass Positions: (Up) Upper arm, (Down) Forearm - (Blue: x position), (Green: y position), (Red: z position)

7.3 Velocities

One of the major aims of this system is to estimate the velocity of the arm segments. Therefore, the velocity of the upper and forearm is given as follows:

$$Vel(Cu) = \frac{\sqrt{(Cu_x - Cu_{xo})^2 + (Cu_y - Cu_{yo})^2 + (Cu_z - Cu_{zo})^2}}{dt} \tag{7}$$

$$Vel(Cf) = \frac{\sqrt{(Cf_x - Cf_{xo})^2 + (Cf_y - Cf_{yo})^2 + (Cf_z - Cf_{zo})^2}}{dt} \tag{8}$$

Where, dt is the time difference between frames.

Next Figure 14 shows the velocities of the centers of mass of the upper and forearm segments.

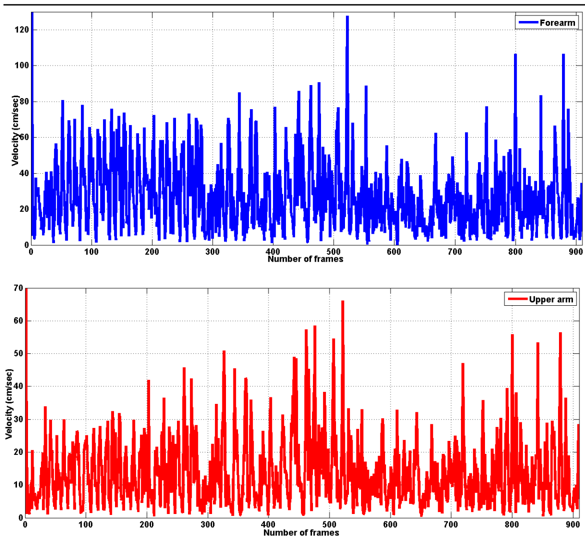

Figure 14: Velocities (cm/sec) of the center of mass of arm segments: (Up) Forearm, (Down) Upper arm

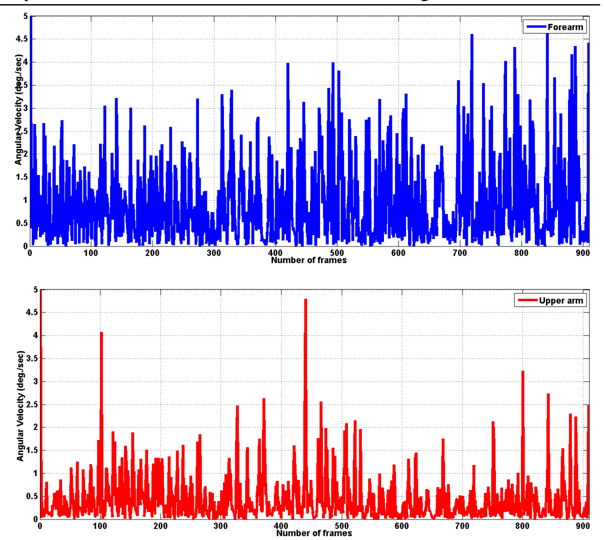

Figure 16: Angular Velocities ($Deg./Sec$): (Up) Forearm, (Down) Upper arm

7.4 Additional Data Representation

In the following figures 15 and 16, some additional data are represented, these data are the angles of shoulder and elbow joints in ($Degree$), and the angular velocities of each arm segment (upper and forearm) in ($Deg./Sec$).

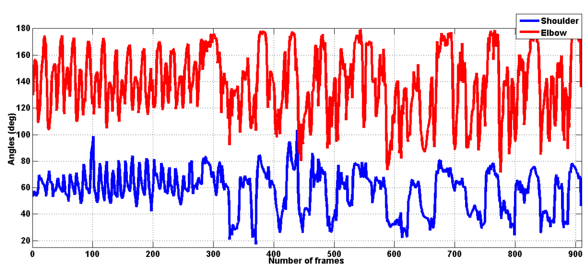

Figure 15: Joints Angles ($degrees$) - (Blue: Shoulder joint), (Red: Elbow joint)

8 Conclusion and Future Work

8.1 Conclusion

In this paper, the main objective is to develop a low cost and accurate vision-based system to characterize the human arm motion for rehabilitation issues.

To achieve this, a markerless human motion capture system was applied by using a Microsoft Kinect sensor as data input.

The proposed allows to estimate the arm joints positions, velocities, angles, the positions of the centers of mass of arm segments (upper and forearm) and its velocities and the angular velocity of each segment in the 3D space.

Furthermore the system is able to calculate the mass of the arm segments with respect to the total weight and height of the human body.

Finally it gives the results to the therapist in terms of velocities and energies.

From the experiments, we found that performing the exercises in a low intensity light helps to eliminate the noise provided by the Kinect, which leads to obtain more accurate data. On other hand taking the reading every 5 frames minimize the probability of having this noise.

8.2 Future Work

Future work planned for this research consists of two directions.

The first direction includes developing the system to be able to characterize the human lower limb motion by detecting the leg joints (hip, knee, and ankle) and its positions and velocities.

Till now the Kinect sensor is not able to detect the human hand and its fingers joints, therefor with the new versions of Kinect, we planned to improve this system to estimate the hand motion and determine its data for the rehabilitation issues.

On the other hand, the second direction will be aimed to integrate this vision based system with inertial sensors to obtain more accurate and more satisfactory results.

Moreover, it is planned to design more 3D games to cover the all possible exercises in order to complete the rehabilitation operation.

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