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DESIGN OF A GAME-BASED REHABILITATION SYSTEM USING KINECT SENSOR

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ABSTRACT

As technological innovation is fused into the rehabilitation process, it gives conventional therapy a new direction with the products of interactive nature and easy to measure techniques. In the recent years, virtual reality based game therapy has turned out to be a promising option for post-stroke patients since it engages patients with fun based exercises during rehabilitation process. It also triggers their neuro-motor functions and accelerates the recovery process. Nevertheless it is necessary to extract some valuable information from the joint movements to measure the recovery condition of patients. Most of the designed games have introduced features to make them interesting as well as challenging for patients, however, only a few measure the joint parameters. We have designed a Kinect based game in Unity3D platform where patients can play game by moving their joints which results in different orthopaedic lessons required for rehabilitation therapy. In contrast to many Kinect based games where only joint movements are considered for playing the game, we have also introduced voice control through speech recognition and feedback provided in terms of audio-visual command to enhance patient's engagement. Different joint parameters such as trajectory, range of motion, joint velocity, acceleration, reaching time and joint torque are also measured to help quantify the heath condition.

Keywords: Rehabilitation, joint parameters, Unity, Kinect

INTRODUCTION

Post-stroke rehabilitation needs a repetitive, intensive and engaging exercise module to drive patients into a competitive environment where they are encouraged to participate in the therapy session. Self-training is beneficial at the chronic stage for post-stroke patients [1]. The process of rehabilitation can be further improved by incorporating engaging activities in to it.
To evaluate patient's health condition during joint movement, various joint parameters such as workspace, trajectory, range of motion, joint velocity, reaching time, joint torque need to be constantly monitored. Different hardware based solutions have been used to evaluate the joint characteristics such as range of motion is normally measured using a protractor or goniometer, however, the information collected from such instruments is affected by low accuracy and is evaluator dependent [2]. The workspace of a joint indicates the reachable points of a patient in 3D space to measure their flexibility and dexterity. Kinematic model along with user's anthropometric data is used to analyze the reaching workspace [3]. Different hardware-based sensors such as EMG (electromyogram), IMU (inertial measurement unit), accelerometer, force sensor are used together to monitor patient's movement conditions. However, the issues such as cost, compatibility with user, efficiency, accuracy and acceptability restrict the use. Fine EMG signal extraction from stroke patients is troublesome due to irregular EMG-torque relations in stroke [4]. IMU and accelerometer are attached to the human body which restricts motion of the users and they feel captive wearing them [5]. Smart haptic gloves normally have force sensor to measure joint angle and grasping force [6], however, sensor with data acquisition unit makes the systems expensive and technically difficult to operate. These hardware based solutions discourage users to exercise at home and force them to visit rehabilitation centre. Sometimes patients are not comfortable to put on these hardware sensors due to its complexity and mechanical look since these sensors are connected to the body of patients [7]. To overcome these problems, contactless measurement systems like motion capture devices during therapy is effective for stroke patients [8]. After reviewing the existing motion capture systems such as Kinect [9] and Vicon [10] for collecting user's data, Kinect was found to be a low-cost, portable, contactless and marker-less option which can be used to evaluate the joint parameters. It is also possible to create game based exercises using Kinect without the assistance of therapist.

Kinect based upper limb rehabilitation proves to be effective for post-stroke patients in home environment [11]. Different types of games have been developed based on Kinect based arm movement such as table tennis [12], bubble game [13] or object placement games [14]. The effectiveness of a game based system for post-stroke rehabilitation can be quantified by three properties; level of activities in the game suitable for post-stroke exercise, feedback command for the user to enhance their participation and performance evaluation of patient after playing the game. Experiments have been performed to prove the authenticity of Kinect measurement by comparing its data with EMG [15], inertial sensor [16] or other motion capture systems [14].

Many advancements have been made to Kinect based game development to make it adaptable to the patient's limitation [9]. To list a few; the idea is to enhance the human-machine interaction, performance evaluation of a patient in a task oriented exercise should be reported back the user and therapist [7]. Auto-report generation after the therapy is also effective for patients [17]. Sometimes illusion are created in game based exercise to engage patients to perform better [18].

To make those exercises more interactive, continuous notification from the game environment to user in the form of text, voice or both can be useful to motivate patients to put more effort. Warning can be provided to users if they follow a wrong track [17]. Mirror feedback also improves the rehabilitation process in Kinect based game [19].

Most of the games have specific performance evaluation process such as no of correct attempts and performance score [7]; the distance, time and velocity of hand movement in a bubble game [13]. Thermographic images were used to evaluate the muscle activity after training [20]. There are games that have been developed which measure various joint parameters such as joint angle [21] and position [22] and joint velocity [23] of the user. Sometimes it is also required to measure the posture of human segments, torque in each of human joints for clinical analysis, so the main aim of this paper is focused on three areas; (i) to plan the game where the goal is achieved by user's joint movement, (ii) to evaluate the performance of post-stroke exercises of a patient by collecting maximum number of attributes from joint movement and (iii) to make those exercises motivating whilst preserving the nature of exercises, therefore, both scoring techniques and audio-visual control cum feedback are included in this paper.

1.1 Methods

With the end goal to build up a stimulating and engaging therapy environment for post-stroke patients, we have combined many software tools in a single platform such as Unity3D, Microsoft visual studio, Microsoft SDK (Kinect V2) and Matlab (Fig. 1). The setup helps in guiding patients to do exercises through intriguing game environment where user is persuaded to put their effort in an interactive environment. The joint parameters are simultaneously measured and recorded during movements to evaluate the health status of the user.

This is designed around a basketball game in which the movement of the ball is controlled by the hand position in 3D space and user can drop the ball in basket using voice control. The game and its environment are designed using Unity Game engine where the position of arm joints is tracked using Kinect sensor. The position of the ball (considered as a gameobject in unity) is synchronized with the movement of the hand using available API of Kinect. The voice control algorithm is implemented in this game using Windows speech reorganization technique (Windows Speech library). The voice command is being matched with the database from Google and the game runs automatically. All motions, measurement of joint vectors and reorganization of voice command are programmed in C# through Microsoft visual studio. We have used Microsoft XBOX-one which is compatible with Kinect V2 and it has direct plug-in interface available within Unity3D. The joint vectors and angles are measured and recorded using Windows SDK 2.0 interface based on the timestamp data. The recorded data can be further analysed to generate some useful information about joint parameters (velocity, trajectory, workspace and torque). This may, however, make the game slow and difficult to operate, therefore, rest of the analysis is performed in Matlab based on the recorded data. In this system, Kinect's reference frame is used as the main coordinate system. Reaching time from the rest position to the goal position is calculated using the difference of the starting time to the ending time taken from timestamp data. Joint trajectory is plotted using the joint's vector collected from the recorded data. The trajectory of the joint travelled during the game is compared with the predefined desired path. Any deviation from the desired path will be recorded and prompted to the user. The PC based system returns motivating words like 'Come on! You can do it, 'Almost reached', 'Hurray! You have scored' and provide 'particle dispersion' after scoring as soon as they cross a milestone. This technique will encourage them to put extra effort to achieve the goal. The joint velocity and acceleration are calculated from differentiation of joint angle with respect to timestamp data. To reduce the noise in the calculation of joint velocity and acceleration, a low pass filter is used to smoothen the data. Joint torque of the user is calculated from the information of segment mass of user, distance of centre of gravity and joint angle.

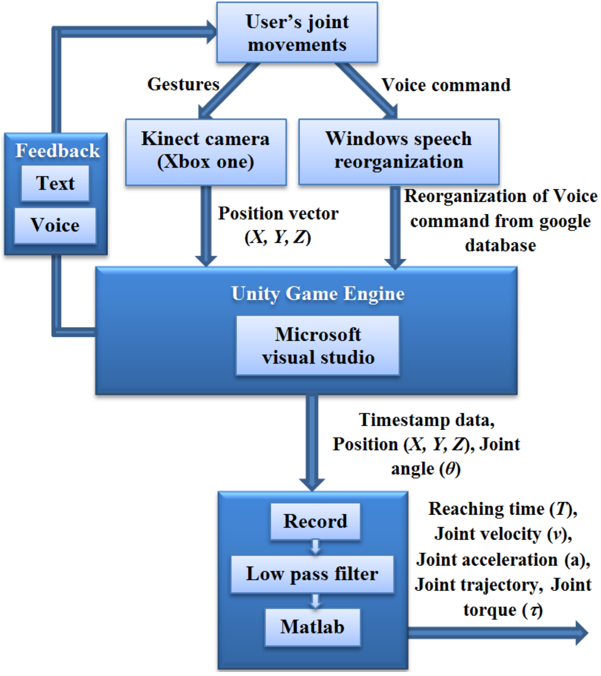


FIGURE 1: STRUCTURE OF THE REHAB CONTROLLER

The distance between the subject and Kinect is 1.5 m and the Kinect is placed at 1.05 m from the ground level (Fig. 2).

The game is tested by a heathy subject to see the operational validity of the Kinect sensor while playing the game.

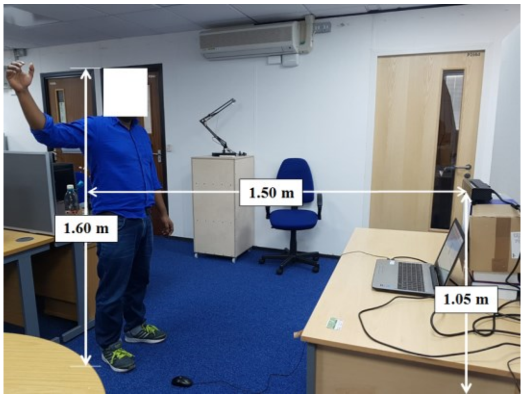


FIGURE 2: GAME ENVIRONMENT POSITIONING

In the basketball game, the trajectory of the ball from the rest position to the basket is designed in such a way that it will require a combination of elbow flexion-extension and shoulder abduction-adduction movement. The starting position is the rest position where elbow is in fully extended state (making an angle of 180^{o} between upperarm and forearm) so as the shoulder joint (making an angle of 180^{o} between the upperarm and clavicle bone). In the scoring position, elbow rotates up to its maximum limit identical to a full flexion state where the angle between upper arm and forearm is 45^{o} (approximately), along with that shoulder joint makes an angle of 140^{o} between upperarm and clavicle bone. The joint angle of shoulder and elbow, interactive communications between game engine and user appear on the game screen. There are two baskets in the game as shown in Fig. 3. The basket on the left side is allocated for the left arm movement and the basket on the right side is for the right arm.

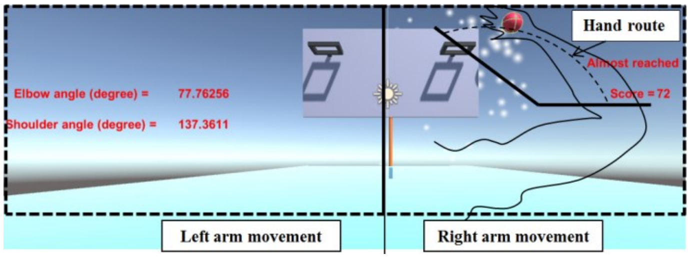
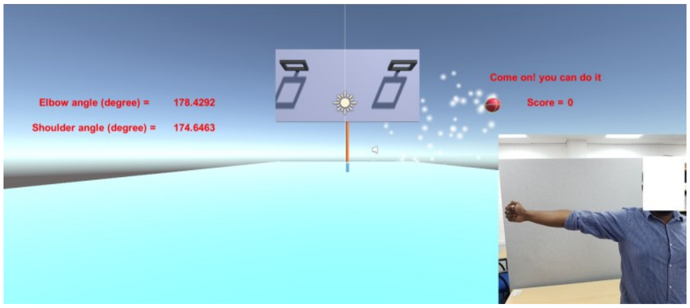


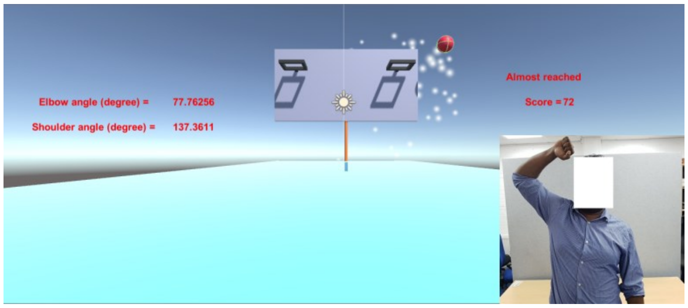
FIGURE 3: WORKING SETUP OF THE GAME

We have divided the game into three stages (Fig. 4) as per the range of arm movement. The joint movement is aligned with the ball from the rest position to basket. After completing each stage, some motivating words will appear on the screen for user and it will also show some winning points. The whole environment is programmed in such a way that gravity force must be applied to each gameobject. After hearing the 'drop' word from user, the holding contact between human hand and ball become zero, therefore it releases the ball. In this way, user can basket the ball from the top of basket (shown here as scoring area). Also it will generate some winning gestures after the user become successful to basket the ball.



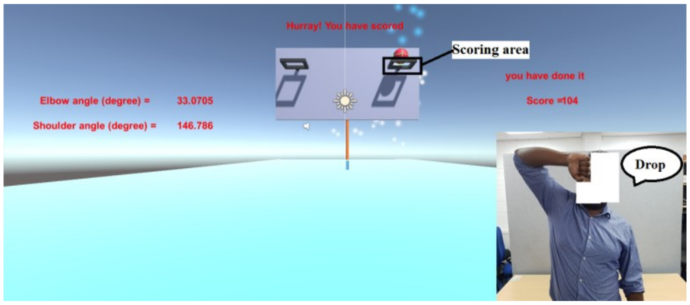
Elbow angle (degree) = 178.4292
Shoulder angle (degree) = 174.6463
Come on! you can do it
Score = 0

STAGE 1



Elbow angle (degree) = 77.76256
Shoulder angle (degree) = 137.3611
Almost reached
Score =72

STAGE 2



Hurray! You have scored
Elbow angle (degree) = 33.0705
Shoulder angle (degree) = 146.786
you have done it
Score =104

STAGE 3

FIGURE 4: THREE STAGES OF JOINT POSITION

1.2 Measurement of joint parameters

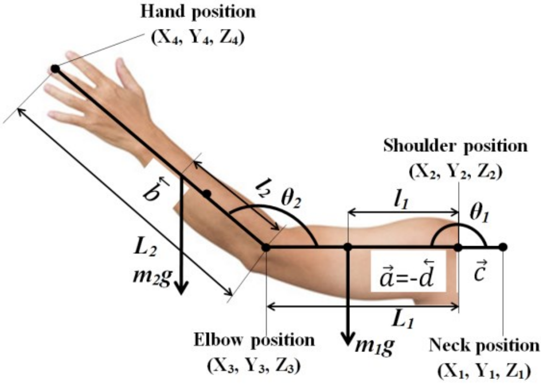


FIGURE 5: KINEMATIC MODEL OF THE HUMAN ARM

Joint positions

Position of neck (X_1, Y_1, Z_1), shoulder joint (X_2, Y_2, Z_2), elbow joint (X_3, Y_3, Z_3) and distal end of hand (X_4, Y_4, Z_4) of right arm of the user are measured using Kinect SDK body tracking interface (Fig. 5). The built-in API of Kinect provides the position vector with respect to the position of Kinect sensor (considered as reference (0, 0, 0) point.

Joint trajectory: Plotting the Cartesian coordinates in 3D space using Matlab.

Joint angle measurement

From Fig. 5, $\vec{a} = [(X_3\text{-}X_2), (Y_3\text{-}Y_2), (Z_3\text{-}Z_2)]$ (1)

$\vec{b} = [(X_3\text{-}X_4), (Y_3\text{-}Y_4), (Z_3\text{-}Z_4)]$ (2)

$$\cos\theta_2 = \frac{a.b}{(|a| * |b|)} \quad (3) \qquad \sin\theta_2 = \frac{|a \text{ x } b|}{(|a| * |b|)} \quad (4)$$

$$\text{Elbow joint angle } \theta_2 = \tan^{-1}\frac{|a \text{ x } b|}{a.b} \quad (5)$$

With the same technique,

$$\text{Shoulder joint angle } \theta_1 = \tan^{-1}\frac{|c \text{ x } d|}{c.d} \quad (6)$$

$$\text{Where } \vec{a} = -\overleftarrow{d}$$

Reaching time

T = Timestamp data (end time (T_2) – start time (T_1)) (7)

Joint velocity and acceleration

Joint velocity of elbow and shoulder are computed by differentiating the joint angle with reference to the timestamp data. We have taken the mean of consecutive five samples of the data and then passed these data through a low pass filter before plotting it. Joint acceleration is calculated using the same technique.

Joint torque

Human arm can be considered as a two degree of freedom manipulator where normal rigid body dynamics can be applied. The length of upperarm and forearm are computed from the position vector collected through Kinect.

So the length of upperarm

$$L_1(\text{Kinect}) = \sqrt{(X_2 - X_3)^2 + (Y_2 - Y_3)^2 + (Z_2 - Z_3)^2} \quad (8)$$

and forearm

$$L_2(\text{Kinect}) = \sqrt{(X_3 - X_4)^2 + (Y_3 - Y_4)^2 + (Z_3 - Z_4)^2} \quad (9)$$

The standard length of arm segments can also be calculated as per biomechanics rule [24] for comparison purpose.

Length of upper arm

$L_1(\text{Biomechanics}) = 0.186 * \text{H}$

Length of forearm

$L_2(\text{Biomechanics}) = 0.254 * \text{H}$

Where H = Height of the user

Therefore a comparative study can be drawn about validity of the Kinect measurement from both values. There is no direct method of measuring the centre of gravity and the mass of the arm, therefore it can be estimated with the proportion between the segment and total body [24].

Distance from shoulder to center of mass
of upperarm (l_1) = $0.436*L_1$
Mass of upperarm (m_1) = $0.028*W$
distance from elbow to center of mass
of forearm (l_2) = $0.682*L_2$
Mass of forearm (m_2) = $0.022*W$
W = Body weight of the user (kg)

In human arm, each of the arm segments is considered as a point mass. Therefore inertia of upperarm with respect to center of mass is $I_1 = m_1*(L_1*0.322)^2$ kg.m^2

and inertia of forearm with respect to center of mass is
$I_2 = m_2*(L_2*0.468)^2$ kg.m^2
where the lengths ($L_1*0.322$) and ($L_2*0.468$) are the radius of gyration with respect to the center of mass

As per Lagrange-Euler formulation,
joint torque of the shoulder is

$$\tau_1 = \left[m_1{l_1}^2 + I_1 + m_2\left({L_1}^2 + {l_2}^2 + 2L_1 l_2 \cos\alpha_2\right) + I_2\right]\ddot{\alpha}_1 + \left[m_2\left({l_2}^2 + L_1 l_2 \cos\alpha_2\right) + I_2\right]\ddot{\alpha}_2 - m_2 L_1 l_2 \sin\alpha_2 \left(2\dot{\alpha}_1\dot{\alpha}_2 + {\dot{\alpha}_2}^2\right) + m_1 g l_1 \cos\alpha_1 + m_2 g(L_1 \cos\alpha_1 + l_2 \cos(\alpha_1 + \alpha_2)) \quad (10)$$

and joint torque of the elbow is

$$\tau_2 = \left[m_2\left({l_2}^2 + L_1 l_2 \cos\alpha_2\right) + I_2\right]\ddot{\alpha}_1 + \left(m_2{l_2}^2 + I_2\right)\ddot{\alpha}_2 + m_2 L_1 l_2 \sin\alpha_2\, {\dot{\alpha}_1}^2 + m_2 g l_2 \cos(\alpha_1 + \alpha_2) \quad (11)$$

Where $\alpha_1 = (180 - \theta_1)$ and $\alpha_2 = (180 - \theta_2)$

1.3 Results

A normal healthy subject (age = 29 years, weight = 70 kg, Height = 1.60 m) played this game in front of a PC and Kinect by moving its right arm.

As per biomechanics rule [24], the length of upperarm and forearm is 0.297 m and 0.406 m respectively whereas the mean lengths of upper arm and forearm measured by Kinect sensor are found to be 0.24 m and 0.366 m respectively. As the anthropometric data from biomechanics rule are considered as standard,

Error in the measurement could be estimated for upperarm as:

$$\frac{0.297 - 0.24}{0.297}\, x\, 100 = 19.19\%$$

Error in forearm measurement:

$$\frac{0.406 - 0.366}{0.406}\, x\, 100 = 9.85\%$$

Joint trajectory is shown in Fig. 6 along with the posture of upperarm and forearm. The joint angle of shoulder and elbow is shown in Fig. 7. Joint velocity and acceleration of shoulder and elbow is calculated using Matlab and plotted with respect to time data as shown in Fig. 8 and 9. Joint torque is computed based on the mathematical model as per the equations (10) and (11), shown in Fig. 10. We have ignored the frictional force and muscle stiffness in the formulation of the joint torque.

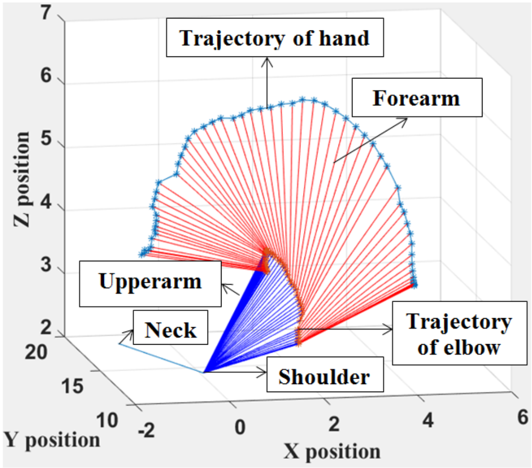


FIGURE 6: TRAJECTORY OF THE HUMAN ARM

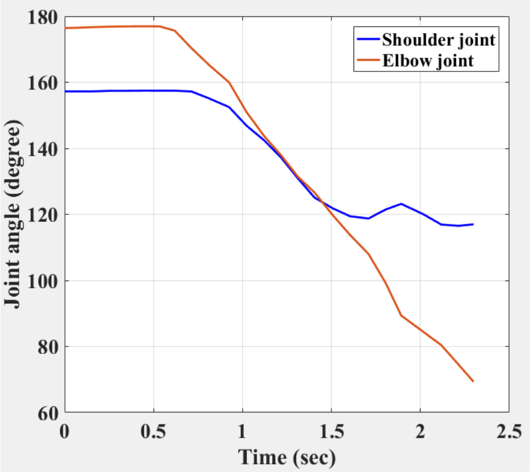


FIGURE 7: JOINTS ANGLE MEASURMENT

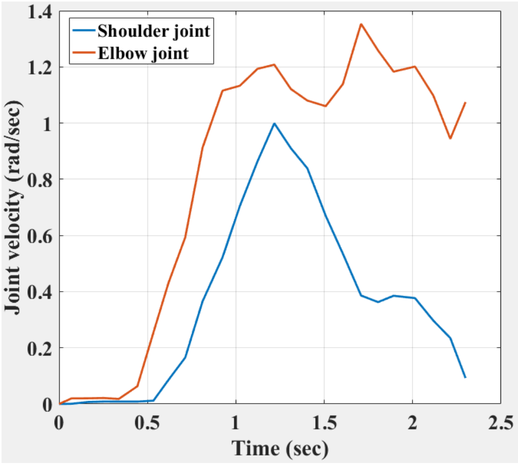


FIGURE 8: JOINT VELOCITY MEASURMENT

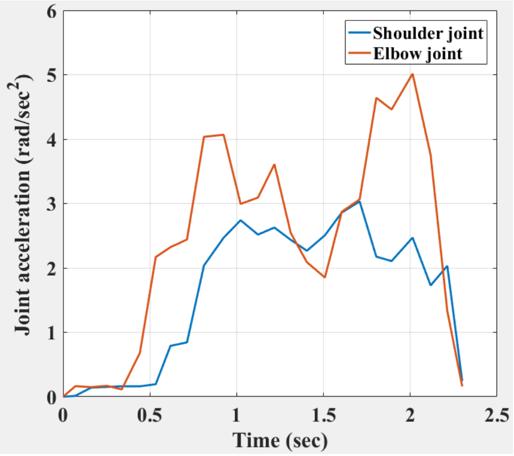


FIGURE 9: JOINT ACCELERATION MEASURMENT

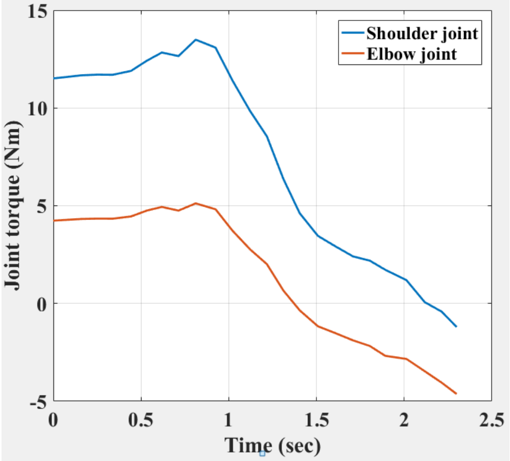


FIGURE 10: JOINT TORQUE MEASURMENT

Interpretation

In this paper, we have demonstrated a Kinect sensor based and voice controlled basketball game for exercise of shoulder and elbow joint suitable for post-stroke rehabilitation. This paper assumes that the user has some residual strength that they are able to move their arm to undertake rehabilitation exercises. Here we have only considered abduction-adduction movement of shoulder and flexion-extension movement of elbow for playing the game.

Microsoft Kinect is an inexpensive device available in market; therefore a user can perform the exercises by playing in front of the sensor at home. Due to the integration of different software tools like Microsoft visual studio, Unity and Matlab, the whole task of the game is distributed and each task is performed by a specific tool. While playing the game, it also prompts motivating words to user after crossing a set level making it interesting and engaging to the user. This technique is aimed to enhance the amount of user effort in joint movement.

For estimating the health condition of users, joint parameters are measured using Kinect sensor without making any physical contact with them. All measured data from Kinect sensor like position vectors and joint angle are stored in a spead sheet (Excel file) and more joint features such as velocity, acceleration and torque are extracted using Matlab programs which could be used for further analysis. Apart from the joint attributes, joint postures of upperarm and forearm can be plotted along with the trajectory to show the coordination between joints and the synergy of pattern movements after stroke. The generated report can be sent to physiotherapist for clinical interpretations. Currently this work is in progress and we intend to compare the results with the standard measurement approaches.

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