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Squat Exercise Abnormality Detection by Analyzing Joint Angle for Knee Osteoarthritis Rehabilitation

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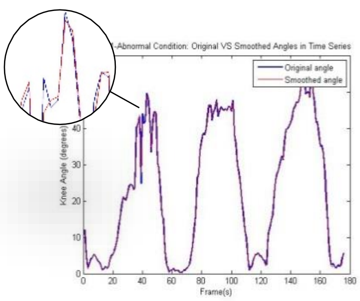
Graphical abstract



Abstract

Normally, osteoarthritic knee patients experienced 1) difficulties controlling their fine motors, 2) lack of muscle strength, and 3) limited range of motion. The limitations can be improved by physiotherapy exercises to 1) enhance flexibility and mobility of joints and 2) increase strength and endurance of the muscles. However, the patients should be individually monitored so that the exercises are performed correctly, effectively and efficiently. This paper focuses on squat exercise monitoring for knee osteoarthritis rehabilitation. The patient's movement is captured by using a low cost 3D camera, Kinect sensor for skeletal tracking to recognize and track people without using marker. 3D coordinates of each joint is retrieved from the skeleton data, where a joint angle is derived based on two intersecting human body segments. Time series of the joint angles during the squat exercise are recorded, which are then smoothed by Double Exponential Smoothing technique to find the variability between them. The proposed method is validated by using simulated videos of squat exercise performed by 10 healthy volunteers of various physiques and gender to simulate the normal and abnormal conditions. Mean Squared Error (MSE) is calculated between the measured and smoothed angles to classify the movement either normal or abnormal. The parameters for smoothing and trend control used are 0.8928 and 0.7256, respectively, which are derived based on optimal MSE of the 10 volunteers. The simulation results show that the average MSE for each 10 samples of normal and abnormal conditions are 3.1358 and 10.5205, respectively. Hence, a simple threshold method has been developed to detect movement abnormality while doing squat exercise.

Keywords: Osteoarthritis, rehabilitation, kinect sensor, double exponential smoothing

Abstrak

Pada kebiasaannya, pesakit osteoartritik akan mengalami 1) kesukaran untuk mengawal motor halus, 2) kelemahan otot dan 3) pergerakan yang terhad. Kelemahan dan kesukaran ini boleh diperbaiki dengan latihan fisioterapi bagi 1) meningkatkan fleksibiliti dan mobiliti sendi serta 2) meningkatkan kekuatan dan daya tahan otot. Walau bagaimanapun pesakit yang menjalani latihan ini perlu dipantau pergerakannya supaya latihan tersebut dilakukan dengan betul, cekap dan berkesan. Kertas kerja ini memberi tumpuan kepada pemantauan senaman mencangkung untuk memulihkan penyakit osteoarthritis bahagian lutut. Pergerakan pesakit semasa latihan dirakam dengan menggunakan kamera 3D berkos rendah, iaitu penderia Kinect di mana ia mampu mengesan kerangka tetulang manusia dan seterusnya mengenali serta menjejaki tubuh badan manusia tanpa memerlukan proses penandaan. Koordinat dalam tiga dimensi untuk setiap sendi diperolehi daripada maklumat kerangka tetulang, di mana sudut sendi diperolehi daripada titik persilangan di antara dua segmen anggota badan. Setiap sudut sendi akan direkod dan seterusnya dilicinkan dengan menggunakan kaedah Pelicinan Eksponen Berganda untuk mengkaji perbezaannya. Kaedah yang dicadangkan disahkan dengan menggunakan video simulasi senaman mencakung yang merangkumi keadaan normal dan tak normal yang dilakonkan oleh 10 orang sukarelawan yang sihat yang terdiri daripada pelbagai bentuk fizikal dan jantina. Ralat Purata Kuasa Dua (RPK) di antara sudut terukur dan sudut terlicin itu dikira untuk mengelaskan pergerakan yang normal dan tak normal. Parameter pelicinan dan arah aliran yang digunakan adalah masing-masing sebanyak 0.8928 dan 0.7256, di mana ianya diperolehi daripada nilai RPK yang optimum daripada 10 orang sukeralawan tersebut. Keputusan simulasi menunjukkan bahawa purata RPK untuk setiap 10 sampel keadaan normal dan tak normal adalah masing-masing sebanyak 3.1358 dan 10.5205. Oleh itu, satu kaedah ambang yang mudah telah dibina untuk mengesan pergerakan yang tak normal apabila melakukan senaman mencangkung.

Kata kunci: Osteoartritis, pemulihan, penderia kinect, pelicinan eksponen berganda

1.0 INTRODUCTION

Osteoarthritis (OA) is the most common type of arthritis, which is also a type of complex multifactorial disorder [1-2]. Furthermore, this well-known joint failure is the leading cause of chronic disability. The occurrence of OA is prevalence in the elderly people due to extended life expectancy, although it may happen to young people. In Malaysia, knee OA is the most treated rheumatic disease that depends heavily on the factors of age, race and gender [3]. From the study by The Control of Rheumatic Diseases, COPCORD has shown that the knee OA contribute up to 64.8% of the cases.

Normally, the osteoarthritic knee patients experience difficulties in controlling their fine motor, lack of muscle strength, and limited range of motion. Physiotherapy, which is a non-pharmacological treatment is considered as the most important intervention in the management of knee OA, where it should be started as soon as possible in order to improve flexibility and mobility of joint, increase muscle strength and endurance of muscle, to reduce pains and to prevent further disability [4-5]. Majority of patients cite that they lack of motivation to perform the exercises regimen regularly [6]. Besides, there is insufficient number of exercises performed in the therapy session due to limited tool kits, which prolongs the treatment period.

Continuous monitoring of patient's movements during rehabilitation is crucial and desirable so that the patient's progress can be monitored to reduce the treatment period. The monitoring measurements need to be sufficiently precise in order to determine whether a patient condition is becoming more stable or deteriorate. However, the monitoring process becomes complicated once the physiotherapist deals with a group of patients. Therefore, an effective tool is needed to help them to monitor the patients exercise during rehabilitation.

This research investigates the potential of low cost 3D Kinect sensor to track the movement of segmented human body and to detect the incorrect movement of the half-squat exercise.

2.0 MOVEMENT DETECTION

The sensing element for data acquisition is very important in medical instrument such as Lukotronic AS 200 (Lutz Mechatronic Technology e.U.). The commercial medical camera system with active markers and a computer with GaitLab software were used to measure movements in 3D space[7]. However, the devices need to be professionally installed by technical personnel due to complex setup, especially to accurately define the anatomical coordinate system, which will influence the mechanical elements on the patient's body segments[8].

As oppose to the previous systems, Masdar et al.[9] used an economical wearable sensor system, multiple micro-electromechanical systems (MEMS) vibratory gyroscope and flex-sensors to track and measure body joint flexion. Unfortunately, relying only on wearable sensors posed significant challenges for a large scale monitoring. These challenges include technological barriers such as energy consumption and efficiency as well as cultural hindrances such as stigma associated with the use of medical assisted devices for home-based clinical monitoring[10].

Depth imaging technology has advanced dramatically over the last few years and Kinect sensor was proven to be practical in various applications such in robotics, medical, surveillance etc.[11-12]. In this study, we demonstrated the use of commercial off-the-shelf product in rehabilitation system and leveraged the advantages for physiotherapist and patients. The Windows based Kinect sensor is a set of technologies that enable humans to interact with the computers. This low cost 3D motion sensor was used in [13] and the results showed that it is suitable to capture the relative 3D Cartesian coordinates with minor errors (<1 cm) in ideal range of 1 m to 3 m. Although, the sensor is less precise than other types of optical motion capture system, still it can be very useful for rehabilitation treatment. Furthermore, this affordable and portable sensor allows direct detection of anatomical axes of the patient's body segments (Fig. 1) without attaching any passive or active markers to the body[14]. Thus, it helps the patients to perform the exercise comfortably and flexibly with respect to the patient and physiotherapist need.

3.0 SYSTEM DESCRIPTION

The system was designed to track the patients' lower extremity for particular exercise without the use of markers. The system aims is to track the right leg segments (tight and shin) of the subject by using Microsoft Kinect for Windows V1 sensor, so that joint angles can be extracted. The sensor consists of RGB-D camera of 640X480 size captured at 30 frames per second with depth sensor range of 0.8 to 3 meters (in Near Range Mode)[15] and the full body detection is within 2.5 to 3 meters. A minimal working space was considered so that the rehabilitation area can be optimized (Fig. 2). The sensor and its Application Programming Interface (API) simplified the process of capturing video stream data, image pre-processing and creating skeleton model of the subject. The skeleton data consists of a set of 20 joints and provides tri-dimensional coordinates (x, y and z) for each joint (Fig. 1). The acquired data sets from the sensor are then fed to the MATLAB workspace to enable further data analysis.

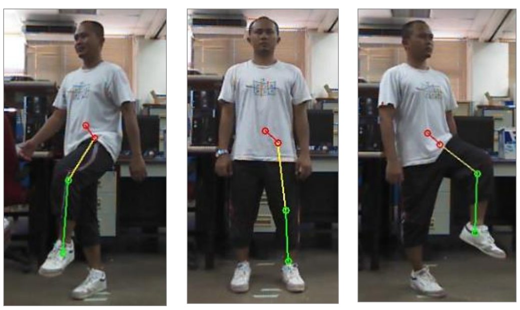


Figure 1 Multiple angles view for marker-less Centre-Hip Knee-Ankle joints detection for right leg

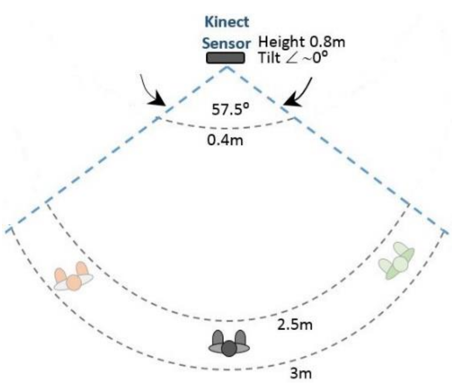


Figure 2 Range of the optimal setup

Then, the vectors of tight and shin (Fig. 3) are computed based on two difference joint coordinates in 3D space. The distance between a pair of joints, *i* and *j* is computed using the Euclidean Distance[16] as stated in equations (1.1 to 1.3):

$$d_{(k,l)} = \sqrt{(x_k - x_l)^2 + (y_k - y_l)^2 + (z_k - z_l)^2} \quad (1.1)$$

$$d_{(k,m)} = \sqrt{(x_k - x_m)^2 + (y_k - y_m)^2 + (z_k - z_m)^2} \quad (1.2)$$

$$d_{(l,m)} = \sqrt{(x_l - x_m)^2 + (y_l - y_m)^2 + (z_l - z_m)^2} \quad (1.3)$$

From the computed vectors, the knee angle, θ_l is calculated using Law of Cosines as shown in equation (2).

$$\theta_1 = cos^{-1}\left(\frac{{d_{(i,j)}}^2 + {d_{(j,k)}}^2 - {d_{(i,k)}}^2}{2d_{(i,j)}d_{(j,k)}}\right) \quad , \quad 0 \leq \theta_1 \leq \pi \quad (2)$$

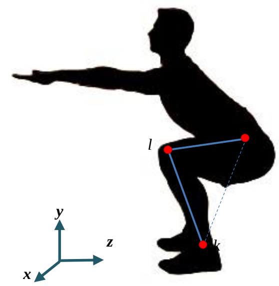


Figure 3 Location of interest points and angles measured during exercise

4.0 REHABILITATION EXERCISE

Physical therapy is an extremely important part of rehabilitation and it should be started as soon as possible to reduce pain and improve physical capability. Apart from aquatic and land-based exercises, rehabilitation also include joint range of movement (ROM) and muscle strengthening exercises[4]. In order to obtain an optimal outcome, it is important for patient to regularly practice home-based physiotherapy.

Squat is a well-known exercise, which is commonly used in rehabilitation programs, especially after knee surgery (Fig. 4). It is an effective and convenient exercise especially for home exercise regimen which does not require any special equipment. It is a closed-chain exercise where the ankle, knee and hip joints must be well coordinated to develop a functional movement pattern as well as to strengthen the muscles that support the knee, which reduce the stress on the knee joint and help the joint to absorb shock.

The steps for the squat exercise are as follow[17]:

Step 1: Stand with feet shoulder distance apart and stretch arms out in front of thighs;

Step 2-3: Slowly bend the knees until half-sitting position. *Note:* Keep your back straight and chest lifted;

Step 4: With feet flat on the floor, hold the position for one second;

Step 5: Then, slowly raise up to the original position (reverse order *Step 1-3*).

The squat exercise is beneficial if and only if it is correctly executed, otherwise it could result in undesirable consequences.

4.1 Normal Condition

In this simulation, 10 healthy volunteers of different physiques and gender performed the double leg half squat exercise (Fig. 4.a). A moderate slow squatting speed was chosen since the patients' movements are expected to be slow during the rehabilitation process. The first and last gait cycle of each process are excluded from the analysis to avoid acceleration/deceleration phase.

4.2 Abnormal Condition

Normally, knee OA patients are facing some degree of pain, discomfort, and stiffness during physical therapy. In order to support the effected knee, an immobilizer is used while undergoing physical therapy. In this simulation, the right knee is treated as the failure joint. Hence, the same set of volunteers performed the single half squat exercise (Fig. 4.b) with a single leg only. The reason is to simulate any abnormality movement, especially the instability. The volunteers experienced pains on the particular joints and muscles with difficulties to balance their position since their full weight is supported by a single leg.

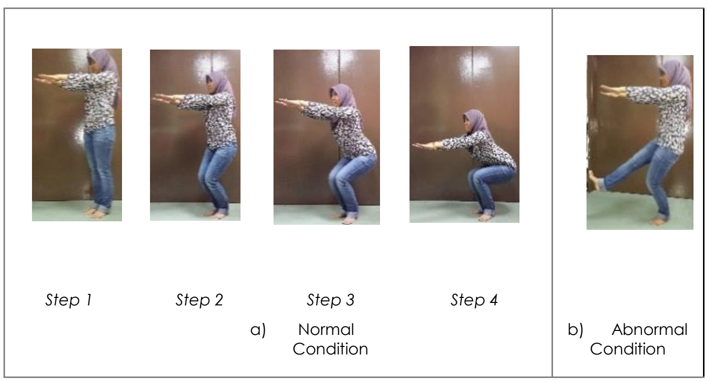


Figure 4 Squat exercise procedure

5.0 JOINT ANGLE TRACKING

As expected, unwanted noise was observed during skeletal tracking, which is a common issue when using a Kinect sensor[18]. There are several parameters that will result in different characteristics such as shadow, room lighting, subject size, apparel, pose and distance from the Kinect. Therefore, an algorithm for filtering the incoming data from the sensor is required to eliminate the random or white noise before it is being used for further process.

Double Exponential Smoothing (DES) are commonly used in financial market and economic data analysis where this technique may be applied to any time series data. Chung and Kim[19] proved DES-based method produced better result than classical extended Kalman Filter and can run 100 times faster. Besides, Juremi et al. [20] also applied DES on EEG signal. Both equations below are associated with DES:

$$S_t = \alpha y_t + (1-\alpha)(S_{t-1} + b_{t-1}) \quad , \quad \alpha \epsilon \, [0,1] \qquad (3)$$

$$b_t = \beta(S_t - S_{t-1}) + (1-\beta)b_{t-1} \quad , \quad \beta \epsilon \, [0,1] \qquad (4)$$

Where y_t is the original raw value (measured angle) and α is smoothing parameter, while S_t stands for smoothed value. The trend, b_t is relative to the trend control parameter and β which must be chosen in concurrence with α. The equation (3) is responsible to tune the S_t by summing the previous b_t to the recent S_t. The equation (4) is used to update b_t, which is expressed as the difference between the last two S_t values. Thus, it helps to eliminate the variation in current S_t value. There are several schemes to choose the initial values for S_t and b_t, but in this paper, the same scheme proposed by [19-21] is used; where $S_1 = y_1$ and $b_1 = y_2 - y_1$.

The knee angle sampling data captured in normal condition from each 10 volunteers were smoothed using DES. Notice that in DES, the smoothing constant determines how fast the weights of the series decays until it produces a stable angle data. In this situation, the constant values objectively have been chosen, where all the normal condition sample angle data are smoothed and then the values of constants that minimizes the error size of Mean Squared Error (MSE) were selected. The MSE formula is as follows:

$$MSE = \frac{1}{n} \sum e_t^2 \qquad (5)$$

Where the error, e is the difference between the original value of the series at the current period and the smoothed angle data of previous current period made. This is written as:

$$e_t = y_t - S_{t-1} \qquad (6)$$

Fig. 5 and 6 illustrate an example of DES implementation on the raw angle data and searching of optimum minimum MSE for all possibilities of $\alpha, \beta \; \epsilon \; [0,1]$, respectively.

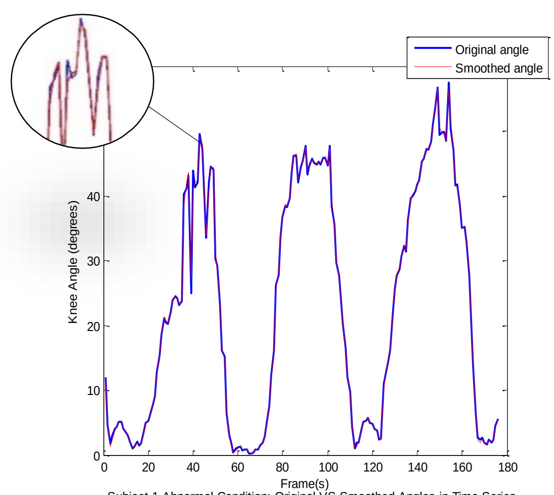


Figure 5 The original and smoothed knee angles

Table 1 summarized the optimum performance of DES associated with different set of α and γ values, where the minimum MSE is 1.3381 and maximum MSE is 4.9345 with an average of MSE with 3.0445.

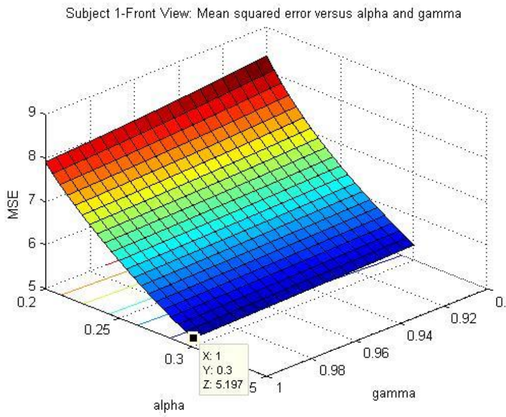


Figure 6 MSE versus alpha and beta constants

Henceforth, the average value of α and γ of 0.8928 and 0.7256, respectively are being used to recalculate the MSE value for each subject for normal and abnormal conditions.

6.0 RESULT AND DISCUSSION

Based on the simulated results, it is clear that the DES technique is able to reduce the random noise of raw angle data from Kinect sensor. From 10 normal exercise data, the average of MSE is equal to 3.1358 for the given constants; α=0.8928 and γ=0.77256. Whereas, the average MSE for 10 abnormal exercise data is 10.5205. From here, it can be concluded that the average MSE for normal exercise condition is lower i.e. better than the abnormal condition. When individually analyzed as shown in (Fig. 7), subject 4 and 8 performed an acceptable correct movement during both normal and abnormal exercises compared to the others. They were able to keep their position in balance while performing the abnormal exercise. On the contrary, subject 1 and 6 movements were considered as poor performances based on the MSE criterion.

7.0 CONCLUSION

This paper described the method for tracking the human movements by using an affordable, marker-less, portable and easy-setup 3D camera, the Kinect Sensor. This sensor is able to track the full body movement within a reasonable range to be used in a minimal space rehabilitation center or in-house exercise. The tracked angle data is smoothed using DES to reduce the random noise due to environment constraint. A simple threshold method is then used to classify the squat exercise either as normal or abnormal. In addition, the acceptable correct movement range during squat exercises were evaluated between two conditions based on the MSE criterion.

Table 1 The performance of DES implementation on raw angle data from kinect sensor

Subject #	NORMAL CONDITION						ABNORMAL CONDITION		
	Optimal Minimum MSE			MSE with constant Alpha and Beta			MSE with constant Alpha and Beta		
	Alpha	***Beta***	***Min MSE***	***Alpha***	***Beta***	***MSE***	***Alpha***	***Beta***	***MSE***
1	0.7750	0.9550	3.5445			3.6033			32.8888
2	0.7550	1.0000	1.3381			1.3924			3.4227
3	0.9150	1.0000	1.6408			1.8635			5.2755
4	0.8900	0.7900	2.0555			2.0620			2.2489
5	0.9150	0.7000	2.5554	***0.8928***	***0.7256***	2.5567	***0.8928***	***0.7256***	7.2127
6	0.9800	0.5700	2.9041			2.9256			23.0376
7	0.8700	0.6450	4.9345			4.9949			8.0802
8	0.9600	0.3950	4.1677			4.4200			5.3442
9	0.9750	0.4750	4.2596			4.4041			6.6557
10	0.8930	0.7260	3.0450			3.1350			11.0383
Min	0.7550	0.3950	1.3381			1.3924			2.2489
Max	0.9800	1.0000	4.9345	***0.8928***	***0.7256***	4.9949	***0.8928***	***0.7256***	32.8888
Mean	***0.8928***	***0.7256***	3.0445			3.1358			10.5205

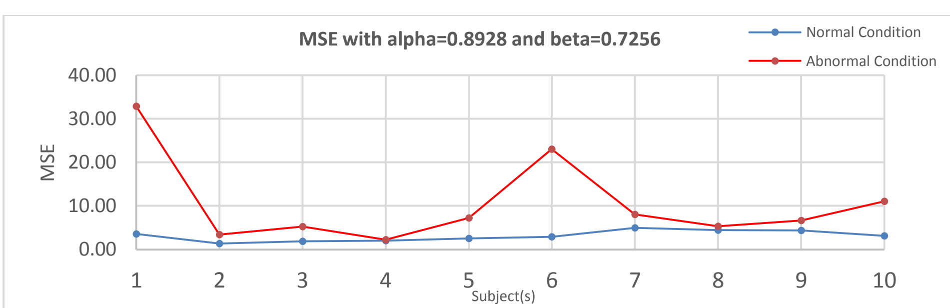


Figure 7 Comparison error-size of normal and abnormal condition for angle data

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