# Evaluating Accuracy and Usability of Microsoft Kinect Sensors and Wearable Sensor for Tele Knee Rehabilitation after Knee Operation

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Abstract: The Microsoft Kinect sensors and wearable sensors are considered as low-cost portable alternative of advanced marker-based motion capture systems for tracking human physical activities. These sensors are widely utilized in several clinical applications. Many studies were conducted to evaluate accuracy, reliability, and usability of the Microsoft Kinect sensors for tracking in static body postures, gait and other daily activities. This study was aimed to asses and compare accuracy and usability of both generation of the Microsoft Kinect sensors and wearable sensors for tracking daily knee rehabilitation exercises. Hence, several common exercises for knee rehabilitation were utilized. Knee angle was estimated as an outcome. The results indicated only second generation of Microsoft Kinect sensors and wearable sensors had acceptable accuracy, where average root mean square error for Microsoft Kinect v2, accelerometers and inertial measure units were 2.09°, 3.11°, and 4.93° respectively. Both generation of Microsoft Kinect sensors were unsuccessful to track joint position while the subject was lying in a bed. This limitation may argue usability of Microsoft Kinect sensors for knee rehabilitation applications.

## 1 INTRODUCTION

Telerehabilitation after knee surgery is recognized as one of the well-known type of telemedicine. Nowadays, this service is wildly provided in the world. Previous studies remarked low-bandwidth Audio/Video communication improved rehabilitation program after total knee replacement remotely (Tousignant et al., 2009; Russell et al., 2011; Tousignant et al., 2011).

Motion capture systems are utilized to evaluated improvements in patients' physical activity performance beside the subjective rehabilitation test. However; marker-based motion capture systems are highly precise and known as a gold standard, they have several limitations. First, the motion capture systems are considerably expensive. Moreover, data acquisition process due to attaching several markers on the subject's body and calibration process is relatively complex. Finally, the marker-based motion capture systems are not portable, and large space is required.

Consequently, the marker-based motion capture systems are not considered as a proper candidate for tracking human activities during daily rehabilitation sessions.

Wearable sensors and Microsoft Kinect sensors are the most common systems are being employed as low-cost, portable and less complex alternative for human motion tracking system.

Several studies utilized Microsoft Kinect sensors as marker-less physical activity tracker for physical rehabilitation program (Pedraza-Hueso et al., 2015;



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Vernadakis et al., 2014; Lange et al., 2012; Pavão et al., 2014).

While wearable sensors were also employed as a human motion capture system for tracking patient's performance during telerehabilitation program (Piqueras et al., 2013; Tseng et al., 2009).

In 2012 Microsoft introduced a RGB-Depth camera as a part of Microsoft Xbox 360 called Microsoft Kinect Xbox 360 (or Kinect v1) (Schröder et al. 2011). Microsoft Kinect SDK v1.8 using the depth images and embedded skeleton algorithm provides the geometric positions of 20 joints of each detected body in the space (Microsoft 2013).

The second generation of Microsoft Kinect was presented together with Microsoft Xbox One and known as Microsoft Kinect One (or Kinect v2). Several improvement in the sensors have been applied in the Kinect v2 (Sell and O'Connor, 2014). Microsoft Kinect SDK 2.0 was developed for Kinect v2 and enables developer to record estimated position of 25 joints for each detected skeleton (Microsoft, 2014).

Consequently, several studies were conducted to assess accuracy and reliability of Microsoft Kinect sensors for static postures(Xu and McGorry, 2015; Darby et al., 2016; Clark et al., 2012), gait (Mentiplay et al., 2015; Auvinet et al., 2017; Eltoukhy et al. 2017), body sway (Yeung et al., 2014), and joints angles in specific physical activities(Anton et al., 2016; Woolford, 2015; Huber et al., 2015) using gold standard marker-based motion capture systems.

Wearable sensors such as accelerometers, gyroscopes and inertial measure units (IMU) are also being used to track physical activities. Boa et al. used five biaxial accelerometers to classify 20 activities with 84% accuracy (Bao and Intille, 2004) while Karantonis et al., (2006) classified 12 physical tasks using a tri-axial accelerometer with 90.8% accuracy. Joints and limb orientation can be estimated by using accelerometer and gyroscope sensors (Hyde et al., 2008; Roetenberg et al., 2013) but it still has one degree of ambiguity in the 3-dimension space. Accuracy of human body orientation was improved by using IMU sensors (Ahmed and Tahir, 2017; Lin and Kulić, 2012).

In this paper, accuracy and usability of both generation of Microsoft Kinect sensors (Kinect v1 and Kinect v2), IMUs and accelerometer sensors for seven common exercises in knee rehabilitation program were investigated by using a gold standard marker-based motion capture system. The main aim of this study was to evaluate Microsoft Kinect sensors and wearable sensors for knee rehabilitation application.

# 2 METHODS

## 2.1 Data Collection

In this study, seven series of recording were performed to assess accuracy and usability of mentioned human activity tracking systems simultaneously while subject doing common rehabilitation exercises for knee. Eight Qualisys Oqus 300/310 cameras were pointed to the area of interest. The recordings were carried out using Qualisys Track Manager 2.14 (build 3180) with 256Hz sampling frequency. Pelvis markers were placed on the Ilium Anterior Superior and Ilium Posterior Superior. Knee joint defined by Femur Medial Epicondyle and Femur Lateral Epicondyle markers, while Fibula Apex of Lateral Malleolus and Tibia Apex of Medial Malleolus landmarks were used for defining ankle joint. Consequently, TH1-4, SK1-4, FCC, FM1 and FM5 landmarks were employed to track lower limbs movement (van Sint Jan, 2007).

Kinematics and kinetics measurement of lower extremities were worked out using Visual 3D v6 software based on the Qualisys recordings (C-Motion, 2017).

A pair of Kinect v1 and Kinect 2 were also utilized to record joint positions. Two custom applications were developed to capture, and store estimated skeleton and corresponding joint positions. Microsoft Kinect SDK version 1.8 and version 2.0 were utilized in the software development. A server application was also developed to establish global timing between applications using transmission control protocol/Internet protocol through the local network. Sampling frequencies were adjusted at 30Hz, which is highest available rate.

Linear acceleration, angular velocity, and magnetic field were acquired using embedded accelerometer, gyroscope and magnetometer sensors in Shimmer 3 (Shimmer Sensing, 2016). Shimmer wearable sensors were fixed on thigh, shin and foot and the data including timestamps were streamed to the computer using Bluetooth in real-time. Sampling frequency for sensor were set at 128Hz. Acceleration, angular velocity, and magnetics field recording range were set at ±2g, ±500dps, ±1.3Ga respectively.

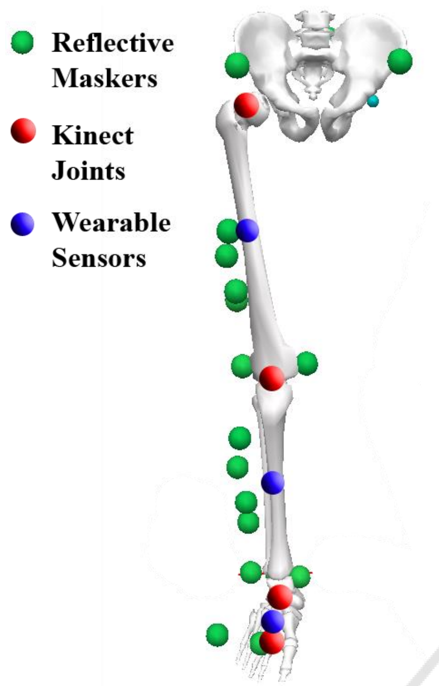


Figure 1: Positions of reflective markers, Microsoft Kinect virtual landmarks and placement of wearable sensors. Green circles show position of reflective markers and red circles show position of estimated joint. Wearable sensors were fixed at blue circles.

## 2.2 Procedure

Seven common exercises for knee rehabilitation were performed during the recordings. These exercises are mainly involving knee flexion and extension. Table 1 describes each exercise and Figure 2 shows the exercise visually.

In the first three exercises both Kinect sensors were mounted on the ceilings while for the rest of exercises Kinect sensors were place on the table with 1m height. The Z-plane of Kinect sensors was perpendicular to coronal plane in all exercises except exercise four and five (which in these two exercises the Z-plane of Kinect sensors was perpendicular to median plane). Figure 3 shows position and alignment of Kinect sensors corresponding to the subject's body.

Table 1: Exercise details.

| | Posture | Physical Activity |
|---|---|---|
| Exercise 1 | Laying | Ankle Dorsi/Plantar flexion |
| Exercise 2 | Laying | Knee flexion/extension |
| Exercise 3 | Laying | Knee flexion/extension |
| Exercise 4 | Sitting | Biking |
| Exercise 5 | Sitting/ Standing | Sit to Stand |
| Exercise 6 | Sitting | Leg bend and stretch |
| Exercise 7 | Sitting | Knee flexion/extension |

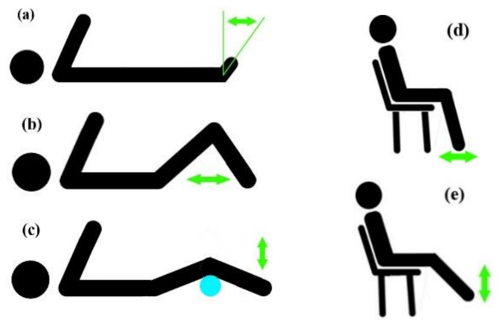


Figure 2: Visual explanation of exercises including posture and movement. The green arrow shows direction of movement. (a) exercise 1, (b) exercise 2, (c) exercise 3, (d) exercise 6, (e) exercise 7.

## 2.3 Data Analysis

The recorded data were filtered using a 10Hz low pass filter implemented using a 20$^{th}$ order IIR Butterworth filter. Data were synchronized in two steps. First data were synchronized using recorded timestamp. In the second step, small delays due to the data transferring and processing latency were removed by using dynamic time warping.

The knee joint in Kinect skeleton data was define by virtual thigh, shin, and foot bones using position of hip, knee, ankle, and foot joints position. Equation 1 represents calculated knee angle ($\theta_{knee}$) using virtual bones.

$$\theta_{knee} = \arccos\left(\frac{\vec{B}_{Thigh}.\vec{B}_{Shin}}{\|\vec{B}_{Thigh}\|.\|\vec{B}_{Shin}\|}\right) \quad (1)$$

Similarly, knee angle was calculated based on acceleration data by using the acceleration vectors of sensors on the thigh, shin and foot.

The knee angle in the gold standard recorded was estimated in Visual 3D software by referencing thigh and shank modelled bones respectively.

Orientation of IMU sensors were calculated using attitude and heading reference system transformation algorithm by fusing triaxial acceleration, triaxial angular velocity, and triaxial magnetic field recording (Kalkbrenner et al., 2014; Madgwick et al., 2011). Consequently, orientation of each sensor was represented by quaternions. Using shin and thigh quaternions, the knee angle was calculated based on equation 2.

$$\theta_{knee} = 2 \times \arccos\left(\left(Q_{Shin} \times Q_{Thigh}^{-1}\right).w\right) \quad (2)$$

## 2.4 Statistical Analyses

The range of motion (ROM) for all recordings were calculated based on estimated knee angle. Root-mean-square error (RMSE) and Pearson correlation coefficient (R) were calculated. Coefficient of variation between two systems was also calculated as a ratio of error to mean comparing the gold standard. 95% limits of agreement (LOA) and bias (B) were analysed using Bland-Altman analysis.

# 3 RESULTS

The results showed Microsoft Kinect SDKs (SDK 1.8 and SDK 2.0) were not able to detect body skeleton and estimated joint positions for those exercises subject laid in the bed (exercise 1-3). However, Kinect sensors were place perpendicular to subject's coronal plane.

The results indicated the estimated knee angle using accelerometer presents less RMSE. Mean RMSE were 2.085° and 3.107° respectively in accelerometers and IMUs recordings, while the mean values for Kinect v1 and Kinect v2 were 13.408° and 4.930°.

The estimated knee angle using IMU sensors introduced lower RMSE than the provided knee angle with Kinect v2 except exercise 4 (biking).

According to the table 2, estimated knee angle was highly correlated with actual knee angle (correlation > 0.796).

Moreover, the results show accelerometer sensors represented higher accuracy in estimating lower boundaries of range of motion in comparison to IMUs. Whereas, Kinect sensors introduced higher difference with actual knee angle during biking exercise (see figure 4).

Bland Altman estimations indicated estimated angle with accelerometer and IMU had higher agreement with calculated values using gold standard comparing with Microsoft Kinect sensor.

# 4 DISCUSSION

This study evaluated accuracy and usability of wearable sensors (accelerometers and IMUs) and Microsoft Kinect sensors (Microsoft Kinect v1 and Microsoft Kinect v2) as a daily tracking system for knee rehabilitation applications. Hence, the most common exercises for knee rehabilitation were utilized and tracking knee angle and range of motion in interested knee were emphasized.

Qualisys marker-based motion capture system was utilized as a gold standard system for tracking lower limbs activities and C-Motion Visual 3D was employed to compute joints angle.

Microsoft Kinect v1 introduced lower accuracy in all the results (more than 10 degrees in average). While the other recording systems presented comparable accuracy. The trials showed the wearable sensors and Microsoft Kinect v2 had acceptable performance for tracking knee angle during exercises with higher and more complex physical activities like biking.

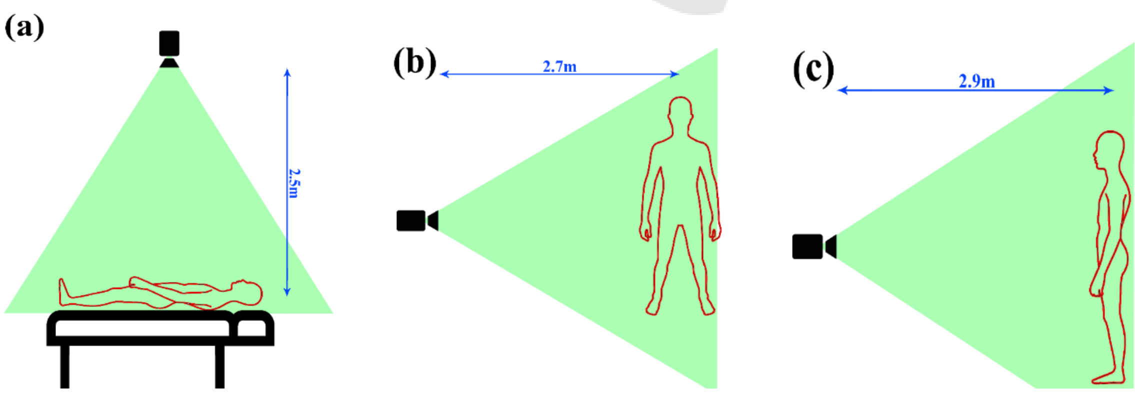


Figure 3: Position and alignment of Kinect sensors corresponding to the subject's body. (a) The subject was lying in a bed for exercise 1-3 and the Kinect sensors were mounted on the ceiling and facing the floor. (b) In the exercise 4 and 5 the Kinect sensors were put on a table with 1m height and subject did the exercises which standing sidewise corresponding to the Kinect view point. (c) In exercise 6 and 7 the Kinect sensors were put on a table with 1m height and subject trained facing the Kinect sensors.

Eltoukhy et al. (Eltoukhy et al. 2017) used Vicon marker-based motion capture system to evaluated Microsoft Kinect v2 and showed Kinect v2 measurements on knee ROM presented high consistency and agreement with the gold standard and the calculated absolute error for knee angle was 2.14°. While in this study average RMSE for knee angle was 4.93°. Bonnechere et al. (Bonnechère et al., 2014) evaluated validity of Microsoft Kinect v1 and the reported poor to no agreement between gold standard and Kinect v1 measurement for knee flexion. Bland Altman calculations for Kinect v1 in this study also emphasizes on lower agreement with gold standard in comparison to other systems. Wiedemann et al. (Wiedemann et al., 2015) used Kinect v2 to estimate knee angle in 16 different static postures. Median difference for the left knee was 0.26° where upper and lower bounds were 16.47° and -11.84°.

Madgwick et al. (Madgwick et al., 2011) and Diaz et al., (2015) used Vicon motion capture system to evaluate developed AHRS algorithm using IMU sensors. The result in this study is comparable with their finding.

In summary, we can conclude that both wearable sensors and Microsoft Kinect v2 had acceptable performance for tracking knee movements while performing knee rehabilitation exercises, but we need to keep it in mind Microsoft Kinect v2 has three noticeable limitation which they may argue usability of Kinect v2 for tracking daily knee rehabilitation exercises. First, Kinect v2 skeleton algorithm was not able to detect skeleton body and estimate corresponding joints position while the subject was lying in a bed. The first three exercises in this study were performed where the subject lying in a bed. Secondly, subjects should stand in front Kinect v2 sensor with optimal distance (2-3.5m) while the body is seen by cameras. This may pose issues while subject is doing the exercise behind a chair or any other objects may cover the body. Final limitation may argue required computation resources for estimating joint positions, while joint angle may estimate without any external computer using wearable sensors.

## 5 CONCLUSIONS

Accuracy and usability of wearable sensors and Microsoft Kinect sensors as low-cost portable alternative human body tracking systems for knee rehabilitation application were evaluated. The findings indicated that wearable sensors and Microsoft Kinect v2 have acceptable accuracy. Whereas, usability of Microsoft Kinect v2 might be argued due to it is unable to track physical activities in particular circumstances specifically while the users laying on the floor or in a bed.



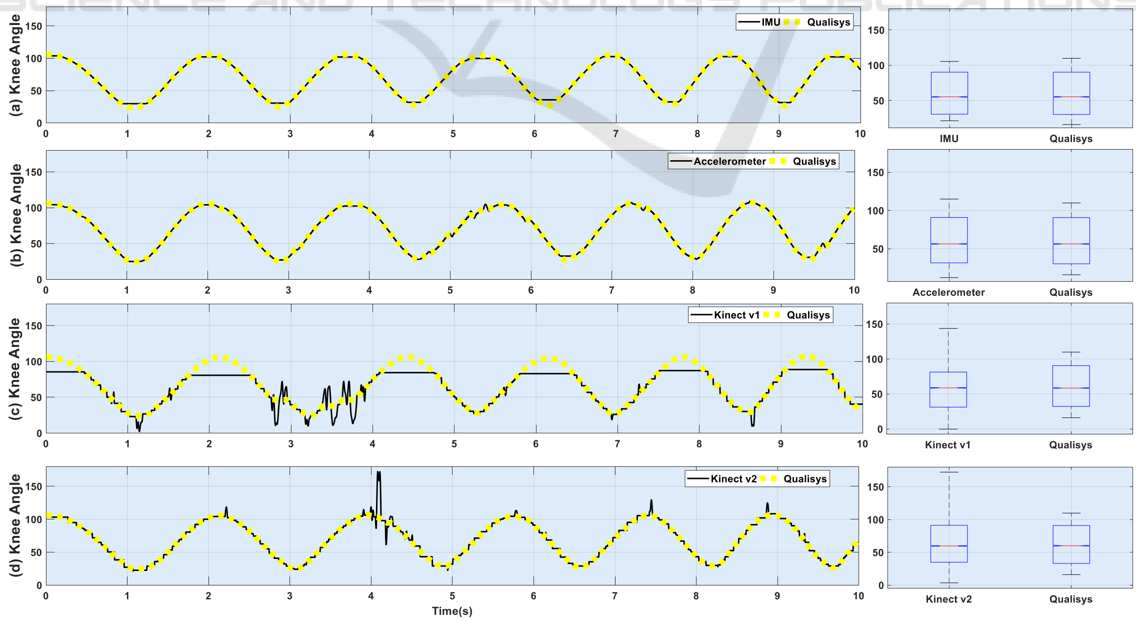


Figure 4: estimated knee angle using gold standard (dotted yellow line), (a) IMUs, (b) accelerometers, (c) Microsoft Kinect v1, and (d) Microsoft Kinect v2.

Table 2: Summary of results on estimated knee angle using Qualisys, Accelerometer sensors, IMU sensors, Microsoft Kinect v1, and Microsoft Kinect v2 for each exercise. ROM stands as range of motion and RMSE represents root mean square error. LOA, B, and CV stand as 95% limits of agreement, bias, and coefficient of variations. Pearson correlation coefficient in this table is shown by R.

| | | Exe 1 | Exe 2 | Exe 3 | Exe 4 | Exe 5 | Exe 6 | Exe 7 |
|---|---|---|---|---|---|---|---|---|
| ROM | Qualisys | [20,25] | [22,102] | [2,95] | [16,110] | [21,85] | [22,105] | [19,116] |
| | Acc | [20,24] | [7,98] | [0,93] | [12,115] | [11,89] | [16,101] | [20,114] |
| | IMU | [18,24] | [11,101] | [3,89] | [21,105] | [33,86] | [31,102] | [23, 201] |
| | Kinectv1 | - | - | - | [0, 144] | [1,81] | [3,72] | [1,85] |
| | Kinectv2 | - | - | - | [ 3,172] | [4,106] | [10,88] | [2,99] |
| RMSE | Acc | 0.46 | 3.44 | 0.92 | 1.00 | 1.66 | 2.78 | 4.34 |
| | IMU | 0.39 | 2.73 | 0.92 | 3.78 | 6.74 | 3.34 | 3.85 |
| | Kinectv1 | - | - | - | 10.21 | 12.52 | 17.61 | 13.29 |
| | Kinectv2 | - | - | - | 5.31 | 3.57 | 6.61 | 4.23 |
| LOA | Acc | 3.86 | 22.07 | 78.28 | 5.8 | 13.41 | 8.46 | 26.21 |
| | IMU | 3.17 | 26.51 | 61.36 | 35.81 | 49.04 | 24.37 | 26.55 |
| | Kinectv1 | - | - | - | 25.25 | 33.23 | 42.63 | 26.47 |
| | Kinectv2 | - | - | - | 38.66 | 23.63 | 14.40 | 13.84 |
| B | Acc | -0.45 | -4.64 | 14.34 | 0.09 | -1.72 | -1.29 | 6.34 |
| | IMU | -0.46 | -2.88 | 11.96 | 7.81 | 13.90 | 3.77 | 4.67 |
| | Kinectv1 | - | - | - | -4.86 | -10.50 | -11.45 | -8.53 |
| | Kinectv2 | - | - | - | 7.35 | -0.76 | -3.70 | -1.78 |
| CV | Acc | 9 | 22 | 280 | 5 | 12 | 6 | 21 |
| | IMU | 7 | 27 | 210 | 31 | 43 | 18 | 21 |
| | Kinectv1 | - | - | - | 22 | 33 | 35 | 24 |
| | Kinectv2 | - | - | - | 32 | 22 | 11 | 12 |
| R | Acc | 0.894 | 0.987 | 0.999 | 1 | 0.998 | 0.994 | 0.991 |
| | IMU | 0.920 | 0.992 | 0.999 | 0.996 | 0.983 | 0.993 | 0.994 |
| | Kinectv1 | - | - | - | 0.964 | 0.908 | 0.796 | 0.949 |
| | Kinectv2 | - | - | - | 0.988 | 0.99 | 0.973 | 0.993 |



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