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Reliability and validity of an innovative method of ROM measurement using Microsoft Kinect V2

Microsoft Kinect V2 tabanlı yenilikçi bir yöntem ile ROM ölçümlerine ait geçerlilik ve güvenirlik çalışması

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Abstract

Measuring Range of Motion (ROM) is the first step of physical therapy. A new method to measure ROM by Kinect V2 whose camera type is time of flight is proposed. Colored markers are attached to related joints and then their camera centered three-dimensional world coordinates are located by Kinect. Using these coordinates, joint angle, and ROM can be accurately calculated. To analyze reliability and validity of the method, ROM measurements of right and left elbow from ten participants are taken by standard goniometer and Kinect separately. For inter-observer reliability, measurements were taken in two sessions by three physiotherapists. The reliability tests Intra-class Correlation Coefficient (ICC), Standard Error of Measure (SEM), and Minimal Detectable Change (MDC) belonging to the measurements have been obtained. To compute absolute accuracy of the method, a goniometer marked with colors has been recorded at four different angles (45, 90, 135, and 180°) by Kinect in six sessions having 50-frame periods each. Mean, Standard Deviation (SD), Root Mean Square Error (RMSE), and Limits of Agreement (LOA) values are given for each angle and session. The measurements taken for absolute accuracy clearly shows that Kinect has 1- to 3-degree error rate and below 1-degree standard deviation. Analyzing the collected data, the ICC values of Kinect measurements that are 0.94 for right arm and 0.93 for left arm in contrast with the ICC values of goniometric measurements taken by observers are 0.78 for the right arm and 0.81 for the left arm. This study indicates the proposed method has a high level of accuracy and reliability, and it can be efficiently used to measure ROM accurately.

Keywords: Kinect, ROM, Joint angle, RGB-D sensors

Öz

Hareket aralığı ölçümü fizik tedavinin ilk aşamasını oluşturmaktadır. Bu çalışmada, derinlik bilgisi veren bir kamera türü olan Kinect V2 kullanılarak yeni bir hareket aralığı ölçüm yöntemi önerilmiştir. İlgili uzva renkli işaretçiler yapıştırılıp bu işaretçilerin her birinin ağırlık merkezine ait kamera merkezli üç boyutlu dünya koordinatları bulunmuştur. Bu koordinatlar kullanılarak eklem açıları ve hareket aralığı ölçülmüştür. Yöntemin geçerlilik ve güvenirliğini test etmek amacıyla 10 katılımcının sağ ve sol dirsek açıları standart gönyometre ve Kinect ile ayrı ayrı ölçülmüştür. Gözlemci içi güvenirliklerin test edilmesi için ölçümler üç oturumda her biri en az 10 yıl tecrübeli üç fizik tedavi uzmanı ve Kinect ile alınmıştır. Güvenirlik analizlerinde ölçümlere ait sınıf içi korelasyon katsayısı (ICC), Ölçüm standart hatası (SEM) ve tespit edilebilir minimal değişim (MDC) hesaplanmıştır. Cihaz ile yapılan ölçümlerin mutlak doğruluğunu gözlemlemek için gönyometre üzerine işaretçiler yapıştırılıp dört farklı açıya (45, 90, 135 ve 180°) ayarlanarak altışar oturumda ölçüm alınmıştır. Her bir açı ve oturum için ölçümlere ait ortalama, standart sapma, ortalama karesel hata (RMSE) ve karar sınırları (LOA) bulunmuştur. Mutlak doğruluk için yapılan ölçümlerde kullanılan yöntemin 1-3° hata payı ve 1° altında standart sapması olduğu görülmüştür. Fizik tedavi uzmanlarının yaptığı ölçümlerde sağ ve sol kol için sınıf içi korelasyon katsayıları sırasıyla 0.78 ve 0.81 olarak bulunurken bu değerler Kinect için 0.94 ve 0.93 olarak elde edilmiştir. Bu çalışmada önerilen yöntemin yapılan analizler sonrası geçerli ve güvenilir olduğu anlaşılıp klinik uygulamalarda kullanılabileceği görülmüştür.

Anahtar kelimeler: Kinect, Hareket aralığı, Eklem açısı, RGB-D sensörler

1 Introduction

As a means to measure the extent of a movement of a joint, Range of Motion (ROM) is used to evaluate and classify impairments of joints in patients and to indicate results of rehabilitation programs. In order to gain ROM measurements for clinical practice, clinicians and researchers mainly use goniometers, inclinometers, and marker-based motion analysis systems in a controlled environment under the directions of medical staff. Many studies have been conducted on reliability and validity of such devices [1],[2].

Among current systems measuring joint angle, marker-based systems are recognized as the golden standard. Even though these marker-based systems provide joint angles with high accuracy, because of their cost, being hard to set up, and difficult use, researchers try to develop affordable and easy-to-use alternatives for angle measurement[3],[4]. Lately, new tools such as Kinect [5]-[9] and smart phones[10]-[12] have appeared in industry. These tools allow physician extenders, primary care physicians, and other non-trained physicians to effectively measure joints ROM and can also be used independently for self-measurements at home. Kinect and smart phones have some advantages such as being small, affordable, and convenient when modified correctly.

In this study, Kinect-based methods are considered and a novel method proposed for measuring elbow ROM. This inspires new studies to measure such as knee, ankle, and any other angles.

In the extant literature, the studies involving Kinect do not use any markers; instead, most of them use skeleton data given by Kinect SDK and the others take posture detection algorithms into account to find joint angles. The reason Kinect has not been developed for the intention of clinical usage is due to the fact that the accuracy is not at an accepted level to obtain angles. Another requirement is to use multiple cameras to increase accuracy. However, using multiple cameras increases the complexity of setup and the calibration of systems. As the skeletal data provided by Kinect do not give satisfying results in studies conducted in this area, researchers use different systems with the skeletal data or making pose estimation from the depth data [13]-[16]. In [16], to obtain kinematics, data of more than one Kinect were used in addition to wearable inertial sensors and then skeletal data were gathered fusing these data. In [13],[14], pose estimation was applied by monitoring related segmented body in the depth map.

Recent studies have focused on the validity and reliability of Kinect device for applications that are specific to postural control and rehabilitation. In [5], shoulder joint angle measurements taken by Kinect were evaluated for testing validity and reliability. In the study, the shoulder joint angle was assessed in four static poses with two trials for each of them. Using the Kinect 3D motion analysis system and two poses from the sagittal view and a clinical goniometer, shoulder angles were measured-all poses were taken from the fontal view except two poses from the sagittal view by Kinect. Considering the reliability, intra-class correlation coefficient (ICC) model (3.2) was used. The standard error of the measure (SEM) and minimal detectable change (MDC) values were calculated to gain absolute reliability. For validity, the 95% limits of agreement (LOA) between Kinect and the two measurement standards were computed for each pose.

In [7], a total of 12 separate movements were recorded by Kinect simultaneously using two different software-based tracking algorithms, IPIsoft and NITE, as well as the Motion Analysis Corporation (MAC) capture system to assess the accuracy of Kinect. Each movement was performed by 10 participants while Kinect and MAC recorded at the same time and then the root mean square (RMS) and maximum errors between Kinect and MAC values were calculated for each movement. The normalized ensemble averages from the Kinect and MAC were used in ordinary least products (OLP) regressions with 95% confidence intervals for parameters of all participants and movements. It was concluded that Kinect is a most suited tool to assess the ROM and the observation of simple movements for teaching, coaching or clinical practices. Moreover, the study advises not to use Kinect to measure longitudinal segment rotations.

In [9], the accuracy and repeatability of Kinect were analyzed comparing with a marker-based system. For that purpose, multiple positions for a testing jig were obtained in seven testing sessions – one session to gather data to assess the accuracy and the others to accumulate data in sake of test-retest reliability. Using Kinect and a marker-based motion capture system, motion data were taken for each configuration. In order to give statistical results about the accuracy of the two systems, a paired t-test was conducted with significance defined as $p<0.05$. Using the three configurations that were collected across six sessions for each configuration, test-retest reliability was assessed as well as the coefficient of repeatability, bias and limits of agreement were calculated for each system.

In the proposed system, the segment locations and joint angles are located using colored markers. After filtering the markers via RGB images, the central coordinates of them are extracted. RGB images are mapped in accordance with their depths in order to find exact locations of these coordinates in 3D. Using the coordinates of these markers, joint angles and ROM measurements have been obtained.

For the validity and reliability tests, a medical universal goniometer was used and taken as ground truth. To test the absolute accuracy, a goniometer on which markers were attached was tested in six sessions by Kinect for four different angles – 45, 90, 135 and 180. The mean and standard deviation rates belonging to each sessions were calculated. To determine validity, the 95% LOA and root mean squared error (RMSE) between Kinect and goniometer were calculated. For reliability analysis of the method, ROM measurements were obtained by both Kinect and goniometer from ten participants for right and left arms. The gonimetric measurements were taken by three physiotherapists in two sessions for inter-observer reliability. Then, the reliability tests ICC, SEM, and MDC have been obtained and the results have been given.

2 Methods

2.1 Participants & observers

Ten patients having no known elbow pathology participated in this study in which four were females and six were males. The age of the participants ranged between 22 and 33 with the standard deviation of 3.56. The measurements occurred in the physiotherapy department of a hospital (Atakent Hospital in Yalova of Turkey). During measurement sessions, the right and left elbow ROM of the participants were actively recorded. All of the participants were informed in the sessions of both Kinect and goniometer measurement. In order to evaluate inter-observer reliability, the measurements of right and left elbow ROM of participants via Kinect and goniometer were taken by three physiotherapists each of whom had a minimum of 10 years' experience. In addition, the observers measured ROM every 30 minutes to analyze intra-observer reliability.

2.2 Procedures

To measure elbow joint flexion ROM via the goniometer, the target person assumes the position of lying on the back or sitting. The arm must be alongside the body in the anatomic position. The pivot point on the elbow is the lateral epicondyle of the humerus. The arm must be positioned in a manner that the upper arm, which must be stable, needs to be parallel to the middle line of the humerus lateral and lower arm that is actively moving must keep track of the middle line of lateral of radius through radial styloid process [17].

In this study, observers used the standard universal goniometer with one degree increments to measure the elbow ROM of participants. The measurements by goniometer for right and left extremity, the patients were lying on back with active joint movement. Pivot point of goniometer put on lateral epicondyle, stable upper arm put parallel to middle line of humerus lateral, and lower arm put parallel to middle line of radius lateral through radius styloid process. The patients were then requested to perform active elbow flexion up to the level they could fold the elbow. In this way, the active elbow flexion angle was measured while the upper arm remained stable (Figure 1).

Kinect measurements were taken while the participants were standing with the active joint movement. The measurements were conducted by the instructions of the expert physiotherapists. The instructions were considered for placing markers on the arm. Therefore, the marker for the pivot point placed on humerus lateral epicondyle and other markers that are in red placed on middle line of humerus and radius lateral (Figure 1). The marker for the pivot point was colored in blue and the others in red for easy labelling. In the meantime, it was ensured that body posture of participants, e.g. fixing shoulder, not rotating arm, attaching upper arm to body while measuring flexion etc. according to the instructions. Records were taken in the sagittal plane (e.g., the Kinect device was placed parallel to participants as in Figure 2).

Figure 1: Active ROM measurement by goniometer.

Figure 2: Active ROM measurement by kinect.

2.3 Kinect tracking method and algorithm

In this study, the measurements were taken by Kinect V2 released in 2014. Its 1080p camera also includes a depth sensor of 512x424 pixel resolution. Kinect V2 provides higher resolution image and has a wider field of view compared to Kinect V1. 3D world coordinates and 2D image coordinates of 25 joints of the body can be acquired without any markers using Kinect software development kit (SDK). However, in order to accurately obtain skeleton data, the Kinect camera must view the whole body and images must be taken from the frontal plane. With the help of the marker-based method proposed in this study, images can be taken from the frontal, transverse, or sagittal planes with reasonable accuracy. The only constraint is that markers must be seen by the camera instead of the whole body.

RGB and depth sensors simultaneously work and construct images in Kinect. Camera-centered 3D world coordinates of the visible points to camera are generated by mapping images constituted with calibration between the sensors on each other [18],[19]. To obtain the elbow angle, three markers are used in this study – two are in red and one is in blue. After filtering these markers on the RGB images, coordinates of their centres are located. Then, the coordinates of marker centres are transformed into camera-centered world coordinates. Aiming to detect elbow angle, the coordinates are correctly labelled and related angle is calculated among the vectors of these coordinate pairs.

Three points are required to find an angle between two vectors in the 3D space. Assuming the center of the marker coordinates are 3D points A, B, and C, the angle between $\overrightarrow{AB}$ and $\overrightarrow{BC}$ vectors needs to be calculated. First, $\overrightarrow{AB}$ and $\overrightarrow{BC}$ vectors are calculated as in (1)and (2).

Note that :

$$\overrightarrow{AB} = \vec{B} - \vec{A} \quad (1)$$

$$\overrightarrow{BC} = \vec{C} - \vec{B} \quad (2)$$

The dot product of two vectors has the property that:

$$\overrightarrow{AB}.\overrightarrow{BC} = \|\overrightarrow{AB}\|\|\overrightarrow{BC}\| cos\theta \quad (3)$$

The angle between two vectors is denoted by θ and can be found by the following equation.

$$\theta = \arccos\left(\frac{\overrightarrow{AB}.\overrightarrow{BC}}{\|\overrightarrow{AB}\|\|\overrightarrow{BC}\|}\right) \quad (4)$$

2.4 Statistical analysis

This study aims to discover accuracy and reliability of the proposed method for measuring ROM. To that extent, accepting standard goniometer used in clinics as ground truth tool, it is compared with measurements acquired by Kinect. The statistical analysis of this comparison was evaluated with the Matlab Statistical Toolbox.

For the test-retest reliability belonging to Kinect, the ICC (3.2) model was used. In scientific studies, the acquired ICC value is interpreted as 'poor' for ICC less than 0.2, as 'fair' for ICC between 0.21 and 0.4, as 'moderate' for ICC between 0.41 and 0.6, as 'good' for ICC between 061 and 0.8, and as 'very good' for ICC between 0.81 and 1.0 [20]-[22]. To evaluate reliability, the SEM was used. The formula of SEM is given in the Equation-5. In the equation, SD indicates standard deviation and ICC stands for reliability coefficient of data. Additionally, in order to show clinically significance of the acquired results, minimal detectable change (MDC) values were obtained at the 90% reliability level using SEM as in Equation-6.

$$SEM = SDx\sqrt{1 - ICC} \quad (5)$$

$$MDC = 1.65xSEMx\sqrt{2} \quad (6)$$

To find the absolute accuracy of measurements gained by Kinect over goniometer, the values RMSE, LOA, SD, and mean were obtained for the four different angles. To that extent, the mean of the two angle measurements, which are the Kinect and the goniometer, was calculated in order to obtain the LOA in each pose. Then, the mean and SD of differences between Kinect (X_1) and goniometer (X_2) measurements were computed as in the Equation7 and Equation9, respectively. The 95% LOA was defined as the mean difference with ±1.96 SD of the difference such that 95% of the difference lay within these limits[21],[23],[24].

$$\bar{d} = \frac{1}{n}\sum_{i=1}^{n}(X_{i,1} - X_{i,2} \tag{7}$$

$$SD = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left((X_{i,1} - X_{i,2}) - \bar{d}\right)^2} \tag{8}$$

Similarly the RMSE results were calculated using Equation-9.

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(X_{i,1} - X_{i,2}\right)^2} \tag{9}$$

3 Results

3.1 Validity

To assess Kinect for absolute accuracy of measuring an angle, the markers 20 mm in diameter were placed on a standard goniometer as in Figure 3. After arranging the goniometer to the desired angle, a record of 50-frame was taken for the angle. This process repeated for four different angles (45°, 90°, 145°, and 180°) in six sessions each.

Tables 1 and 2 illuminate the comparison results between measurements taken by the Kinect and the goniometer. In Table-1, the statistical results of the measurements can be seen for each session. Here, mean, SD, and RMSE belonging to the error of deviation from goniometric angle were obtained for a 50-frame record taken in each session. According to these results, the higher error rate was detected for the angle 180° such that the other angles were providing up to 2° error and the 180° angle provided up to a 4° error.

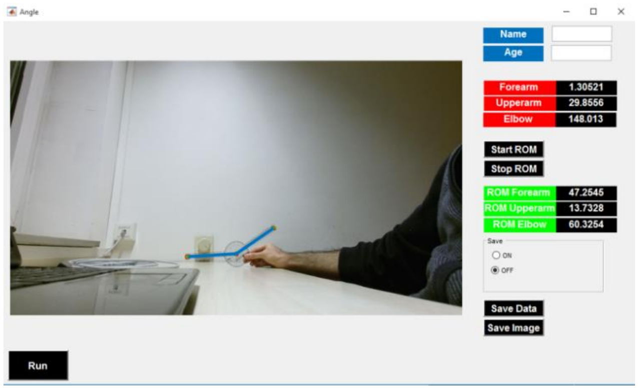

Figure 3: Marker attached goniometer to evaluate absolute accuracy and the program interface.

Table 2 shows the results that were obtained by taking the means of all the sessions. The results found by mean values are analogues with the results found for different sessions and again the higher error rate was obtained for the measurements of 180°. In order to illuminate the validity of Kinect, all of the angles were evaluated by the model ICC (2.1). As seen in Table 2, the ICC (2.1) value of 0.99 was calculated.

3.2 Reliability

For inter-rater reliability, observers conducted measurements of the right and left arm ROM from each participant in two sessions half an hour apart. Similarly, the ROM values were obtained by Kinect in three sessions.

Table 1: Statistical results for each session.

Angle		S1	S2	S3	S4	S5	S6
	Mean	44.63	44.00	44.18	45.93	44.88	44.13
45	Std	0.34	0.27	0.06	0.50	0.75	0.61
	RMSE	0.07	0.08	0.04	0.07	0.03	0.08
	LOA	-1.02/0.29	-1.52/-0.48	-0.94/-0.70	-0.04/1.92	-1.58/1.34	-2.06/0.32
	Mean	91.08	90.12	90.98	91.33	90.70	90.93
90	Std	0.50	0.30	0.06	0.42	0.40	0.43
	RMSE	0.12	0.13	0.11	0.11	0.17	0.18
	LOA	0.09/2.06	-0.47/0.71	0.85/1.12	0.49/2.17	-0.08/1.49	0.08/1.78
	Mean	134,65	133,55	135,60	135,89	134,85	135,31
135	Std	0,4296	0,7788	0,5665	0,4629	0,1853	0,4711
	RMSE	0.01	0.01	0.00	0.02	0.00	0.01
	LOA	-1.19/0.49	-2.98/0.07	-0.50/1.71	-0.01/1.80	-0.50/0.21	-0.61/1.23
	Mean	177.28	178.26	177.60	177.37	178.06	177.10
180	Std	1.10	0.99	1.07	0.99	1.07	1.09
	RMSE	0.24	0.26	0.24	0.25	0.41	0.36
	LOA	-4.88/-0.54	-3.69/0.22	-4.49/-0.29	-4.57/-0.66	-4.04/0.16	-5.04/-0.75

Table 2: Validity of the kinect compared to goniometer (Mean of all sessions).

	Mean	Std	LOA		ICC
45	44.62	0.42	-1.79	1.0	
90	90.86	0.35	-1.79	1.67	0.99
135	134.97	0.48	-1.66	1.62	
180	177.61	1.05	-3.28	-1.48	

In Table 3, the ICC, SEM, and MDC results of the right and left arm ROM for goniometer and Kinect can be seen. When considering acquired ICC results, it is obviously concluded that measurements of goniometer and Kinect both have 'very good' reliability

Comparing the measurements taken by Kinect and goniometer, it can be seen that the results belonging to Kinect has more consistency than goniometric results. According to SEM and MDC results in Table 3, it can be understood that the results have clinical significance.

Table 3: Inter-rater reliability of goniometer and kinect.

	Goniometer		Kinect	
	Right	Left	Right	Left
ICC	0.78	0.81	0.94	0.93
SEM	2.04	2.14	1.63	1.54
MDC	4.77	5.01	3.81	3.59

4 Discussion

Improvements in camera technology have made 3D motion capture systems using a single camera easy. Compared to a universal goniometer, it was observed that usage of marker-based single Kinect for measuring joint angles and ROM has higher reliability. According to the results belonging to the accuracy and reliability, it can be clearly concluded that the proposed method is a viable tool for calculating elbow joint angles and ROM.

However, there are some constraints to be considered. First, as the distance from the camera gets higher, the random error in depth measurements increases too the reason accuracy of Kinect depth sensor is a function of distance from Kinect. Additionally, this constraint causes decrease in resolution – reaching up to 4 cm in depth measurement error at the range of the camera view [9],[25]. Thus, the distance between Kinect and participants was within 1-2 meters.

Second, any change in the region found by filtering markers on RGB images alters the located centers of the markers. Such alterations cause inconsistent measurements taken in different sessions and thus reliability of the method becomes less. This situation generally happens in poorly or strongly illuminated recording environments such that shining or faded areas on markers change center of the markers when filtering. Normally, markers are colored raw circles without any deflection.

Lastly, markers that placed on humerus lateral epicondyle become partly or completely invisible to Kinect camera when measuring arm flexion especially for patients that have thick arms. Thus, measurements will be thoroughly affected because of invisible or deflected markers. For these participants, the markers were placed on a determined projective location that should not be invisible during measuring instead of exact location of lateral epicondyle itself. This projection also causes inconsistencies between measurements and, therefore, decreases reliability of the method.

Despite the constraints mentioned above, it is obvious that the ICC reliability results obtained by Kinect are better than the goniometric results taken by expert physiotherapists.

5 Conclusion

In this study, our goal is using the single Kinect for joint angle measurement with high accuracy and reliability. Unlike other research in this field, markers have been used to detect the exact 3D location of limb and joints. For the absolute accuracy of method, Kinect measurements were compared with a universal goniometer with different angles. The results for the absolute accuracy were satisfying for the clinical assessment. The method also tested in vivo. The elbow ROM of 10 participants were captured in three sessions by the Kinect and measured by three physiotherapists to find reliability. The method agreed well with goniometer and even gave higher consistency. In addition, results illustrate the feasibility of a marker based method (with a single ToF camera) to accurately measure upper extremity ROM and can be used in clinics. Although it allows physician extenders, primary care physicians, and other non-trained physicians to effectively measure joints, ROM and can also be used independently for self-measurements at home.

Further studies the method will be tested for more complex movement patterns and more than one joint. The constraints that were mentioned in the discussion will be considered.

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