Microsystem Technologies (2018) 24:4317–4327
https://doi.org/10.1007/s00542-018-3769-6

TECHNICAL PAPER

An IMU-compensated skeletal tracking system using Kinect for the upper limb

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Received: 22 November 2017 / Accepted: 19 January 2018 / Published online: 13 February 2018

Abstract

The Kinect device is being increasingly used in conjunction with rehabilitative actions. However, the use of Kinect as a skeletal tracking system requires several further modifications and technological breakthroughs. This study used inertial measurement units (IMUs) to complement skeletal tracking with the Kinect. The IMUs were used to compensate for errors in calculating shoulder and elbow joint angles detected by the Kinect device while the patients performed rehabilitation movements. Thirty normal participants were recruited, and their shoulder and elbow joint angles were recorded and calculated using the Kinect and IMUs while they moved during movement games. If movement with a larger measuring error was detected, the measurement was directed to the IMU to calculate the angle and calibrate the angles measured by the Kinect device. The mean percent errors of the Kinect measurements with respect to the IMU measurement at the shoulder joint during shoulder flexion and rotation at 90° of shoulder flexion were 15.08 ± 4.13 and 26.00 ± 7.41%, respectively. The mean percent errors of the Kinect measurements with respect to the IMU measurements at the elbow joint during shoulder flexion, shoulder rotation at 90° of shoulder abduction, and shoulder rotation at 90° of shoulder flexion were 12.92 ± 2.43, 17.75 ± 4.91, and 23.3 ± 7.01%, respectively. The mean percent errors for the participants' shoulders in Game 2 and Game 3 were 15.47 ± 4.88 and 28.13 ± 8.51%, respectively, and the mean percent errors of the participants' elbows in Game 3 were 55.62 ± 13.74%. The proposed method to calibrate the angles detected using the Kinect have a greater mean accuracy rate (84.58%) and a higher processing rate (10 ms/frame) than traditional methods that use only Kinect or IMUs. The proposed system increases the accuracy of movement detected by the Kinect device, and this increases the processing rate of the IMUs, thereby improving clinical practicality.

1 Introduction

Advances in medicine and technology have resulted in an increase in the lifespan of humans with a corresponding increase in chronic disease, so the development of rehabilitation and disability care methods has gained an increasing amount of attention (Ding et al. 2013). Due to the increase in the number of people suffering from age-related disabilities, there is a shortage of physical therapists, and this has become a critical problem for rehabilitation institutes. Indeed, physical therapists are unable to meet the demand for one-on-one guidance due to an increase in the number of patients. Therefore, therapists usually have to instruct family or caregivers accompanying patients on how to help for the patients to perform rehabilitative actions under the supervision of a family member

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or caregiver. However, patients' family or caregivers often do not possess the required expertise, and this renders their rehabilitative actions ineffective (Recio et al. 2013). In addition, patients may give up highly repetitive in-house rehabilitation measures due to low motivation.

Virtual reality allows users to have realistic experiences and offer real-time interactive features that provide immediate user feedback, so virtual somatosensory technology is being increasingly used in conjunction with rehabilitative actions. In rehabilitation, the techniques most commonly used to retrieve the body posture include using infrared cameras to dynamically identify user-adhesive reflective points (Krause et al. 2015), using accelerometer or gyroscope sensing for posture recognition (Salarian et al. 2010), and recently, using the popular Kinect device to provide skeleton-tracking information (Pastor et al. 2012). All of these techniques have expanded the applicability of posture recognition.

Several studies used the Kinect device in body-posture recognition and gesture identification (Bleiweiss et al. 2010; Liu et al. 2012; Patsadu et al. 2012; Raheja et al. 2011). However, the use of Kinect in a rehabilitation clinic has particular requirements for the spatial environment (e.g., the environment cannot be too messy) (Cheung et al. 2013; Erdogan and Ekenel 2015). The design of rehabilitation operations is based on the patient's symptoms, so an occurrence of overlapping limbs cannot be avoided, which interferes with Kinect operation during limb recognition and results in misjudgments. Thus, using a Kinect as part of a comprehensive rehabilitation treatment system requires several modifications and technological breakthroughs.

Inertial movement units (IMUs) are lightweight, energy efficient, inexpensive wireless transmission devices that can be implemented as wearable rehabilitation devices (Filatov et al. 2015; Ompusunggu and Bey-Temsamani 2016). IMUs combined with electronic protractors, accelerometers, and gyroscopes have been used to identify human activity (Liu et al. 2009; Tamei et al. 2015; Yun and Bachmann 2006) and accurately calculate the movement trajectory information, including the speed, angle, and movement. This enables IMUs to be substituted for Kinect in human activity recognition. However, IMUs provide limited user feedback, such as simple angle and speed information, and they also lack instant visual feedback and a sense of in-game immersion. Thus, the use of IMUs for inpatient rehabilitation remains somewhat limited (Han et al. 2016; Huang et al. 2012).

In 2015, Yushuang et al. used the angle information calculated by an IMU to correct the depth distortion problem encountered when using a Kinect (Tian et al. 2015). Although they verified that the IMU could be used to correct the positioning measurement of the Kinect, they did not discuss the clinical rehabilitation movements. Thus, there is little movement data that can be applied to clinical rehabilitation. In the present study, we used the Kinect skeleton tracking system to design rehabilitation games for the upper limb. To test the proposed system for compensation calculation, we embarked on a simulation that replicates subjects with upper arm disabilities using the rehabilitation game system. IMUs were worn on participants' upper limbs, and the posture angles detected by Kinect and the IMUs were compared. We determined that the IMUs improved the Kinect's depth judgment.

2 Methods

In this study, a virtual somatosensory skeletal tracking system was developed using the Kinect and IMUs. During movement, normal participants wore IMUs on the dominant upper extremities (UEs), and the therapists adjusted the game settings and difficulty levels to meet each simulated patient's conditions and demands. Kinect uses a human skeleton tracking system that detects movement and feeds the information back to the game engine. The device can also provide instant feedback and status messages to the users using sound and virtual objects. Similarly, the IMUs can transmit body movement information wirelessly to a computer to conduct calculations. During each session, the movement detection for both devices was compared. The proposed system structure is illustrated in Fig. 1.

2.1 Kinect system

The Kinect collects color images, infrared photographs, and sound through three lenses. The middle lens is a red–green–blue color camera that records color images, while the left and right lenses are 3D depth sensors that comprise an infrared laser projector and a monochrome complementary metal–oxide–semiconductor sensor. The 3D depth sensor captures depth data (i.e., distinguishes the distance of an object from the camera), whereas the middle camera is used to identify body or face features, and it can also recognize basic facial expressions.

2.2 Angle algorithm for the Kinect

The Kinect retrieves information in 3D coordinates using its depth sensor. It uses its own location as the reference point to retrieve 20 articulation points on a skeleton. The relative differences between the articulation points and the reference point are used by the Kinect to calculate the 3-axis coordinates of the human body as well as the movement tracking information and corresponding 3D joint angles.

In this system, the joint angle of a patient's upper arm must be immediately detected. However, since the Kinect

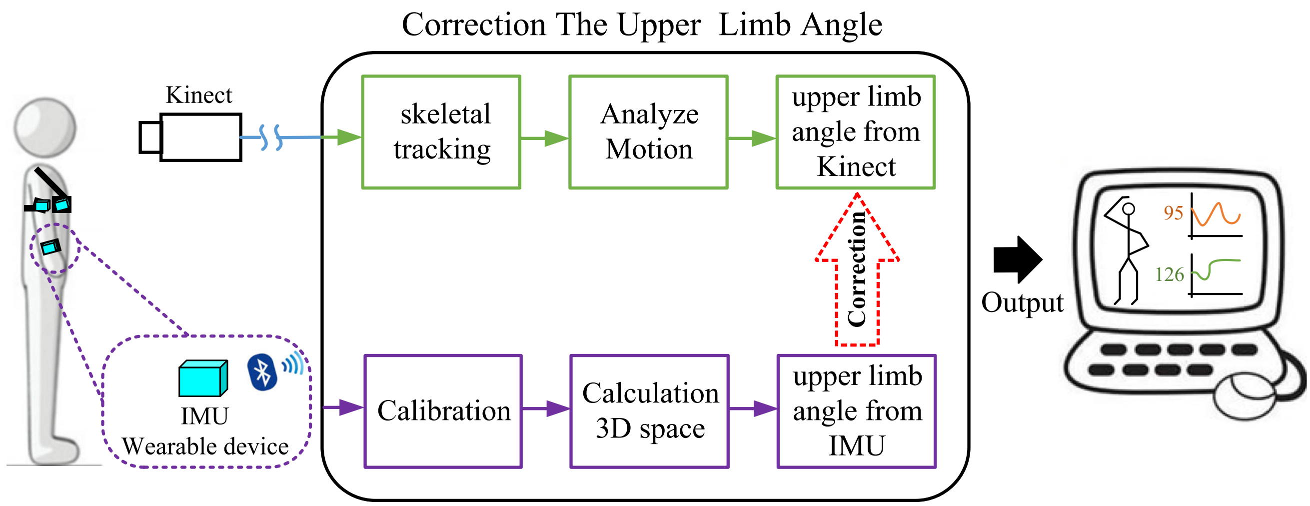


Fig. 1 System structure

can provide only one set of 3D coordinates for human limbs, the joint angle needs to be calculated from the 3D coordinates at the back-end system (see the example of a subject's right upper arm in Fig. 2). Moreover, the angle from the Kinect was calibrated with the extremity angles calculated by the IMU system.

In Kinect's 3D coordinate system, the 3D coordinates defined for the shoulder, elbow, and wrist were retrieved using the Kinect with the following vector formulas to calculate the shoulder-to-elbow vector ($\vec{S}\,E$) and the elbow-to-wrist vector ($\vec{E}\,W$), respectively:

$$\vec{A}\,B = B(X_b, Y_b, Z_b) - A(X_a, Y_a, X_a) \tag{1}$$

$$\begin{aligned}\vec{S}\,E &= Elbow(X_{Elbow}, Y_{Elbow}, Z_{Elbow}) \\ &- Shoulder(X_{shoulder}, Y_{shoulder}, Z_{shoulder}) \\ \vec{E}\,W &= Wrist(X_{Wrist}, Y_{Wrist}, Z_{Wrist}) - Eblow(X_{Elbow}, Y_{Elbow}, Z_{Elbow}).\end{aligned} \tag{2}$$

Then, the elbow angle was calculated using the following formulas:

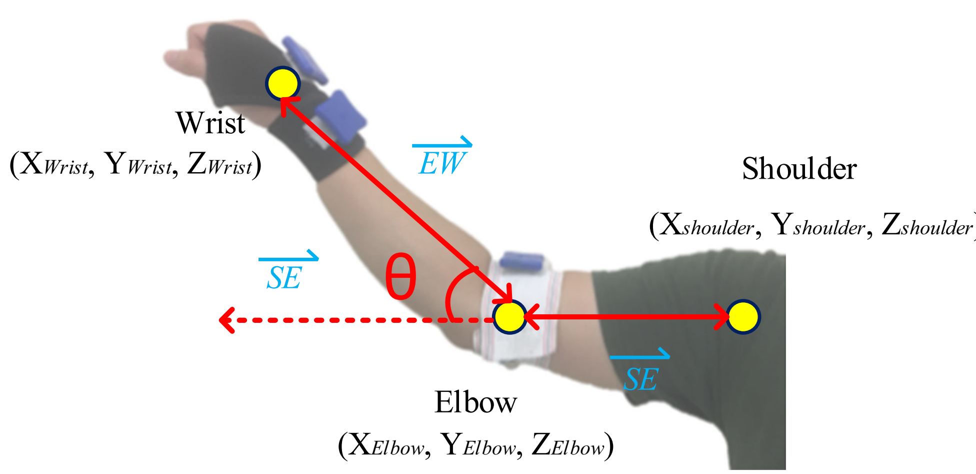
$$Cos\theta = \frac{\vec{SE} \cdot \vec{EW}}{\left|\vec{S}\,E\right|\left|\vec{E}\,W\right|} \tag{3}$$

$$\theta = Cos^{-1}(\cos\theta). \tag{4}$$

2.3 IMU system

The IMUs (LPMS-B2, LP-RESEARCH, Tokyo, Japan) (Copyright © 2016 LP-RESEARCH; http://www.lp-research.com/lpms-b2/2016) used in this study includes a 3-axis gyroscope, 3-axis accelerometer, and 3-axis magnetometer.

Fig. 2 Right upper arm angle calculation by Kinect



2.4 Kinematic model for measurement of upper limb 3D angles with IMUs

To show the user's real-time body movements, the signals received from the IMUs were projected on a framework. The virtual IMU skeleton starts with the pelvis and is hierarchically built. The joint angles of the UEs were calculated based on the framework measuring the UE kinematics (Yang et al. 2013). In this study, the shoulder and elbow joints were investigated since the games were mainly designed for shoulder and elbow joints.

Each IMU placed on the body segment was related to the reference IMU, and this information is reflected on the framework skeleton. The relationship (rotation matrix) between each IMU on the extremities and its corresponding joint at the neutral position (initial calibration) was constructed, and it is calculated as follows:

$$^{IMU\_joint}R^{const}_{joint} = \left(^{g}R^{init}_{IMU\_joint}\right)^{-1} \cdot {}^{g}R^{init}_{IMU\_Ref}, \quad (5)$$

where $^{IMU\_joint}R^{const}_{joint}$ is the constant relationship between the rotation matrix of each segment and the reference IMU, $^{g}R^{init}_{IMU\_joint}$ is the rotation matrix provided by IMU at neutral position, and $^{g}R^{init}_{IMU\_Ref}$ is the rotation matrix provided by the reference IMU.

After obtaining the rotation matrix between each IMU and the corresponding joint (initial calibration), the orientation of each corresponding joint was calculated during free motion. The updated orientation (rotation matrix) for each joint with respect to the global coordinates was calculated as follows:

$$^{Ref}R_{joint} = \left(^{g}R_{Ref}\right)^{-1} \cdot {}^{g}R_{IMU\_joint} \cdot {}^{IMU\_joint}R^{const}_{joint}, \quad (6)$$

where $^{Ref}R_{joint}$ is the updated orientation of each joint with respect to the global coordinate system, $^{g}R_{Ref}$ is the rotation matrix of the reference IMU, and $^{g}R_{IMU\_joint}$ is the rotation matrix provided by the IMU for each segment.

Subsequently, the orientation of each joint with respect to its parent coordinate system (relative rotation matrix) was calculated as follows:

$$^{joint}R_{next\_joint} = \left(^{Ref}R_{joint}\right)^{-1} \cdot {}^{Ref}R_{next\_joint}, \quad (7)$$

where $^{joint}R_{next\_joint}$ is the updated orientation of each joint with respect to its parent coordinate system (e.g., shoulder and chest), and $^{Ref}R_{joint}$ and $^{Ref}R_{next\ joint}$ represent the rotation matrix of each parent joint and joint, respectively.

Each joint angle was then calculated. Since the rotation matrix is a 3×3 matrix, the value can be marked as follows:

$$R = \begin{bmatrix} r11 & r12 & r13 \\ r21 & r22 & r23 \\ r31 & r32 & r33 \end{bmatrix}. \quad (8)$$

Finally, the following equations can be used to calculate the deflection angle (φ), depression angle (τ), and angle of roll (ψ) from the computed R:

$$Sin\tau = -r31 \quad (9)$$

$$\tan\psi = r32/r33 \quad (10)$$

$$\tan\varphi = r21/r11 \quad (11)$$

2.5 IMU and Kinect calibration

Since calculating the angles using IMUs is time consuming, the system load increases considerably if the IMUs have to be used for each rehabilitative action. Therefore, our proposed system applies IMU calibration only to movement angles with larger deviations, as measured using the Kinect. The procedure is shown in Fig. 3. A laptop (HP Envy 13-d016TU, HP, Taipei, Taiwan) with an Intel 6-series chipset was used to perform this calculation. The calibration method coupled with an IMU and Kinect

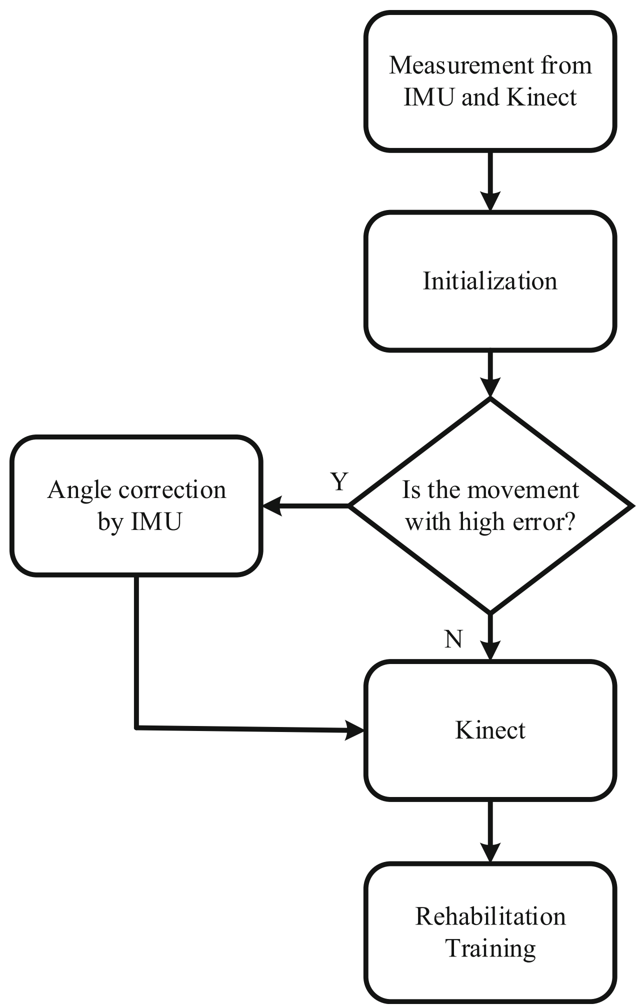


Fig. 3 IMU and Kinect calibration process

proposed in this research allows the system to judge whether there are action elements with a large error in current action. If there is a motion element with a larger error, the system will calculate the angle of the IMU and then calibrate that converted from the Kinect. In this way, the number needed for the IMU to perform the rotation matrix conversion can be greatly reduced, thereby allowing the system to maintain a high angular accuracy without reducing the operational efficiency.

2.6 Skeletal tracking game and movement design

Three games were designed in this study to make the user feel interested during the experiment. In the first skeletal tracking game (Game 1), the participants were requested to move their UEs like a roulette. Each participant had to turn the shoulder joint with their elbow extended to "rotate the roulette" toward a designated position, as depicted in Fig. 4. The goal of this game was to provide rehabilitation through shoulder circumduction and upper arm lifting.

In the second skeletal tracking game (Game 2), the participants were assigned to place randomly appearing washed dishes back into their designated area. To move an object, participants had to extend their elbow as outlined in Fig. 5. The goal of this game was to achieve rehabilitation through shoulder horizontal abduction, horizontal adduction, and arm elevation.

In the third skeletal tracking game (Game 3), the participants simulated driving a vehicle on grassland. The subjects were required to lift their arm to a 90° shoulder elevation and 90° elbow flexion position to simulate driving a car with one hand on the steering wheel, as illustrated in Fig. 6. The goal of this game was to rehabilitate participants' external and internal shoulder rotation by flipping their arms in and out during operation.

2.7 Experimental procedure

This study contained two parts. The first was an IMU angle experiment (which was performed to confirm the accuracy of the IMU angles after the algorithmic calculation), and

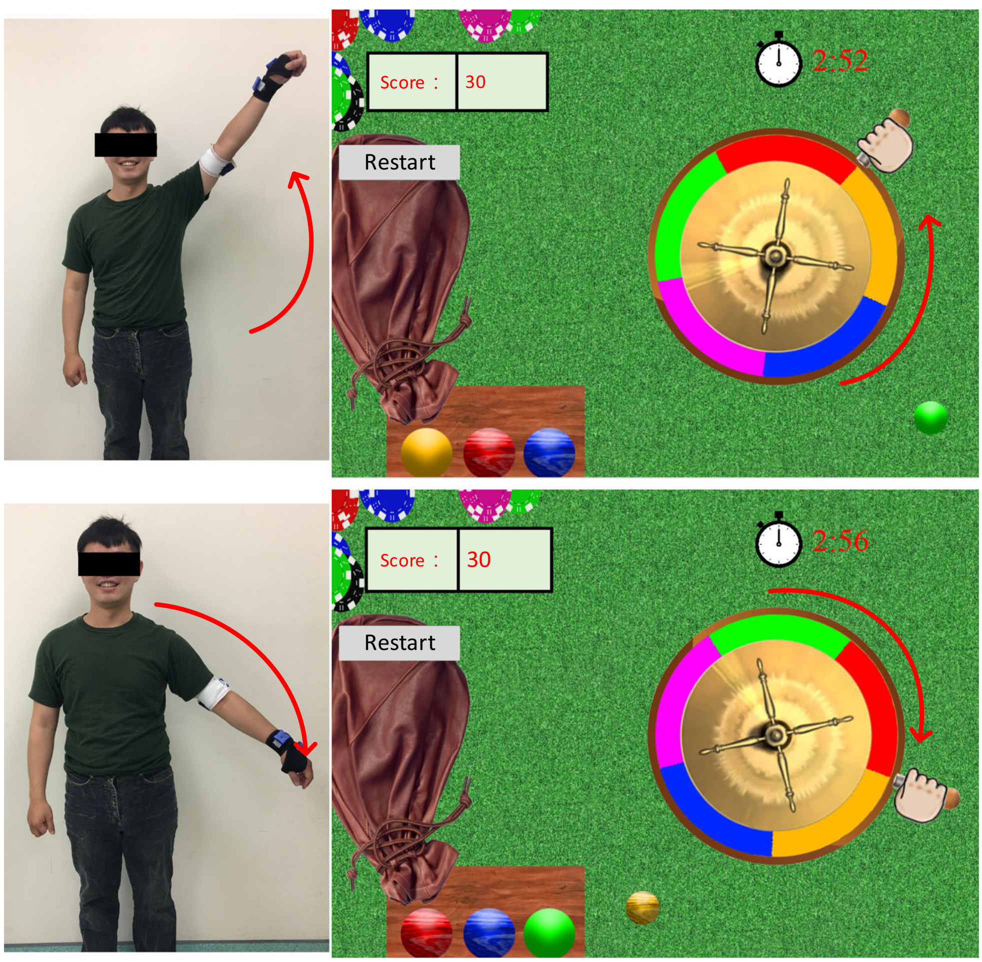


Fig. 4 Layout and operation of the roulette game (Game 1)

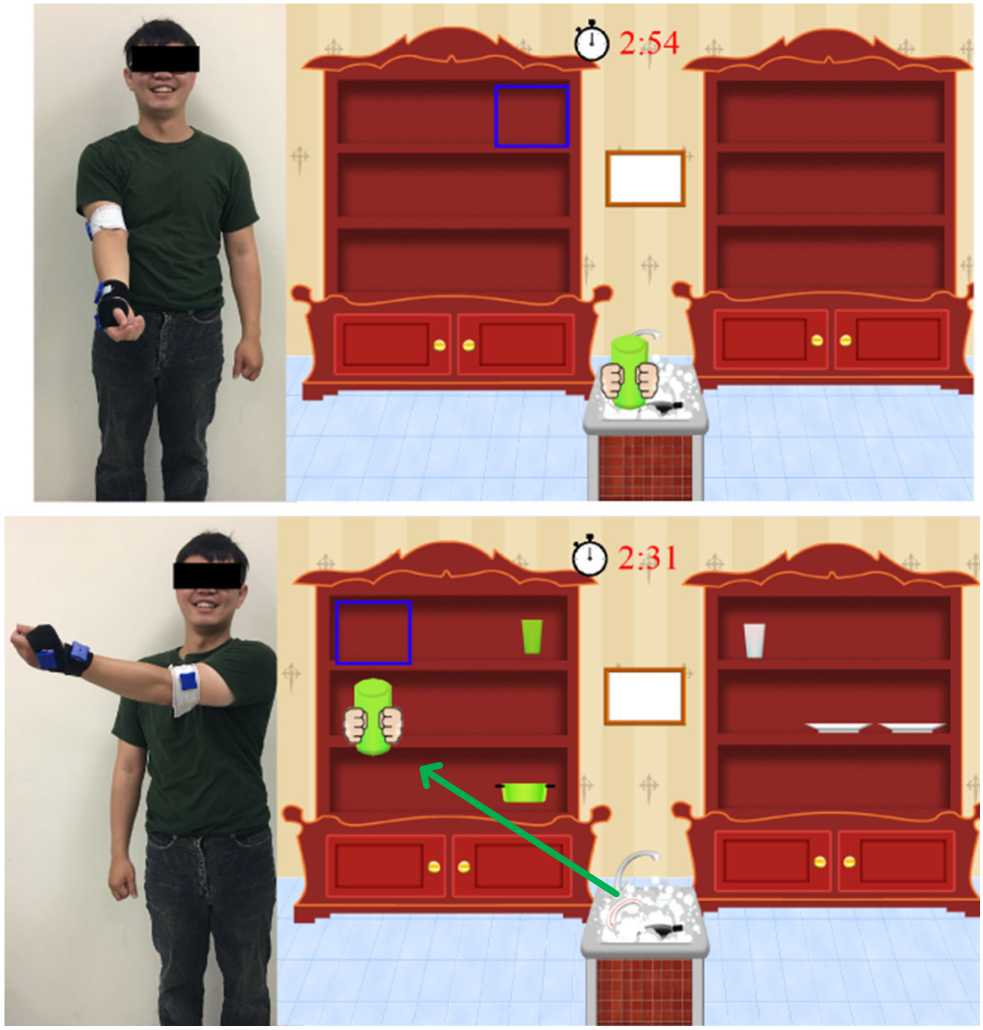


Fig. 5 Layout and operation of the placement game (Game 2)

the second was of mono-axis and multiple-axis experiments of the Kinect and IMU angles. Six movements were performed in three games to compare the angle difference between the two systems. The two parts of the experimental procedure are described as follows.

2.7.1 IMU angle verification

The IMU system was attached to a goniometer used for clinical rehabilitation, and five measurements were performed at each setting for angles 15°, 30°, 45°, 60°, 90°, 105°, 120°, 135°, 150°, 165°, and 178° to verify the high-angle measurement accuracy of the IMUs.

2.7.2 Angle comparison between the Kinect and the IMU

Thirty normal participants were recruited for this study. Prior to the experiment, each participant read and signed an informed consent form approved by the Institutional Review Board of E-Da Hospital. Three IMUs were attached to the bony end of the arm, forearm, and hand, respectively, to track the UE segments of each subject. Another IMU affixed to the table was used as reference.

This experiment comprised six simple or complex shoulder and elbow movements: (A) elbow flexion, (B) shoulder horizontal abduction, (C) shoulder abduction, (D) shoulder flexion, (E) shoulder rotation with 90° shoulder abduction, and (F) shoulder rotation with 90° shoulder flexion. In each initial position, the user stood straight and faced the monitor, placing both hands naturally at the side of the body.

Each patient was asked to perform six movements and to play three designed games. The angle measurement information was gathered from the IMUs and Kinect and was then used to conduct a 3D axis comparison. The Kinect errors with respect to the IMU measurements were expressed as percent errors and were calculated using Eq. (12):

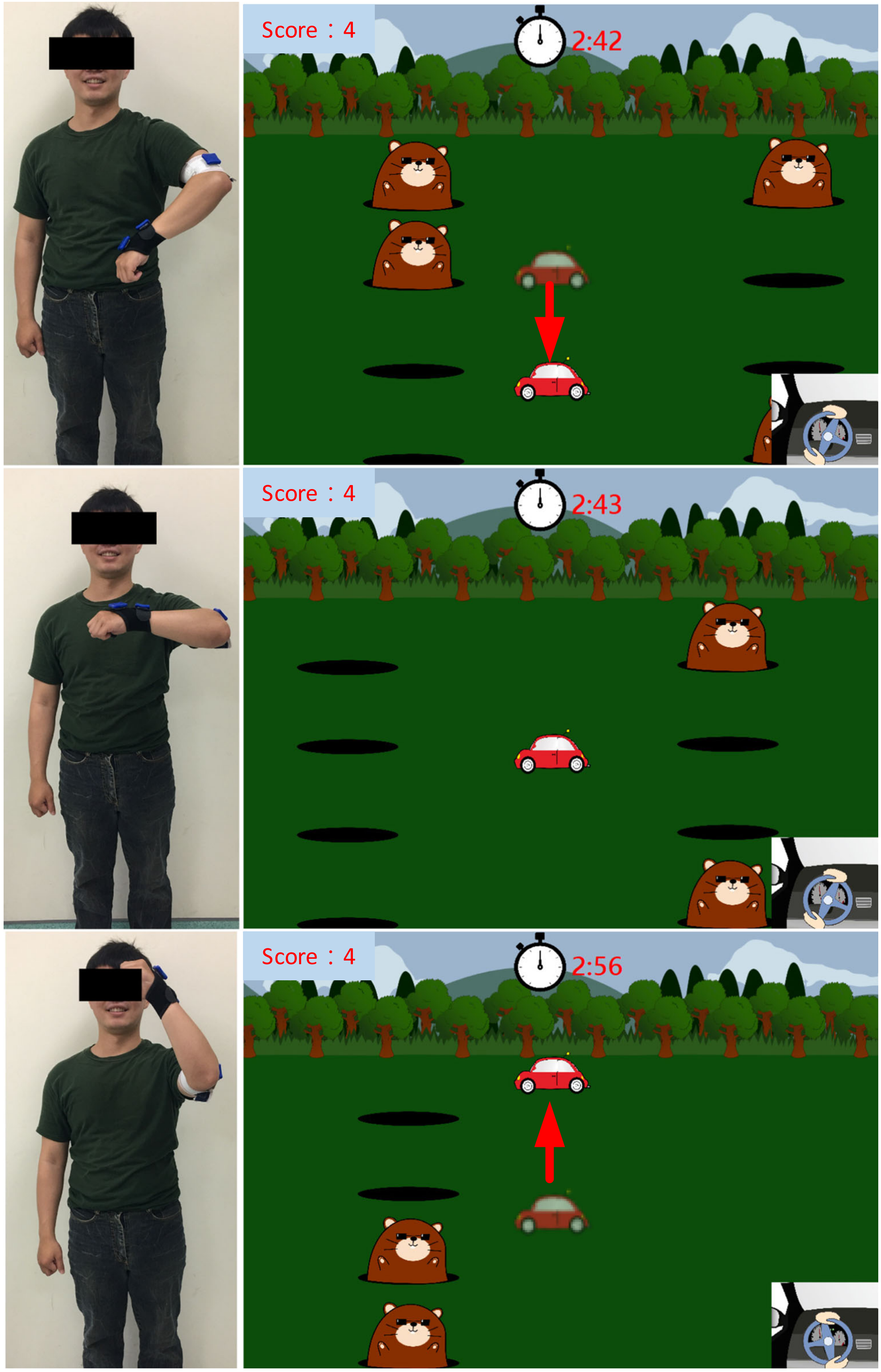


Fig. 6 Layout and operation of the driving game (Game 3)

$$Error(\%) = \frac{\sum_{n=1}^{\infty} |IMU(n) - Kinect(n)|}{\sum_{n=1}^{\infty} IMU(n)}, \tag{12}$$

where $Error(\%)$ is the percent error, $IMU(n)$ is the sum of the IMU angles for the movement, and $Kinect(n)$ is the sum of the Kinect angles for the movement.

3 Results

3.1 IMU angle verification

The results of the measurement are shown in Table 1, which shows that the IMU measurements were accurate and free of any deviation or drifting.

3.2 Angle comparison between Kinect and IMUs

Equation (12) was used to calculate the percent error of the Kinect measurements with respect to the IMU measurements. The results are shown in Table 2. Notably, for the movement (E), a significant difference was observed between the Kinect and the IMU measurements. This may be because while performing a shoulder rotation with 90° shoulder abduction, an overlap of the elbow and wrist may cause a greater misjudgment in the articulation from the Kinect. The error position during movement (E) is depicted in Fig. 7a.

Additionally, the movement (F) was determined to have a significantly high percent error. Figures 8 and 9 respectively show the shoulder joint angle of the movement (F) on the x-axis (angle of shoulder flexion) and z-axis (angle of shoulder rotation). When the shoulder overlaps the elbow, the shoulder joint angle detected by the Kinect showed misjudgments, and sometimes, no angle was detected. However, the IMUs were able to fully capture the shoulder flexion angle, and the error position during movement (F) is shown in Fig. 7b, c.

According to the percent errors shown in Table 3, the mean percent error of the shoulder in Game 2, which comprised movements (B) and (D), was more than 15% on average. The posture when misjudgment occurs is shown in Fig. 10. During this movement, a subject's whole arm may be perpendicular to the Kinect device, which makes the elbow overlap the shoulder and results in erroneous 3D elbow information being produced by Kinect.

Game 1 comprised movements (B) and (C). As revealed in Table 3, when large angle 2D movements were

Table 1 Angle measured by the IMUs and the goniometer

Angles from goniometer (°)	IMU angles (°)					Mean	Error (°)	Error (%)
	1	2	3	4	5			
15	14.27	16.18	14.49	14.69	14.25	14.78	0.22	1.47
30	30.87	31.10	30.08	30.28	29.21	30.31	0.31	1.03
45	45.43	43.43	43.67	44.31	45.29	44.43	0.57	1.27
60	60.37	59.83	59.86	60.25	59.69	60.00	0.00	0.00
90	90.32	90.97	90.88	90.41	90.37	90.59	0.41	0.40
105	104.05	104.72	105.91	105.59	105.09	105.06	0.06	0.05
120	120.15	121.71	121.91	118.62	120.54	120.59	0.59	0.05
135	134.20	135.41	135.13	135.60	134.93	135.05	0.05	0.03
150	150.65	151.24	151.07	150.91	150.26	150.82	0.82	0.54
165	164.50	163.95	164.37	164.30	165.10	164.44	0.56	0.33
178	176.96	176.79	177.20	177.56	177.10	177.12	0.88	0.49

Table 2 Angle error results in Kinect and IMU measurements

Kinect compare with IMU		
Movement	Percent ratio by shoulder (%)	Percent error by elbow (%)
A	0.89 ± 0.09	9.37 ± 2.11
B	8.31 ± 1.86	9.77 ± 2.29
C	5.62 ± 0.81	2.49 ± 0.67
D	15.08 ± 4.13	12.92 ± 2.43
E	5.75 ± 0.83	17.75 ± 4.91
F	26.00 ± 7.41	23.30 ± 7.01

A elbow flexion, *B* shoulder horizontal abduction, *C* shoulder abduction, *D* shoulder flexion, *E* shoulder rotation with 90° shoulder abduction, *F* shoulder rotation with 90° shoulder flexion

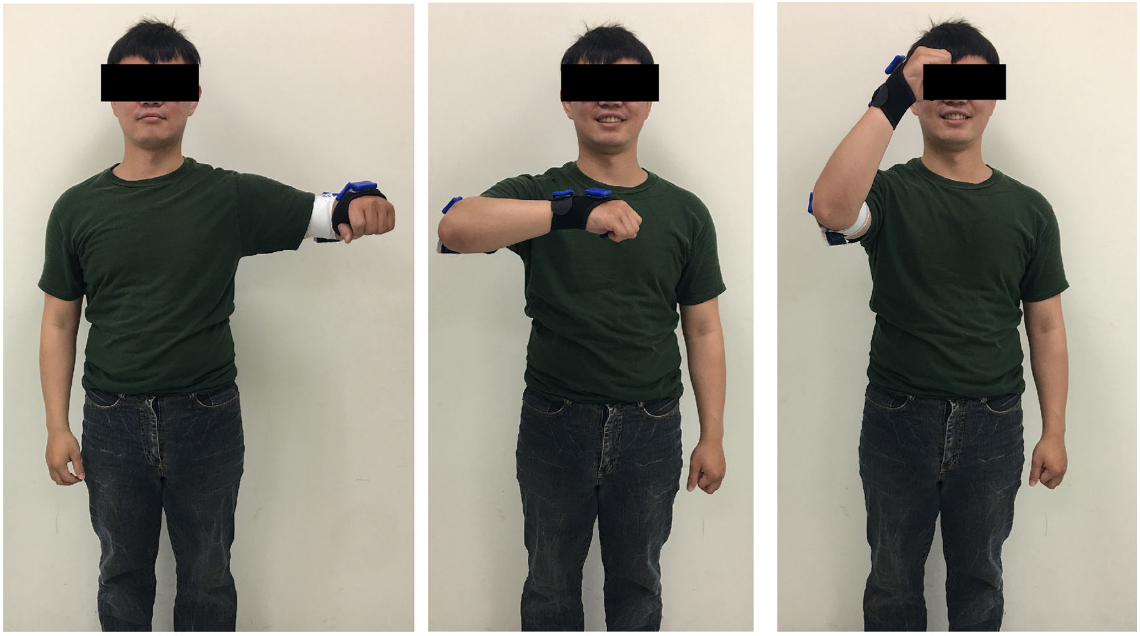


Fig. 7 Misjudged movements. **a** Movement (E) with elbow misjudgment. **b**, **c** Movement (F) with misjudgment caused by shoulder and elbow overlap

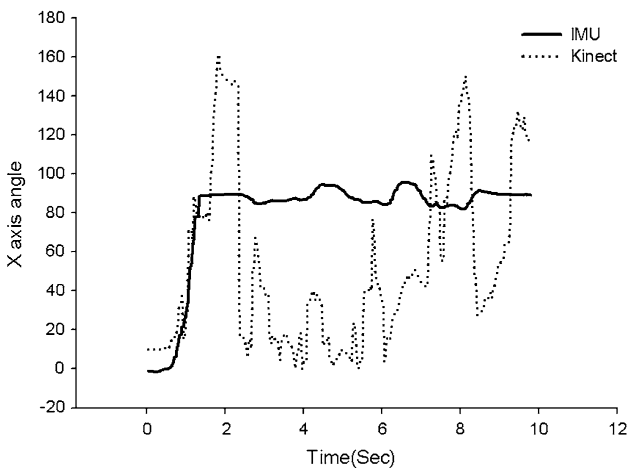


Fig. 8 Angle of movement (F) on the x-axis

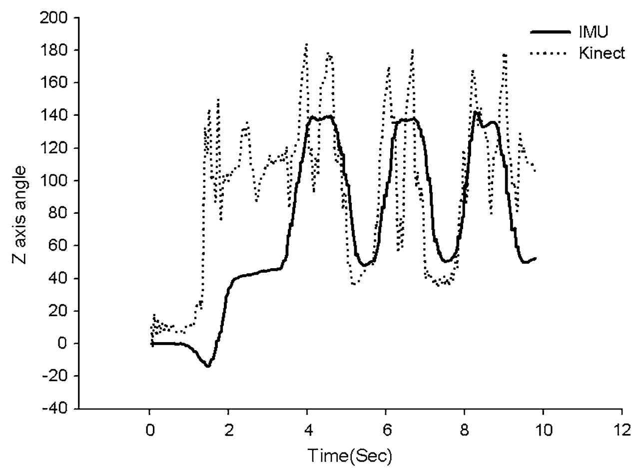


Fig. 9 Angle of movement (F) on the z-axis

performed with the shoulder joint (which was the main training target), the percent errors from the Kinect and IMU measurements were smaller. However, the overall percent error for Game 1 was still more than 8%. The main reason for such is that the upper arm leans slightly forward during shoulder circumduction, causing a small difference between the angles calculated by the Kinect and the IMU systems (Fig. 11). This also indicates that the Kinect device is less sensitive than the IMUs to angles produced by small movements.

To increase the accuracy when measuring rehabilitative actions using this system, four movements with high percent errors, (B), (D), (E), and (F), were calibrated as depicted in Fig. 3. Based on the calibration results and the laptop processing speed (Fig. 12), we determined that the accuracy rate of the Kinect before calibration was approximately 50%, whereas that of the IMUs was 93%. After calibration, the mean accuracy rate for Kinect improved considerably to approximately 85%.

4 Discussion

Several studies have used the Kinect and IMUs for motion detection in clinical physical therapy or telerehabilitation (Ding et al. 2013; Krause et al. 2015; Liu et al. 2012; Pastor

Table 3 Angle error results of Kinect and IMU measurements during skeletal tracking games

Kinect compare with IMU			
Skeletal tracking game	Action included by	Error ratio by shoulder (%)	Error ratio by elbow (%)
Game 1	B, C	8.03 ± 2.18	6.67 ± 1.36
Game 2	B, D	15.47 ± 4.88	8.56 ± 2.27
Game 3	A, C, F	28.13 ± 8.51	55.62 ± 13.74

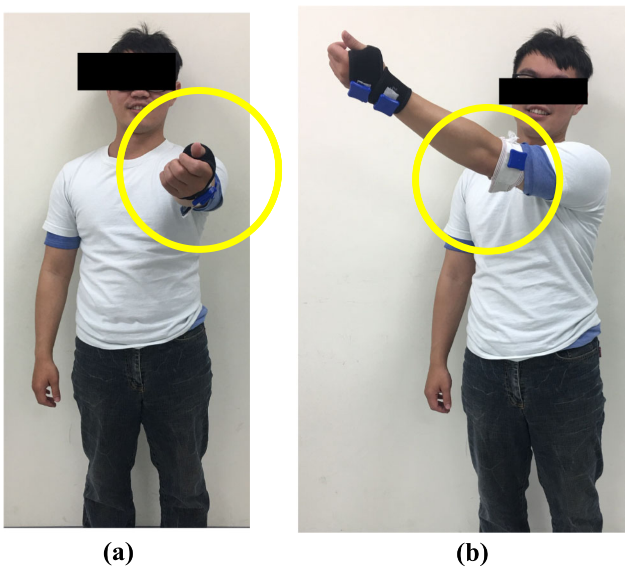


Fig. 10 Movements in Game 2 that cause misjudgment. **a** Wrist or elbow overlapping with shoulder. **b** Elbow and shoulder extremity overlapping

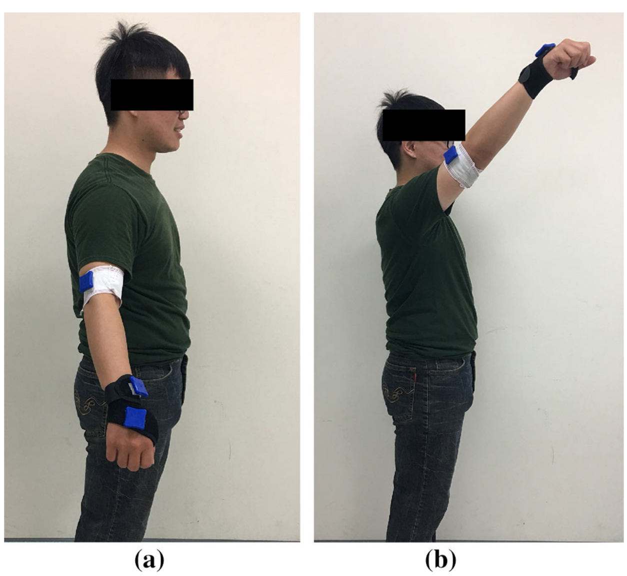


Fig. 11 Movements in Game 1. **a** Initial state. **b** Arm slightly forward during shoulder joint circumduction

et al. 2012; Patsadu et al. 2012; Raheja et al. 2011; Recio et al. 2013; Salarian et al. 2010). However, these studies have certain limitations. In the present study, we found that

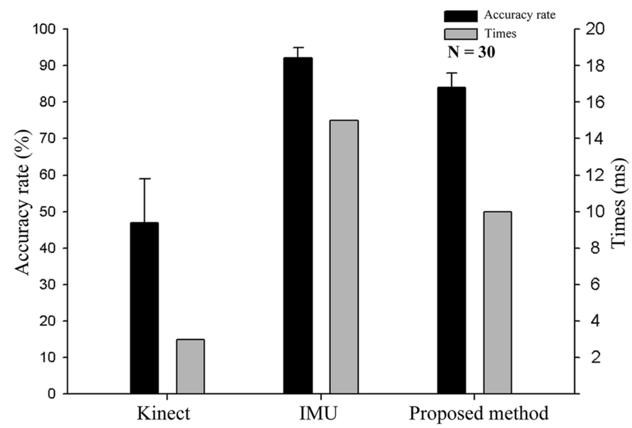


Fig. 12 Calibration results and processing speed information

the shoulder angles tracked by the Kinect had greater percent errors due to the overlap of the limbs. In contrast, the IMUs provided a higher accuracy but slower processing rate due to a lag in real-time data collection. Our results are consistent with those obtained by Yushuang et al., who argued that the IMUs are more accurate than a Kinect to calculate the angle in the case of an overlap in the extremities or small movements, and IMUs can effectively help calibrate the angles measured using the Kinect (Tian et al. 2015). However, the results of their experiment showed that the method incorporating both the IMU and Kinect is superior to a method with IMU internal sensors, produce greater accuracy for the position estimation and elbow adduction angles. Compared to using the Kinect alone, our IMU-compensated approach can achieve better results in terms of accuracy of the shoulder and elbow angles. In addition, when compared to using the IMU alone, our approach improves the processing rate. Our UE rehabilitation system maintains satisfactory efficiency despite the complex angle-calculation operations in both systems.

The integrated system that is introduced here also overcomes the environmental problems associated with the Kinect that have been discussed in previous studies (Ding et al. 2013; Liu et al. 2012; Pastor et al. 2012), and accurate visual feedback provided using the Kinect solved the problem of the IMUs lacking feedback (Bleiweiss et al. 2010; Cheung et al. 2013). In addition, with frequently-used clinical rehabilitative, this system verified the accuracy of the movement detection and provided an important basis for clinical rehabilitation movement. All of these results improve the practicality of this system. Since the system's interface and game content are related to UE rehabilitation, our design focused more heavily on the utility of the interface and rehabilitation value than general games do. In the future, we intend to apply this system for UE rehabilitation of patients with upper limb disabilities, such as patients with a frozen shoulder. A limitation of this study is that a rather simple uniaxial goniometer was used in the IMU verification, and a golden standard instrument should be used in the future to verify the 3D angles of the human upper limb.

5 Conclusions

An upper limb tracking system was developed by integrating inertial measurement units and a Kinect device. The system proposed in this study increases the accuracy of the movement detected by the Kinect and increases the processing rate of the IMUs, thereby improving clinical practicality.

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