Home-based Senior Fitness Test Measurement System Using Collaborative Inertial and Depth Sensors

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***Abstract*—This paper presents a home-based Senior Fitness Test (SFT) measurement system by using an inertial sensor and a depth camera in a collaborative way. The depth camera is used to monitor the correct pose of a subject for a fitness test and any deviation from the correct pose while the inertial sensor is used to measure the number of a fitness test action performed by the subject within the time duration specified by the fitness protocol. The results indicate that this collaborative approach leads to high success rates in providing the SFT measurements under realistic conditions.**

I. INTRODUCTION

Senior Fitness Test (SFT) [1] is an established set of tests or kinetic body movements that elderly patients are asked to perform in order to identify their physical fitness. Rehabilitation specialists use the outcome of SFT tests to identify physical weaknesses towards taking preventative or treatment actions. SFT is currently conducted with the help of a medical assistant personnel. This requires elderly patients who need fitness test and rehabilitation to commute between home and clinical centers which in many cases poses challenges for the elderly. A home-based system with proper visual and audio feedback capabilities will allow more frequent or longitudinal SFT measurements of the elderly. Such a system can play the role of a medical assistant at home by providing both visual and audio feedback to guide the elderly through SFT tests. Frequent SFT measurements allow clinicians to weekly or bi-weekly observe the status of rehabilitation based on measurements provided by the system, thus being able to provide a more effective patient care and treatment.

For rehabilitation applications, a number of studies using wearable wireless inertial sensors have appeared in the literature. For example, in [2], wearable inertial sensors were deployed to monitor the activity and position of the upper trunk and lower extremities. A customizable wearable inertial sensor for physical rehabilitation was discussed in [3]. A support vector machine classifier was used within a body sensor network to estimate the severity of Parkinsonian symptoms in [4]. Wearable inertial sensors were used for mobility and balance evaluation to improve gait performance and to decrease fall risk in [5].

On the other hand, since the introduction of the Microsoft Kinect depth camera, rehabilitation applications have been studied using this camera. For example, in [6], a multiple Kinect camera system was utilized to assess the falling risk via measuring temporal and spatial gait parameters, where the position of the feet rather than the trunk and limb was measured. In [7], a Kinect-based system was deployed to motivate physical rehabilitation in a public school setting. Commercial game-based rehabilitation tools using Kinect have also appeared in [8].

However, the simultaneous utilization of both wearable inertial sensors and Kinect camera has been fairly limited in the literature. The collaborative utilization of these low-cost sensors is a new approach that we are introducing in this paper for the purpose of carrying out SFT measurements. More specifically, a low-cost home-based SFT system based on the simultaneous cooperative utilization of a wearable sensor and a Kinect camera is introduced in this paper in order to detect and measure the four motion tests involved in SFT. It is shown that the utilization of both of these two differing modality sensors (Kinect camera and inertial sensor) in a collaborative way makes the deployment of the system feasible in home environments due to its ability to cope with realistic conditions.

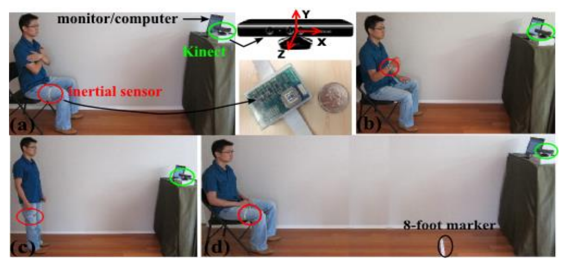

Figure 1. System setup: (a) chair-stand test, (b) arm-curl test, (c) step-in-place test, and (d) 8foot-up-and-go test

II. KINECT AND INERTIAL SENSOR COLLABORATIVE SETUP

Kinect is a low-cost RGB-Depth sensor introduced by Microsoft for human-computer interface applications [9]. The Kinect SDK [10] is a publically available software package which can be used to track 20 body joints. In our system, the subject stands in front of a Kinect camera so that his/her correct position and action can be monitored. An audio/visual warning is provided via a monitor in front of the subject when the wrong position or action is performed. At the same time, the subject is asked to wear a small size (1”×1.5”) 9-axis wireless body sensor, which was developed at the University of Texas at Dallas [11]. The sensor can be easily worn on the wrist or thigh depending on the fitness test. This sensor generates 3-axis acceleration and 3-axis angular velocity signals, which are transmitted wirelessly via a Bluetooth link to the monitoring computer.

Four of the six tests in SFT involve body movement measurements and two of the tests involve reaching

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measurements. In this work, only the body movement measurements are considered, which include chair-stand test, arm-curl test, step-in-place test, and 8foot-up-and-go test. For each test, the subject wears a wireless inertial sensor and stands or sits in front of a Kinect camera. Figure 1 illustrates the system setup for the above four SFT tests.

III. Collaborative Sensing and Measurements

In our developed collaborative sensing approach, Kinect is first used to detect a subject’s position and give instructions via visual and audio feedback to guide the subject into a proper starting position. Then, a start time-stamp is activated to synchronize the measurements between the Kinect and the inertial sensor. In SFT, it is desired to count the number of movements within a specified amount of time. If the movement is done incorrectly, the system detects and gives a warning via audio/visual feedback to restart the movement or repeat until one set of movements is properly completed without any errors within the specified time. The SFT movements and the design of the system are explained in more details in the subsections that follow.

A. Chair-stand Test

The chair-stand test assesses leg strength and endurance. The procedure is as follows. The subject sits on a secured chair with the feet flat on the floor, placed shoulder width apart with the arms crossed at the wrists and held close to the chest (a required pose throughout the entire test). From the sitting position, the subject needs to stand completely up, then completely back down. This action is to be repeated for a time duration of 30 seconds. The total number of complete chair stands (a consecutive up and down is considered one stand) is then counted over this time duration. The Kinect camera is placed on a table and is connected to the program running on a computer. The subject is instructed to sit in front of the Kinect with one inertial sensor tied to the left or right thigh. The Kinect camera is used to record the positions of the body joints and the inertial sensor is used to record the bending angle of the subject's thigh. The flowchart of the algorithm for the chair-stand test is shown in Figure 2. In this flowchart, the dashed line boxes indicate the Kinect is guiding the program flow, and the dashed line boxes with shade indicate the inertial sensor is guiding the program flow. The major steps involved in the program flow are stated below.

Step 1. Position check - The Kinect camera is used to detect the subject’s position. The SDK has the software tools for tracking the coordinates (x, y, z) of the spine joint within the distance range of 0.8m to 4.0m. The coordinate system of the Kinect camera is exhibited in Figure 1(a). Voice instructions guide the subject into the proper position to make sure that the Kinect camera can reliably track the body joints.

Step 2. Pose detection - When the subject appears within the above distance range from the camera, a correct pose detection module is activated. This detection module utilizes the positions of the left and right wrists, denoted by $P_{lw}(x_{lw}, y_{lw}, z_{lw})$ and $P_{rw}(x_{rw}, y_{rw}, z_{rw})$, the hip center denoted by $P_{hc}(x_{hc}, y_{hc}, z_{hc})$, and the shoulder center, denoted by $P_{sc}(x_{sc}, y_{sc}, z_{sc})$. Specifically, the following conditions are examined to determine a correct pose: (i) $y_{hc} < y_{lw} < y_{sc}$ and $y_{hc} < y_{rw} < y_{sc}$ which indicate both of the wrists are in a position between the shoulder center joint and the hip center joint, and (ii) if $x_{rw} < x_{lw}$, the arms are then considered crossed. A graphical display of the correct pose is displayed on the monitor providing a visual feedback while voice instructions are also provided at the same time. Only if the correct pose is detected, the system proceeds to the next step.

Step 3. Sitting position check - In this step, voice commands instruct the subject into a sitting position. Then, the sitting position is detected by the inertial sensor when the thigh bending angle becomes close to 90 degrees. If the subject is in the sitting position, the program proceeds.

Step 4. Measurement - In this step, once the subject is in a sitting position, voice instructions inform the subject how to complete a correct stand up and sit down movement. Then, a 5-second countdown starts. The timer for the chair-stand test is set to 30 seconds as per the SFT protocol and a counter for counting the number of chair stand is placed on the monitor. When the 5-second countdown ends, the measurement begins immediately. The timer starts to count down and the inertial sensor and the Kinect begin to record data. If the timer reaches 0, the test is completed. The total number of chair stands is displayed on the monitor. Although we could have used the Kinect to do the measurement, our experimentations revealed that the thigh bending angle provided by the inertial sensor was more accurate or reliable than the position data provided by the Kinect. That is why in our system the Kinect is primarily used for monitoring purposes, that is making sure that the tests are done properly, and the inertial sensor is used for collecting measurements.

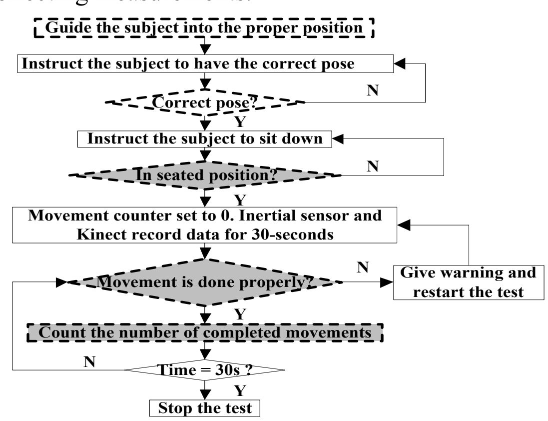

Figure 2. Flowchart of chair-stand test by collaborative Kinect and inertial sensing

During the chair-stand test, if any of the following situations occurs, the test will terminate and restart, *i.e.* the system returns to Step 4. This is done to make sure that the subject follows the exact guidelines of the chair-stand test so that valid measurements are recorded at the end of the test.

Situation 1: The subject loses the pose during the test. The Kinect continuously checks the arm-cross pose during the measurement.

Situation 2: The subject does not perform stand up or sit down action correctly (e.g., the subject does not stand up or sit down completely).

Note that the Kinect is used to monitor the position of the subject all the time. Anytime the subject is not in the proper field of view or position, the system warns the subject and returns to Step 1.

B. *Arm-curl Test*

The arm-curl test assesses upper body strength and endurance. Subjects are required to sit on a chair, hold a weight of 8 pounds (men) and 5 pounds (women), and do as many arm curls as possible in 30 seconds. The subject is required to fully bend and fully straighten the arm at the elbow for one count to be considered.

The flowchart of the arm-curl test is shown in Figure 3. First, the Kinect is used to detect the subject's position. To set up the synchronization between the two sensors (the Kinect and the inertial sensor), a countdown timer is utilized to start the measurement time-stamp and give audio instructions to the subject to get into the proper test position. For example, if the subject gets too close to or too far from the Kinect camera, the body skeleton does not get generated properly and the subject is warned of the incorrect starting position. Once the start time-stamp is synchronized, the subject hand is checked to make sure it is close to the body. For this part, both the Kinect camera and the inertial sensor are used to determine the distance between the hand and the body. If the hand is not close to the body, the system provides a warning and restarts the test.

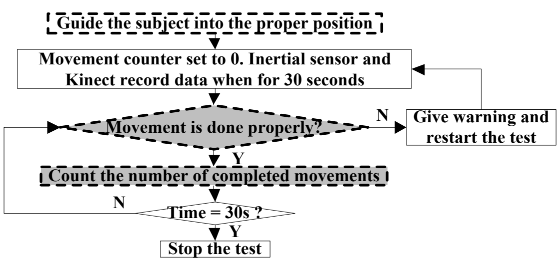

Figure 3. Flowchart of arm-curl test by collaborative Kinect and inertial sensing

Let H_0 denotes the hand initialization position (arm in a vertically down position). A state array with two Boolean components $[X_I\, X_{II}]$ is used to represent the states of the hand position. The state of the hand in the initialization position H_0 is denoted by [1 0], while the state of the hand up to the shoulder is denoted by [1 1]. When the inertial sensor detects the arm bending angle falls close to 180 degrees, the number of curls is increased by 1, and the state array turns into [0 0]. When the hand goes down to the initialization point H_0, the array goes back to [1 0]. If the hand position is far away from the body (x coordinate of the shoulder), the system provides an audio warning and restarts the test. If the state array $[X_I\, X_{II}]$ = [0 0] and the y coordinate of the current hand position is larger than the previous hand position (this means the hand is going up), the system gives an audio warning and restarts the test. If the state array $[X_I\, X_{II}]$ = [1 0] and the y coordinate of the current hand position is smaller than the previous hand position (this means the hand is going down), the system gives an audio warning and restarts. If the first Boolean component $X_I = 1$ and the y coordinate of the hand position is greater than the shoulder position, the state array $[X_I\, X_{II}]$ turns into [1 1].

C. *Step-in-place Test*

The step-in-place test assesses aerobic endurance. The subject stands up straight next to a wall and marches in place for two minutes, lifting the knees to the height of the hip bone. The system records the total number of such marches in two minutes.

For the step-in-place test, the experimental set up is similar to the arm-curl test except that the inertial sensor is placed on the right upper thigh and the time duration is 2 minutes. The flowchart of the step-in-place test is similar to the one shown in Figure 3 and thus it is not shown here to save space. The subject is again guided by the audio instructions to get into the proper starting position. The subject is required to lift the right and then the left leg up to the hip center. Each completed cycle of this movement is then measured by the inertial sensor and is considered to be one count. Whenever the movement is not done correctly or completely, the system gives a warning and skips the count.

D. *8foot-up-and-go Test*

The 8foot-up-and-go test assesses speed, agility and balance while moving. A marker is placed 8 feet in front of a chair. The subject starts fully seated. On the voice command "Go", a timer gets started and the subject needs to stand and walk as quickly as possible to the marker and return to the chair and sit down. The timer stops as the subject sits down.

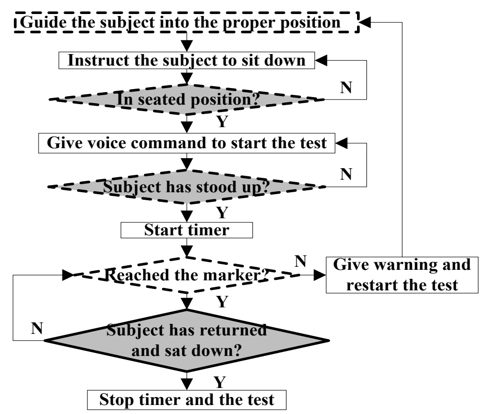

Figure 4. Flowchart of 8foot-up-and-go test by collaborative Kinect and inertial sensing

For the 8foot-up-and-go test, the Kinect is placed in front of the 8-foot maker as shown in Figure 1(d). The distance travelled is obtained by measuring the position of the subject's spine joint as tracked by the Kinect SDK via the z value of the Kinect world coordinate. As a "Go" voice command is given by the system, both the Kinect and the inertial sensor start recording data with the initial position of the subject denoted by z_s. When the thigh bending angle measured by the inertial sensor becomes close to 0 degree, it is considered that the subject has stood up, and thus the system starts a timer. When the thigh bending angle becomes close to 90 degrees and the position of the subject measured by the Kinect becomes close to z_s, it is considered that the subject has returned and sat down, and the timer is thus stopped. The time duration of this sequence of actions is recorded for this test. If the subject either does not reach the marker or goes beyond the marker, it is considered that the movement is not done correctly and the system provides a warning and restarts the test. Let z_{min} be the smallest subject's position. For a test to be considered correctly done, the condition $8foot - \sigma < z_s - z_{min} < 8foot + \sigma$ is checked, where σ denotes a distance threshold which we set to $\sigma = 1foot$ in our experiments. The flowchart of the 8foot-up-and-go test is shown in Figure 4. The box represented by both a solid line and shade indicates that both of the sensors are guiding the program flow for this step.

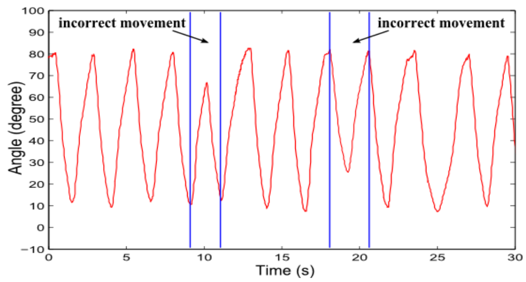

Figure 5. A typical measurement signal (angle) from inertial sensor for the chair-stand test

TABLE I. SUCCESS RATES OF CORRECT/INCORRECT MEASUREMENTS

Subject	TP	TN	FP	FN
Chair-stand test				
Subject 1	20	20	0	0
Subject 2	19	20	0	1
Subject 3	20	20	0	0
Subject 4	20	20	0	0
Subject 5	19	20	0	1
Arm-curl test				
Subject 1	19	20	0	1
Subject 2	20	20	0	0
Subject 3	20	20	0	0
Subject 4	18	20	0	2
Subject 5	20	20	0	0
Step-in-place test				
Subject 1	20	20	0	0
Subject 2	20	20	0	0
Subject 3	19	20	0	1
Subject 4	20	20	0	0
Subject 5	20	20	0	0
8foot-up-and-go test				
Subject 1	20	20	0	0
Subject 2	20	20	0	0
Subject 3	20	20	0	0
Subject 4	20	20	0	0
Subject 5	20	20	0	0

IV. RESULTS AND DISCUSSION

In this section, the results of the system operation for five subjects (3 male and 2 female subjects) are reported. To evaluate the robustness of the developed home-based system, the subjects were asked to repeat each of the above tests 40 times. For each test, the subjects were asked to alternate randomly between performing the test correctly and performing the test incorrectly or not completely. In other words, for each test, 20 times the test was done correctly and 20 times incorrectly. Table I shows the outcome of the correct/incorrect measurements for the above four SFT tests. In this table, TP denotes true positive, TN true negative, FP false positive, and FN false negative. As can be seen from this table, the developed system generated no FP and very low FN rates. A typical measurement signal from the inertial sensor for the chair-stand test is displayed in Figure 5 exhibiting example durations of correct and incorrect movements. Videoclip demos of the system in action can be viewed at http://www.utdallas.edu/~kehtar/SFT_video_demo.

It is worth emphasizing that the Kinect depth camera and the inertial sensor operate in a collaborative way meaning that a handshaking of tasks takes place between them. The proper position and pose checking tasks are carried out by the Kinect camera while the measurement task is carried out by the inertial sensor.

V. CONCLUSION

In this paper, a Senior Fitness Test measurement system based on a low-cost Kinect depth camera and a low-cost wearable inertial sensor has been introduced. It has been shown that by utilizing the signals from these two differing modality sensors in a handshake or collaborative manner, the measurements associated with Senior Fitness Test can be obtained with high rates of success under realistic conditions. In our future work, we plan to deploy this system in a senior rehabilitation center with seniors performing the tests.

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