35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Quantitative Analysis of the Fall-Risk Assessment Test with Wearable Inertia Sensors

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Abstract—**We performed a quantitative analysis of the fall-risk assessment test using a wearable inertia sensor focusing on two tests: the time up and go (TUG) test and the four square step test (FSST). These tests consist of various daily activities, such as sitting, standing, walking, stepping, and turning. The TUG test was performed by subjects at low and high fall risk, while FSST was performed by healthy elderly and hemiplegic patients with high fall risk. In general, the total performance time of activities was evaluated. Clinically, it is important to evaluate each activity for further training and management. The wearable sensor consisted of an accelerometer and angular velocity sensor. The angular velocity and angle of pitch direction were used for TUG evaluation, and those in the pitch and yaw directions at the thigh were used for FSST. Using the threshold of the angular velocity signal, we classified the phase corresponding to each activity. We then observed the characteristics of each activity and recommended suitable training and management. The wearable sensor can be used for more detailed evaluation in fall risk management. The wearable sensor can be used more detailed evaluation for fall-risk management test.**

I. Introduction

Almost 30% of elderly people aged 65 and above fall each year, and in most cases the fall is not witnessed. Falling causes elderly people to become immobile and sometimes bedridden. As falls represent a major problem among the elderly population, prevention of falls and injuries has become an important issue due to the aging of population. Subjective methods such as questionnaires and surveys are commonly used, but lead to inconsistent results as they are dependent on individual observation and interpretation. Various standard test assessments for physical activities, such as the TUG, FSST, step, and walking tests, are also subjective and dependent on the experience of the therapist. The main outcome measure is the performance time. On the other hand, force plate and 3D Motion Capture Systems, such as VICON, are objective methods that were introduced for evaluation of fall risk. Nonetheless, objective methods incur high costs, and the evaluation can be conducted only in a limited space. Therefore, a low-cost, simple, compact method for quantitative clinical evaluation of falling risk that provides greater sensitivity is required.

Standard tests for physical activity assessment have been widely used by therapists globally. Here, we focus on two standard tests: the Timed Up Go (TUG) test developed by Podsiadlo and Richardson [1], and the Four Square Step Test (FSST) by Dite and Temple [2].

The TUG test uses the time that a person takes to stand up from a chair, walk 3 m, turn around, walk back to the chair, and sit down, as shown in Fig. 1. During the test, the person is expected to wear their regular footwear and use any mobility aids that they would normally require. The TUG is used frequently in the elderly population, as it is easy to administer and can generally be completed by older adults. Shumway-Cook *et al.* suggested 13.5 s to complete the whole test as the threshold for discrimination of fallers and non-fallers [3]. Higashi *et al.* and Greene *et al.* suggested that the sensitivity of current practice is dependent on the subjective judgment and experience of the therapist [4][5]. They suggested that use of a wireless inertia sensor for classifying fall risk among the elderly would reduce the inconsistency of the results. In a recent study, three wireless inertia sensors attached at the waist dorsally and at both the right and left thighs were used to determine phase transitions [4 – 6]. However, to avoid restraining the subject with too many sensors, the study was performed with only one sensor attached dorsally at the waist. The subjects were asked to stand completely upright before beginning walking to avoid the requirement for two sensors attached at the thighs. In addition, the waist angular velocity sensor provides an accurate measurement of postural displacement [4]. Similarly, Greene *et al.* [5] used wireless inertia sensors to perform the TUG test and provide comprehensive quantitative analysis of phases. The use of a single waist-mounted triaxial accelerometer for phase determination in classifying human movement was first reported by Karantonis *et al.* [7].

The FSST can be used clinically to assess the ability to change direction when stepping. As a clinical test, the FSST is reliable, valid, easily interpreted and administered, and requires little space and no equipment. It is incremental in that

*Resrach supported by Reginald innovation program, Ministry of Education, Science and Culture Japan .

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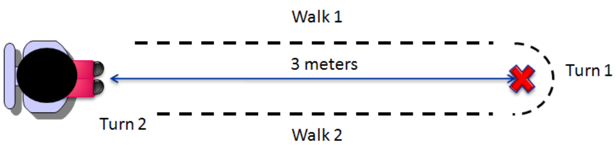
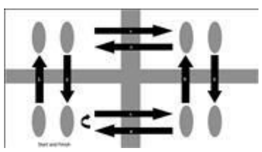
it involves stepping over low objects (2.5 cm) and movement in four directions, as shown in Fig. 1(b). Performance time is evaluated mainly in terms of balance deficits and risk of falling [8 – 10]. However, the FSST focuses only on the total performance time, without separating the performance of the subject in each phase; this is a limitation of the test. Both tests include several activities, and if the time of each activity can be evaluated separately, it may be possible to recognize distinct reductions in ability. In subjects with reduced walking ability, the therapist may focus on walking training.

This study was performed to determine whether phase classification using inertia wireless sensors attached at the waist and thighs dorsally was useful for classification of fall risk in the elderly.



(a)



(b)

Figure 1 (a) Trail of a Touch Up and Go test. (b) Trace of a Four Square Step Test.

II. Method

A. Measurement system

The wireless motion system can be divided into four parts: sensor, amplifier, transmitter, and data processor. The sensor part was installed with a combination of 3D (anteroposterior, lateral, and vertical axes) accelerometers (Freescale, MMA7260Q) and three 1D angular-velocity sensors (Murata, ENC-03R & XV-3500CB, Epson Toyocom) for roll, yaw, and pitch axes. The measured signal was then amplified. The accelerometer could measure acceleration in three axes of ±2 g with a sensitivity of 600 mv/g and ±4 g with a sensitivity of 400 mv/g. The angular velocity sensor could measure only a single axis, and so three sensors were required with sensitivity of 0.67 mv/deg/s. For data processing, amplified signals were converted from analog to digital using a microcontroller (microchip, dsPIC30F3013). The digitized information was then transmitted to a PC via the transmission section using Bluetooth. Use of more than one motion sensor required synchronization to ensure that the data were measured simultaneously by all sensors. The wireless motion sensors were attached to the subject's trunk (near the second lumbar vertebra) to capture the acceleration and angular velocity signals for all physical assessments during the test. Two sensors were attached to the thighs. The positions of the accelerometer and angular velocity sensor are shown in Fig. 2. The signal from the sensor unit was recorded on a PC at a sampling frequency of 100 Hz and sampling interval of 10 ms.

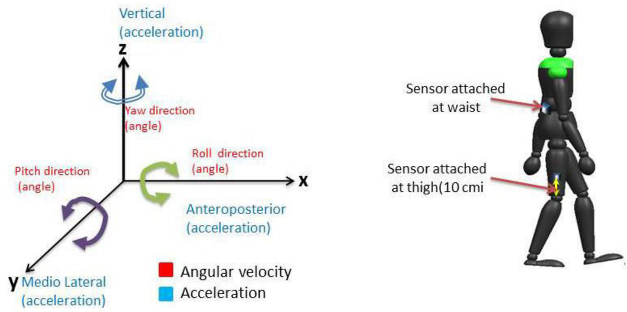


Figure 2 Alignment of sensors

B. Subjects

Forty elderly subjects aged ≥65 years from Fujimoto Hayasuzu Hospital, Japan, participated in the TUG test. Those who completed the test within 13.5 s were categorized as 13 low-fall-risk (LFR) subjects (63±8.9 yrs), while those who did not were categorized as 27 high-fall-risk (HFR) (71.1±5.8 yrs) subjects. Ten outpatients with hemiplegia (65.4±2.8 yrs) who suffered stroke and six healthy volunteers (65.4±5.2 yrs) performed the FSST test.

The experiments were approved by Ethics Committee of Fujimoto Hayasuzu Hospital and informed consent was obtained from all subjects.

During experiments the physiotherapist accompanied the subject for safety reason.

. C. Signal Analysis

For classification, the signals were compared with the three-dimensional acceleration and angular velocity signals.

In the TUG test, signals were divided into classifying the signal, we compared with three dimensional acceleration and angular velocity signals.

In the TUG test obtained signals were divided into eight basic activities; sit-bend, bend-stand, walk 1, turn 1, walk2, turn 2 ,stand-bend and bend-sit.

During sit to stand, the waist angle signal, based on the integral of angular velocity in the pitch direction, was used to classify the phase. Classification used a 10 dps threshold, which was used as the initial point to determine the time at which the subject stood up. In the walking phase, pitch angle started around zero, reached a threshold value of 3°, and increased gradually. The yaw angle then changed at the turning phase. After stabilization of the yaw angle, return walking started with a relatively stable pitch angle. During the second turn, the yaw angle changed suddenly. Using the waist angular velocity sensor in pitch and yaw directions, we estimated the phase of TUG. We used a 3° threshold for the TUG test based on a previous report [4].

For FSST classification, thigh angles were used to classify the phase. The movements associated with FFST were pitches and rolls due to striding over the obstacles. Thus, we focused on the angular velocity signal related to thigh extension and flexion. In the resting stage, a threshold pitch angular velocity of 5 dps was used. In the anteroposterior direction, the pitch angle has priority, while the focus is on angular velocity during roll in the lateral direction. A signal higher that the threshold indicated that the activity has started, while a signal below the threshold indicated that the activity has terminated

The time to complete the whole test and the timings of the various phases were calculated from the acceleration, angular velocity, and angular signals.

After classification, we can evaluate signals in each phase.

III. RESULTS

A. *TUG test*

Total performance time of Low fall risk (LFR) subjects and high fall risk (HFR) subjects were 10.09 ± 1.86s and 15.77 ±1.41s, respectively.

Figure 3 shows the phase classification. . Each activity was classified clearly.

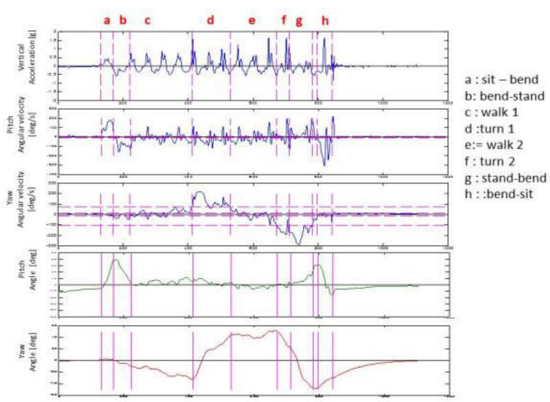


Figure. 3 Phase classification in the TUG test

Figure 4 shows both total performance times and those of each phase. Subjects in the HFR group took significantly longer to complete both the whole test, and each phase, than the LFR group.

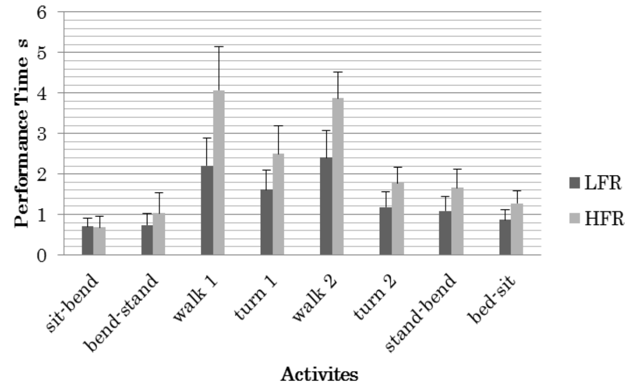


Figure 4. Comparison of the HFR and LFR groups in terms of the total time and that required to complete each phase..

B. *Four square step test*

Total FSST performance times in normal subjects and stroke patients were 9.02 ± 1.92 and 9.76 ± 2.33 s, respectively. Figure 5 shows the phase classification.

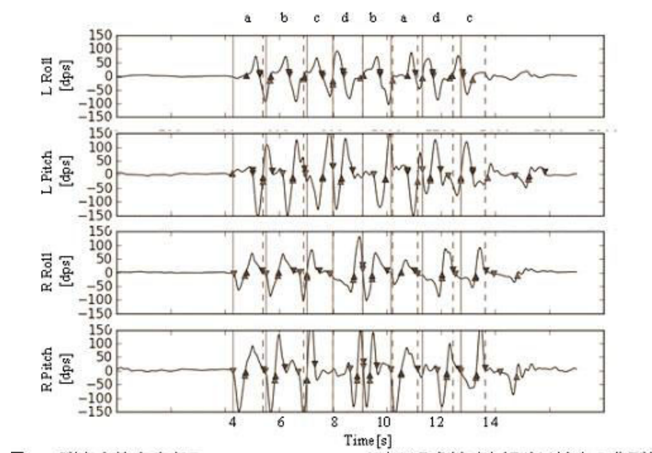


Figure 5 Phase classification in the FSST test. a – e indicate individual phases.

Figure 6 shows the time required to complete individual phases. There were no significant differences between normal and hemiplegic subjects. Performance times in the lateral direction in left and right hemiplegia patients were 9.73 ± 3.21 and 9.79 ± 1.36 s, respectively.

Table 1 Examples of Time duration in phases and total for HFR

	High fall-risk									
Sub	Sit-bend	Bend-stand	Sit-stand	Walk 1	Turn 1	Walk 2	Turn 2	Stand-bend	Bend-sit	Stand-sit	Total
A	0.93	0.86	1.79	3.95	3.46	3.36	1.97	1.58	1.33	2.91	16.27
B	0.36	0.44	0.8	5.51	1.93	3.91	1.07	1.43	1.22	2.65	15.2
C	0.91	1.62	2.53	2.33	2.03	3.85	1.56	2.02	1.35	3.37	14.52
D	0.4	0.67	1.07	5.63	2.3	4.95	1.63	1.47	1.15	2.62	17.25

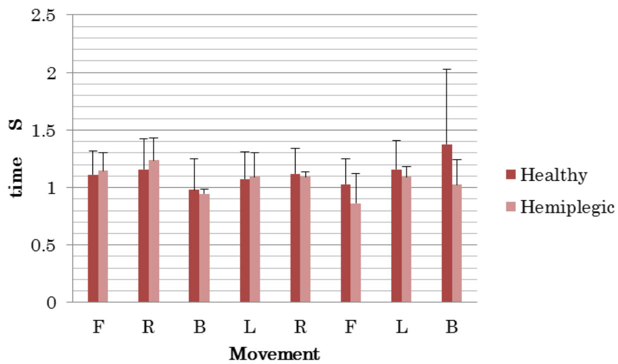


Figure 6 Times required to complete individual phases.

There were no significant differences in the time required to complete individual phases in the FSST test between healthy elderly subjects and patients with hemiplegia.

IV. DISCUSSION

We evaluated fall risk assessment tests using wearable inertia sensors and demonstrated the differences between the individual phases. In the TUG test, the sit-stand, walking, and turning activation could be distinguished. The time required to complete each phase could be evaluated and the results used as the basis for recommendation of suitable training and identification of areas that require particular attention to enhance daily living

Using this approach, the subjects could be classified as HFR or LFR. Moreover, the therapist was able to determine which activities would place the subject at risk of falling. Four subjects are shown as examples in Table 1.

All four subjects were classified as HFR. Total time for all subjects was over 13.5 s. Using only the total time, the therapist would be able only to classify these subjects as HFR. However, phase-by-phase analysis revealed the performance of each activity individually. For example, subject A show good performance in sit-stand and stand-sit but very poor performance in the turning phase, while subject B took a longer time to complete the walking phase but showed good performance in other phases. In subject C, the longer time required for the stand-sit phase indicated poor performance. In subject D, it is long time for walking .These data can be used by a therapist for training or to improve the performance. The therapist may train subject A in turning, subject B and D in walking, and subject C in the sit-stand and stand-sit movements.

FSST cannot be used to recognize differences between healthy elderly subjects and patients with hemiplegia. The data included both left and right hemiplegic patients. The square movement requires use of the foot on the paralyzed site as a pivot. If right hemiplegic patients move right to left, the right foot must be the pivot. We assumed that if the pivot foot is on the paralyzed side, the movement would be faster than in a healthy elderly subject as the paralyzed pivot foot is unstable. However, we did not observe such a tendency.

This study was performed only for classification of phases. Further studies should assess the individual phases to identify characteristics, such as weakness of movement, using the acceleration and angular velocity signals.

The FSST test addresses rather high-level activities, and even hemiplegic patients who could perform the test had high levels of activity.

V. CONCLUSION

In this study, the use of wireless inertia sensors for evaluation of fall risk among elderly subjects in phases was evaluated. Phase classification demonstrated the characteristics of each phase. In TUG, time required for most phases was significantly greater for high-fall-risk subjects compared to those at low risk. Although there were differences in the times required by normal and hemiplegic subjects for the FSST test, these were not significant. Analysis according to phase not only facilitated detection of fall risk in the elderly, but also provided the therapist with extra insight regarding the performance of the subject in each phase.

We believe that evaluation of individual phases could enhance fall-risk classification, resulting in more sensitive and specific clinical assessment.

ACKNOWLEDGMENT

The authors are grateful to the graduate students of Chiba University for their assistance with the study.

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