Quantitative evaluation of movement using the timed up-and-go test

Quantitative Evaluation of Movement Using the Timed Up-and-Go Test

Detection of Task Phase and Clinical Application to the Rehabilitation of Hemiplegic Patients

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Many hemiplegic patients who have suffered strokes need rehabilitation. The expected outcome of rehabilitation is the patient's independence and freedom from the aid of a nurse and a consequent improvement in the quality of life. Thus, occupational and physical therapy should be carried out efficiently, and the development of support technology for therapy is important. Developing independence in basic activities is essential in the early stage of rehabilitation as it influences the subsequent recovery of the patient's normal way of life. The timed up-and-go test (TUG-T) is a simple technique for evaluating competence in the following basic activities: standing up from a chair, walking forward, turning around, walking back to the chair, turning one's back to the chair, and sitting down. The total time taken to complete the TUG-T is used to predict the risk of falling [1]–[4]. However, no objective criteria exist for demarcating each activity phase of the TUG-T. At present, these are evaluated subjectively based on the experience of the therapist, and thus it is difficult to obtain objective data for clinical rehabilitation. Conventionally, the therapist evaluates how well the patient performs the TUG-T, at a detailed motion level, and confirms the patient's problems with particular activities. The therapist then determines ways to resolve the problems. Although the TUG-T measurements are easy to perform and accurately predict the risk of falling, it is necessary to perform an evaluation applying appropriate objective data. Acquiring quantitative data would be of great benefit in a rehabilitation program.

Measurements during clinical rehabilitation have been attempted using a triaxial accelerometer to measure the activity objectively, which allows a quantitative evaluation. The triaxial accelerometer enables motion evaluation in the frontal, sagittal, and horizontal planes by measuring the motion in the anteroposterior, vertical, and lateral directions, respectively. The acceleration signals can also be used to evaluate muscle power, joint function, and postural reflexes. Consequently, this assessment provides key information for evaluating the walking activity phase and the other basic activity phases of the TUG-T.

Previously, the activity was examined to evaluate quantitatively using only the signal from an accelerometer attached at the waist because it was believed that it would facilitate measurement during clinical rehabilitation [5]. The literature on evaluating posture using commercial, low-priced, accurate accelerometers is extensive [6], [7].

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During clinical rehabilitation, the measurement method should not restrain the subject with too many sensors. Angular measurements can be derived using Kalman filtering of the direct current (dc) element of the acceleration signal. However, this method has a reported error margin of $\pm 2°$ [6]. During clinical rehabilitation, it was difficult to identify hemiplegic walking from the angular displacement signal. It was also difficult to identify the activity phase clearly, which was our objective, using the acceleration signal alone.

A waist gyrosensor is useful for measuring the postural displacement with high accuracy. The posture can be determined by measuring the acceleration and angular velocities, although this method has never been used to evaluate and verify continuous activity from static sitting to walking [8]–[10]. Therefore, an accelerometer and rate gyrosensor was attached to the subject's waist and lower limbs to evaluate postural displacement. A further objective was to identify the activity phases of the TUG-T. Trained therapists measured the time for each activity phase from a videotape recording (VTR) of the TUG-T for reference [11]. This combined accelerometer or gyro method was used during clinical rehabilitation sessions during which the subject performed the TUG-T independently or while being supervised. Under both conditions, the walking phase activities extracted from the TUG-T data were compared qualitatively.

Method

The Measurement System

The measurement system used for the TUG-T consisted of two sensor units (Gyrocube), a multitelemeter system (WEB-5000), and a personal computer with a built-in analog-to-digital converter.

Each sensor unit can measure the three axes of acceleration (the waist accelerometer measures ± 3 g with a sensitivity of 1.33 V/g, whereas the lower limb sensor measures ± 5 g and 0.80 V/g, respectively, with a frequency response dc of 60 Hz) and the three axes of angular velocities (angular velocity ratings $\pm 400°$/s, sensitivity 10.0 mV/°/s, and frequency response

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dc of 40 Hz). The sensor measured $30 \times 40 \times 20$ mm^3 and weighed 7 g.

The signal from the sensor unit was recorded on a personal computer at a sampling frequency of 128 Hz via the multitelemeter system (the high cutoff frequency was 30 Hz).

The transmitter of the multitelemeter system measured $128 \times 80 \times 28$ mm^3 and weighed about 300 g.

Measurement Method

The measurement task was based on the TUG-T introduced by Podsiadlo and Richardson [11], and the procedure is as follows:

1) The subject sits with his or her back in contact with the back of the chair (the seat is 460 mm high and lacks armrests)
2) The TUG-T begins with the therapist's go sign and the subject stands up (standing up)
3) The subject begins walking (walk 1)
4) The subject turns around a post placed 3 m away from the chair (turn 1)
5) The subject walks back toward the chair (walk 2)
6) The subject turns away from the chair to sit down (turn 2)
7) The subject sits on the chair (sitting down).

The acceleration measurement points are at the waist dorsally (near the second lumbar vertebra) and at the lower limb on the side that takes the first step. Figure 1 indicates the positions of the accelerometer and gyroscope. The activity was captured with a CCD camera (EVI-D30) and recorded with a VTR (GV-D900NTSC). The therapist recorded the duration of each activity phase using a stopwatch while watching the video. Ten young, healthy subjects and 20 hemiplegic patients from Fujimoto Hayasuzu Hospital, Japan, were studied (Table 1). Twelve experienced therapists from the clinical rehabilitation center measured the durations of the activity phases. For safety, a therapist stood beside the hemiplegic patients during the activity.

The Method of Detecting and Evaluating the Activity Phase of the TUG-T

The data gathered from the healthy subjects were used to identify the data from the sensor signals corresponding to each activity phase. The features of these corresponding points were examined, and a method of detecting each activity phase was proposed. Figure 2 shows a typical example of the TUG-T in a normal young healthy subject (mean age, 21.0 ± 2), and Figure 3 shows the flowchart used to detect the phase changes. First, each activity phase was identified from the video images using a stopwatch.

From the perspective of rehabilitation training, the ability to stand up and walk is the most important task leading to the activity. Therefore, these two phases must be identified.

1) *Standing-up phase*: During the sitting phase, the waist pitch angular velocity, which is integrated in the angular velocity per unit time, is determined uniquely. In fact, the angular velocity in the sitting phase should be zero. In the healthy volunteers, the waist pitch angular velocity is almost zero, although a maximum waist pitch angular velocity of 10°/s was observed in a healthy subject. Therefore, the standing-up phase occurs when the output of the waist gyrosensor in the pitch direction exceeds a threshold of 10°/s.

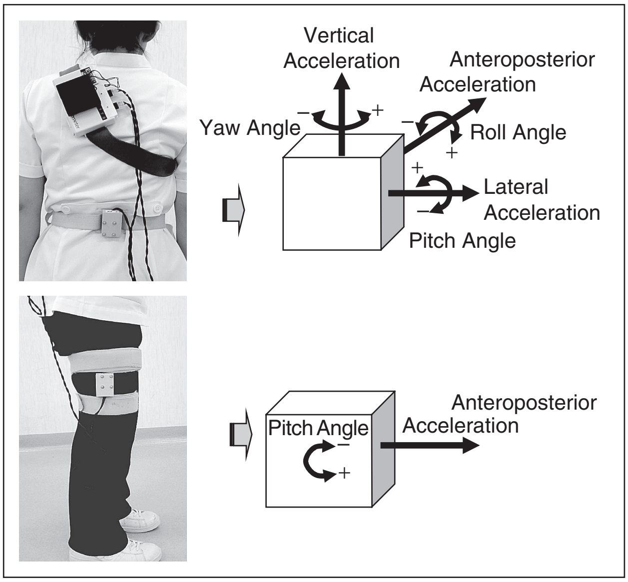

Fig. 1. Sensor unit positions.

Table 1. Subject profiles.

Case	Sex	Age (years)	Paralyzed Side	L/E Br. Stage	Gait Level
1.	Female	66	Right	III	Supervised
2.	Female	51	Right	III	Supervised
3.	Female	82	Right	IV	Supervised
4.	Male	74	Left	IV	Supervised
5.	Male	83	Left	IV	Supervised
6.	Male	65	Right	IV	Supervised
7.	Male	39	Right	III	Supervised
8.	Female	66	Left	IV	Supervised
9.	Female	65	Left	IV	Supervised
10.	Female	62	Right	IV	Supervised
	(Mean age, 65.3 ± 13)				
1.	Female	63	Left	IV	Independent
2.	Female	75	Left	IV	Independent
3.	Male	75	Right	IV	Independent
4.	Female	78	Right	IV	Independent
5.	Male	74	Right	III	Independent
6.	Female	70	Left	V	Independent
7.	Male	57	Right	IV	Independent
8.	Male	70	Right	IV	Independent
9.	Male	74	Left	IV	Independent
10.	Female	76	Left	IV	Independent
	(Mean age, 71.2 ± 6)				

Developing independence in basic activities is essential in the early stage of rehabilitation.

Similarly, the start of the sit-down phase is when the pitch angle is below 10°/s.

2) *Walking phase*: This phase is defined as the first instance when the output of the lower limb gyrosensor in the pitch direction exceeds the threshold Th_w, which equals 10°/s. In fact, the zero-crossing time (the time when the readout is no longer zero) is sufficient to indicate the start of walking. However, to eliminate the effects of the subject swaying and swinging, the value of 10°/s instead of the zero-crossing time was used.
3) *Turning phases*: For turning, the turns while walking (turn 1, t_1) and for sitting down (turn 2, t_2) were identified by a large angular velocity signal in the yaw direction from the waist sensor. To obtain t_1 and t_2, the yaw direction angular velocity signal was processed by applying low-pass filtering using second-order Butterworth filters with a cutoff frequency equal to the walking cadence.

To obtain T_{max}, the time when the yaw direction at the waist is the maximum, and ω_{max}, the maximum value of the yaw direction, β as 35% of ω_{max} was first determined empirically. When the angular velocity exceeded $\omega_{max} \times \beta$, this gave the duration of t_1 (the blue line in Figure 2). Furthermore, the value of $\omega_{max} \times \beta$, which is one step before and after the time of $\omega_{max}(T_{max})$, was considered. When the angular velocity exceeded $\omega_{max} \times \beta$ within $T_{max} \pm \alpha$, these periods (the green line in Figure 2) was added to the duration of t_1 (red line).

The duration of turn 2 (t_2) was obtained in a similar manner. Both made use of the necessary assumptions that turn 1 occurs not long after the start of the walking phase, and turn 2 takes place before the sitting-down phase.

4) *Sitting-down phase*: The sitting-down phase begins at the end of turn 2 and ends when the output of the waist gyrosensor in the pitch direction falls below the threshold Th_s.

When the proposed method was applied to hemiplegic patients, it was taken into account that the movement of both legs during walking is not symmetrical. Therefore, the value of α was set to double the period of one step by a healthy volunteer.

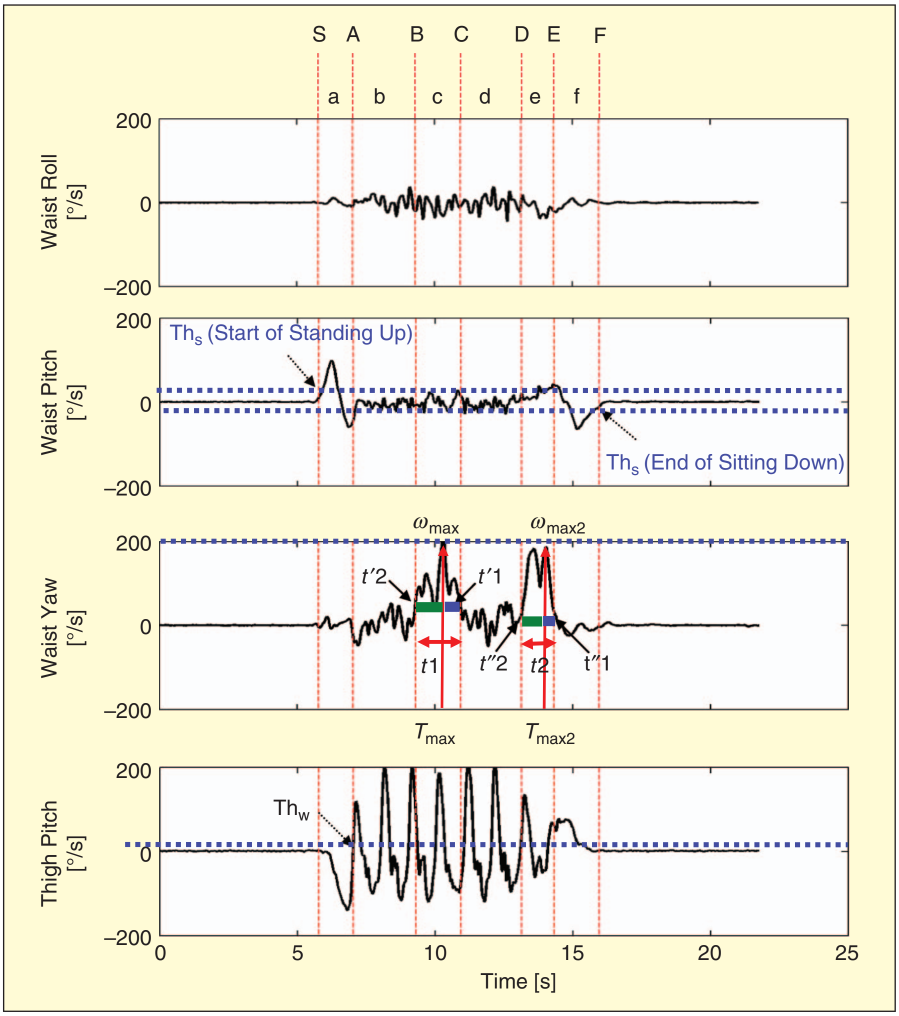

Fig. 2. Typical angular velocities and the points at which the phase changed in a young subject during the TUG-T: (section a) standing up, (section b) walking 1, (section c) turn 1, (section d) walking 2, (section e) turn 2, and (section f) sitting down.

These parameters were uniquely determined from the healthy subjects. The maximum error was included in the proposed assumptions.

Clinical Application of the Proposed Method

The subjects were 20 hemiplegic patients. Ten subjects were able to walk independently, whereas the other ten could only walk under supervision. Table 1 shows the details of the subjects. The various activity phases were identified, and their durations were obtained from the angular velocities signals during the TUG-T. The data were examined for qualitative differences in walking among subjects, and the independent and supervised walking subjects were compared. The cadence was calculated from the signals for walk 1, turn 1, and walk 2. The root mean square (RMS) value of the acceleration signal, and hence the coefficient of variation (CV), was calculated from the walking cycle. The acceleration signals were compared using these values and the direction of movement. The *t*-test was used for statistical comparisons, and Bland-Altman plots were used to evaluate the accuracy of our method. Using this method, the data were compared to the measurements made with a stopwatch while the therapist was watching the VTR.

Results

Correlation Between the Proposed Method and Therapists' Measurements

Figure 4 shows that the activity phases of a typical hemiplegic patient identified using the proposed method was similar to the results with a healthy volunteer. The results using the

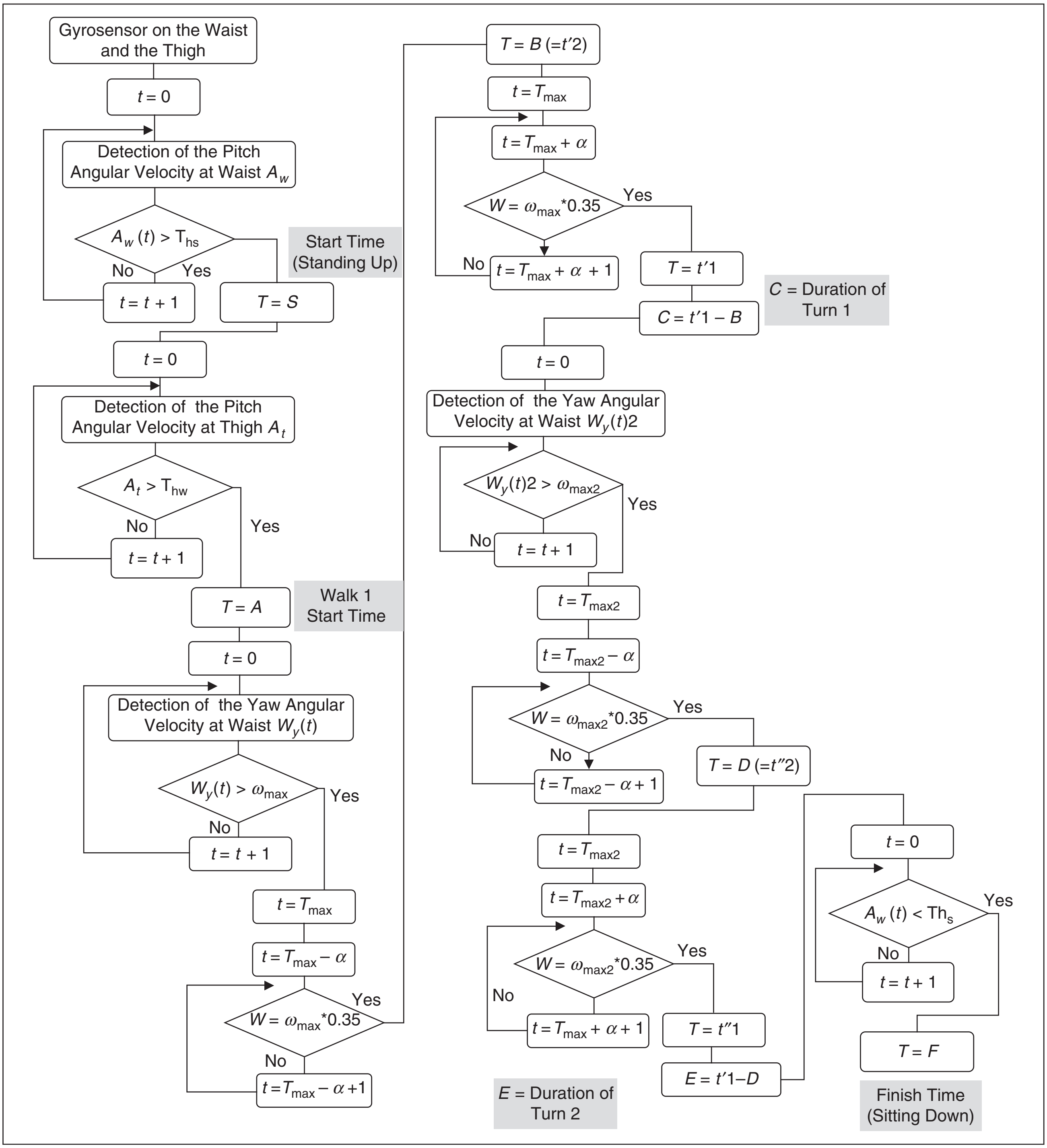

Fig. 3. Flowchart used to detect the changes in phase.

proposed method were strongly correlated with those based on the therapists' observations (Figure 5). Furthermore, most values were included in the Bland-Altman plot within ±1.96 SD (Figure 6).

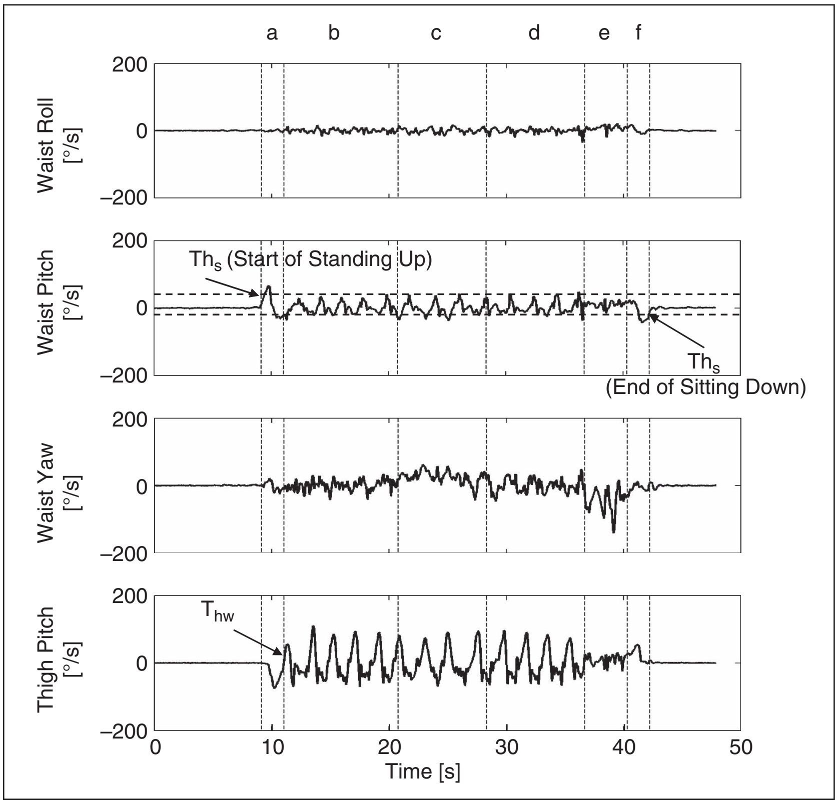

Fig. 4. Typical angular velocities and the points at which the phase changed in a hemiplegic patient during the TUG-T. (a) Standing up. (b) Walking forward. (c) Turn 1. (d) Walking backward. (e) Turn 2. (f) Sitting down.

One feature of the signal for a hemiplegic patient was that the angular velocities in the roll and pitch directions were large, whereas those in the yaw and lower limb pitch directions were small. The results suggested a good correspondence between the times measured by the therapists and the times estimated using our method.

Clinical Application of the Proposed Method

1) Comparing the total TUG-T time, the supervised group took longer than the independent group ($P < 0.05$; Figure 7).
2) Comparing the duration of each activity phase, the supervised group took longer than the independent group for walks 1 and 2 (walk 1: $P < 0.05$, walk 2: $P < 0.01$), while no significant differences were observed for the other activity phases (Figure 8).
3) Comparing the RMS values of acceleration, the supervised group had lower values than the independent group. Specifically, the RMS value in the lateral and vertical directions was smaller ($P < 0.01$; Figure 9).
4) Comparing the CVs, the supervised group had a higher value than the independent group in the lateral direction ($P < 0.01$; Figure 10).

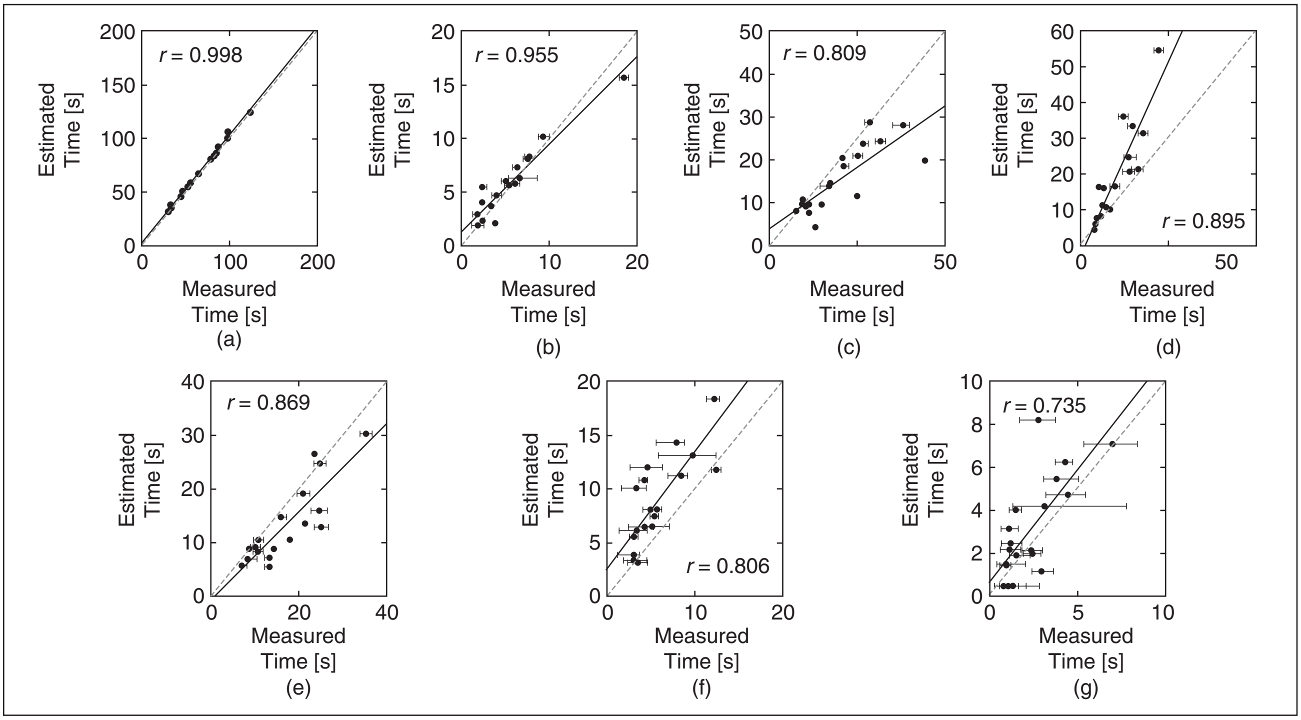

Fig. 5. Comparison of the time measured to hemiplegics by the therapists and that estimated using our method. (a) Total time. (b) Standing up. (c) Walking forward. (d) Turn 1. (e) Walking backward. (f) Turn 2. (g) Sitting down. (The error bar indicates the minimum and maximum values. The solid and broken lines show the regression and identity lines, respectively.)

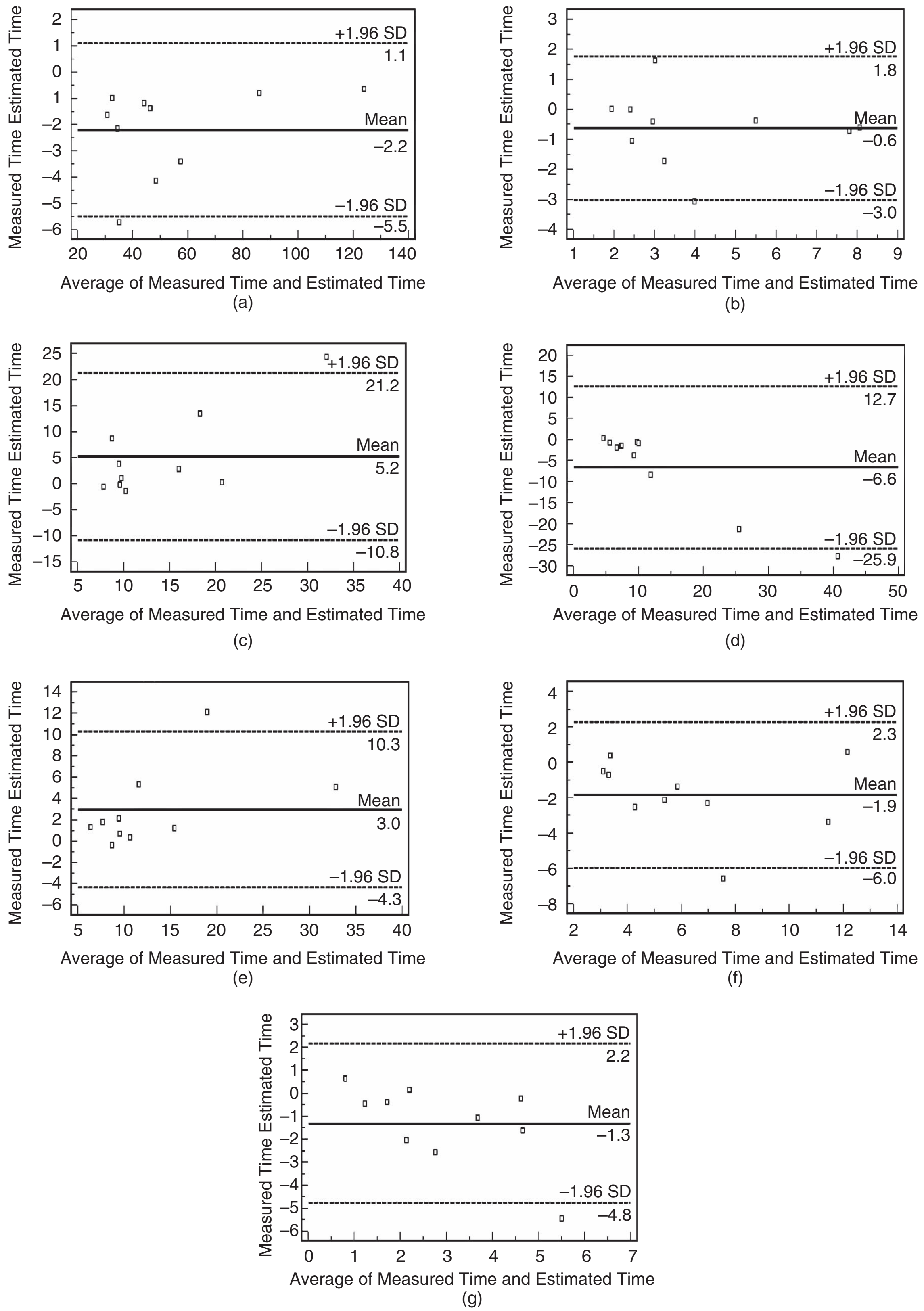

Fig. 6. Comparison of the time measured to hemiplegics by the therapists and that estimated using our method with the Bland-Altman plot. (a) Total time. (b) Standing up. (c) Walking forward. (d) Turn 1. (e) Walking backward. (f) Turn 2. (g) Sitting down.

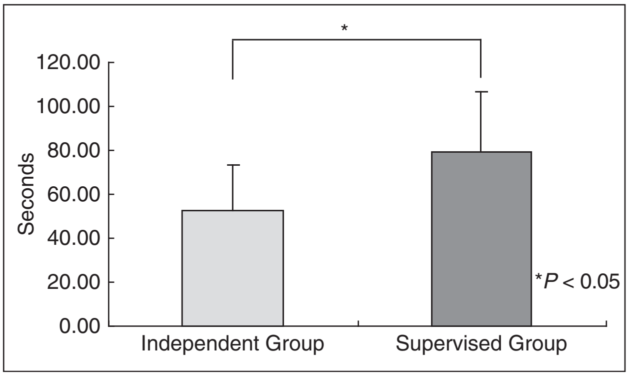

Fig. 7. Comparison of the total times between the independent and supervised groups.

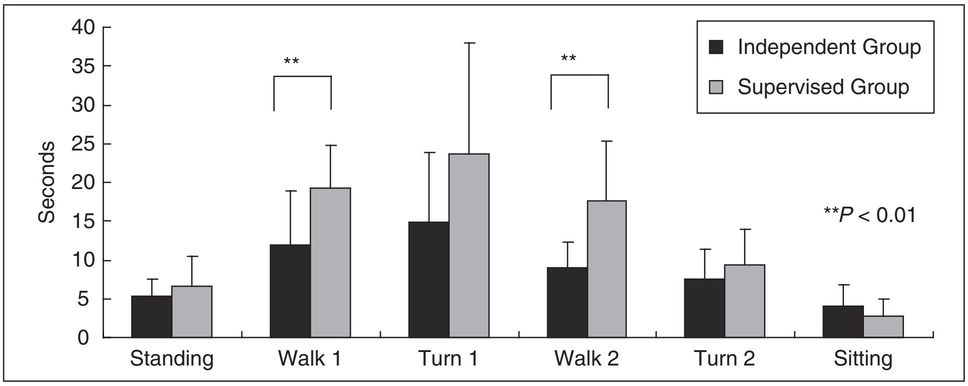

Fig. 8. Comparison of the time for each activity between the independent and supervised groups.

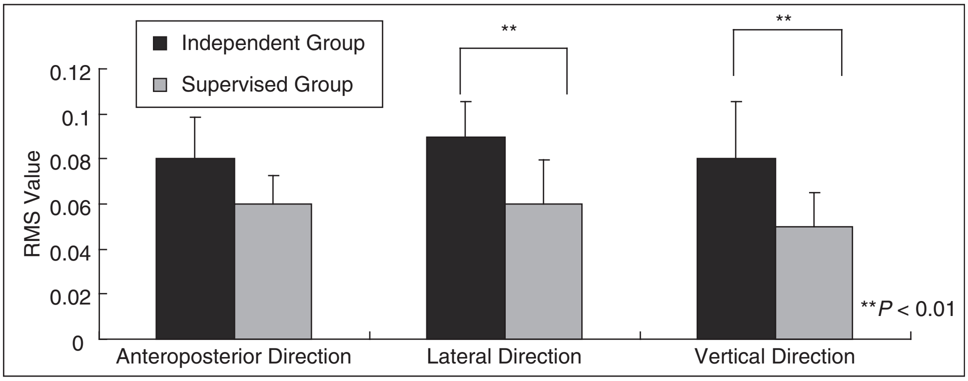

Fig. 9. Comparison of the RMS value for each direction between the independent and supervised groups.

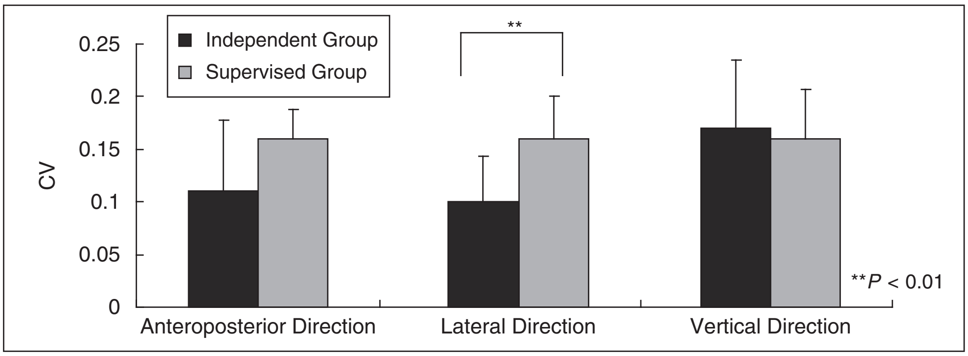

Fig. 10. Comparison of the CV for each direction between the independent and supervised groups.

5) Looking at typical data for supervised and independent subjects, the RMS value for the supervised subjects varied widely at the beginning of walking after standing up (Figures 11 and 12). Similarly, the RMS value varied widely just before sitting.

Discussion

Activity Identification and the Use of Acceleration and Angular Velocity Measurements

The TUG-T is a convenient first test used in teaching fall prevention. The general practice in current research is to measure the activity time in the TUG-T with a stopwatch. However, the TUG-T consists of several activity phases (i.e., standing up, walking 3 m, turning, and sitting down). To better understand the complete performance, it is necessary to evaluate the consecutive sequence of activities. However, because it is difficult to isolate individual problems within each activity phase in the clinical environment, it becomes necessary to identify each activity phase and evaluate each individually.

The Method Used to Detect the Activity Phases in the TUG-T

The start of the standing-up phase could be detected using the waist gyrosensor signal in the pitch direction. Generally, at the time of standing up, a hemiplegic patient shifts his or her trunk by inclining forward markedly, shifting the center of gravity forward to counter the weakness of the lower limbs. The measurement of the pitch angular velocity of the waist was excellent for detecting this forward inclination. The activity of sitting down is similar to, but opposite, that of standing up.

The start of the walking phase immediately after the standing-up phase could be detected from the pitch direction signal of the lower limb angular velocity sensor. Several methods for evaluating walking quantitatively have been used; e.g., electric goniometers, force plates, and impact acceleration [12]–[14]. However, to identify walking as one of a consecutive series of activities, we obtained excellent results from the pitch angular velocity signal of the lower limb.

The identification of the turning phase from the waist yaw direction angular velocity using the proposed method was correlated with the judgment of the therapist. Some features of walking were then considered when hemiplegic patients made turns. For example, hemiplegic patients turn slowly because the radius of gyration is widened to prevent falls. Another feature of walking in hemiplegic patients is the reduced step length to confer stability. This is evident from the small signal of the lower limb pitch direction angular velocities. A small signal for the yaw direction angular velocity showed rotation of the waist, and the signal for the waist roll direction angular velocity had a large amplitude, reflecting the compensational reaction of the waist in the lateral direction while drawing in the lower extremity.

In addition, the signal of the waist pitch direction angular velocity had a large amplitude. This reflects the left-right asymmetry in walking because of the paralysis. Our results showed that the signal information from the gyrosensors worn during the TUG-T can be used to identify the individual activity phases. Our results from the accelerometer can also be used to analyze the activity effectively. In the near future, we should be able to analyze the consecutive activity phases.

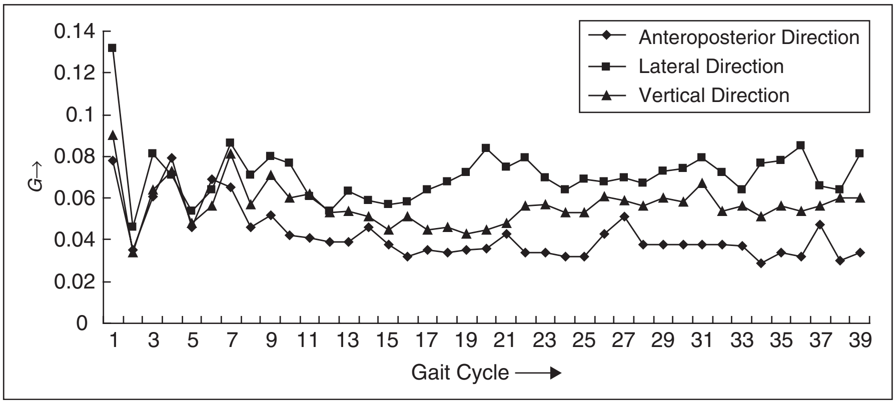

Fig. 11. Typical RMS value in a supervised case.

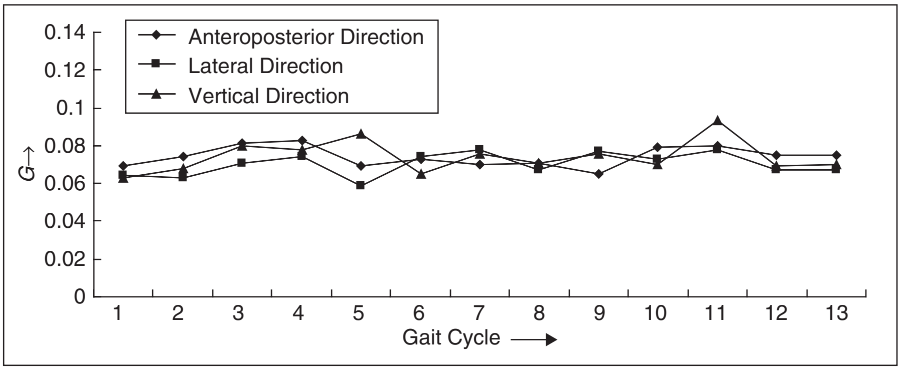

Fig. 12. Typical RMS value in an independent case.

Correlation Between the Proposed Method and Therapists' Measurements

In this study, the length of each activity phase identified using the proposed method was compared with the times measured by the therapist. A high positive correlation was observed between the two, but the error margin for the turn was large among the therapists. Usually, it is easy to identify the activity from a video recording of the frontal and sagittal planes, but to identify the beginning and end of a turn, a video recording of the horizontal plane is necessary. However, it was difficult to cover all angles in the video recording. This explained the comparatively large error margin in the durations of walks 1 and 2, which occur immediately before and after the turn, respectively. The durations of walks 1 and 2 determined using our method tended to be shorter than those determined by the therapists, whereas the duration of the turn between walks 1 and 2 tended to be longer. Therefore, the error margin of both the sensor-derived results and human perception should be considered.

Clinical Application of the Proposed Method

1) Comparing the total TUG-T time, the supervised group took longer than the independent group in walks 1 and 2, but not for the other phases.
2) Comparing the RMS values, the supervised group had lower values than the independent group because the walking velocities of the independent group were greater.
3) The RMS of the acceleration for the supervised group in the lateral direction was smaller because during steady walking, their step length decreases, reducing the vertical movement. Their stride width also decreases, reducing lateral movement. The combination of these two factors prolongs the walking phase.
4) Comparing the CV, the supervised group had a higher value than the independent group in the lateral direction because of less constancy in the stride width.
5) Comparing the data from different subjects, the RMS value varied widely at the beginning of walking after standing up. Similarly, the RMS value varied widely just before sitting because the subject is not steady while walking.

Conclusions

In this study, the combined use of an accelerometer and rate gyrosensor to identify the activity phases of the TUG-T was proposed. For the comparison, trained therapists measured the duration of each activity phase from a video recording. As a result, the proposed identification of the activity phases was well correlated with the therapists' observations. By using both the accelerometer and gyrosensor signals, it was possible to detect the activity phases, which were similar to those observed by the therapists. In addition, the walking activity was extracted from the TUG-T, and the RMS value and CV from the acceleration were calculated in every walking cycle. A qualitative difference between the subjects who could walk independently and those requiring supervision was revealed.

It is currently believed that the TUG-T performance is correlated with the risk of falling. By identifying each activity phase in detail, it is possible to evaluate both the activity from beginning to end (standing up → sitting) and the switches between activity phases (walking → turn → walking). Detailed information was obtained for each activity phase so that the evaluation of the consecutive sequence of activity phases could be realized.

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