Estimation of Gait Parameters based on Motion Sensor Data

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Abstract: Recently, the spreading application of intelligent mobile devices with integrated sensors such as inertial measurement units (IMU) has attracted the interest of the researchers for designing gait analysis methods based on the captured sensor data. This paper focuses on designing a system which can evaluate the walking ability and the physical agility level of normal people and people with Parkinson's disease or stroke. The motion signal is collected by three wearable MPU9250 sensors located on both ankles and the center of the waist. Three test scenarios, including 10 meters walking test (10MWT), Time up and go test (TUGT) and Dual-task walking (DTW), are designed in this paper. The results, which concluded time parameters such as standing up time and turning back time as well as walking parameters such as stride length and stride frequency, showed good consistency and high accuracy with Vicon device.

1 INTRODUCTION

Wireless motion sensors can be placed on different positions of people to evaluate walking ability and physical agility. The analyzed features can be delivered to the scale assessment module to quantify the physical condition (Hanson et al., 2009). Currently, the unified Parkinson's disease rating scale (UPDRS) and the Glasgow coma scale (GCS) are widely used methods to do the assessment to Parkinson's and stroke patients (Mov, 2003).

Normally, evaluators can assess the body condition of patients by experience. However, this method is not objective enough and it is the reason for the extensive attention of using data collected from sensors to quantify the body condition. Moreover, according to the normal algorithm designed to process the motion signal, there is still improvement should be done to get better performance. Different division methods for movement periods and different data fusion methods for transformation of axes were discussed and developed. For example, Madgwick (Madgwick, 2010) developed an attitude and heading reference system (AHRS) algorithm. Besides, classic data fusion modules, such as Kalman filter and Complementary filter, are also extensively used and developed. Generally speaking, data fusion modules need to achieve different requirements to obtain the ideal result, such as Kalman filter needs to establish a complicated prediction model, in which the covariance matrix is difficult to establish and the signal processed must be linear.

In this paper, we aim at designing a system to quantify some parameters used in the scale assessment module which are hard to quantify by observation methods. New methods used to divide motion periods and fuse the 6 axis data are discussed and tested. Specifically, three test scenarios, 10 MWT, TUGT and DTW, are designed. During the test process, three data acquisition modules with IMU units are placed on two ankles and the center of the waist. The collected motion data is pre-processed by a digital signal processor integrated in the data acquisition module and then transmitted wirelessly to the stationary computer. Three data processing functions are designed on stationary computer corresponding to the three test scenarios mentioned above. The designed motion periods division methods used in the three functions should be able to eliminate the effect of slight shaking or movement of sensors (select profit axis). Firstly, the up and down

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function divides standing up and sitting down periods and outputs standing up time and sitting down time. Secondly, the turn back function divides turn back periods during the walking process and outputs turning back time with turning back angle. Thirdly, the walking calculation function divides gait periods and outputs stride length as well as relevant parameters.

To validate the efficiency of functions, reference outputs calculated by the Vicon device are recorded and compared with the results calculated by the proposed functions. Vicon is an optical motion capture system produced by OML Company. The accuracy rates are shown by tables and the advantages and disadvantages of the designed method is discussed in this work.

2 EXPERIMENTS AND METHODS

The system can be divided into two main modules: the data acquisition module and the data processing module. According to the data acquisition module, a hardware system is designed to collect 9 degree of freedom motion signals of individuals. Two data acquisition modules are placed on both ankle joints and one data acquisition module is placed on the center of the waist. As for the data processing module, a reliable and promoted algorithm which is used to obtain features during the gait process of participants is designed. The following figure shows the simple system flow,

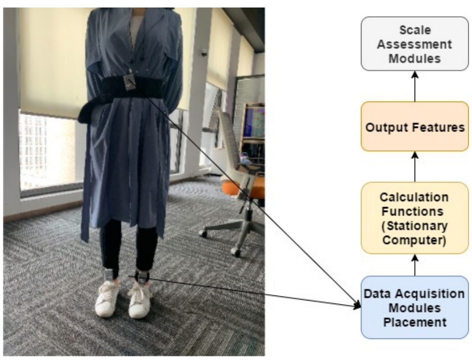

Figure 1: System flow chart.

2.1 Data Acquisition Module

The multi-chip module, MPU9250, which concludes a 3-axis gyroscope, a 3-axis accelerometer and a 3-axis magnetometer, is applied in the data acquisition module. The initial motion signals are amplified and digitalized in the module and transmitted to the stationary computer wirelessly.

2.2 Sensors Wearing

As is shown in Figure 1, the data acquisition modules are adhered to the elastic bandages with adhesive tapes and then the bandages are wore on two ankle joints and the center of the waist of the user. Considering there might be trembles or waggles during the process of experimental paradigms, positions of the first two data acquisition modules are not required to be precisely placed on the center of feet. The third module is required to be placed on the center of the waist as much as possible. The impacts of trembles and waggles are designed to be tackled in algorithms.

2.3 Test Scenarios

The tests aim at evaluating the walking ability and the physical agility level of normal people, Parkinson's disease patients and stroke patients. Three designed test scenarios are shown as below:

- **10 Meters Walking Test (10MWT):** The participant is wore with three data acquisition modules and asked to walk straightly on a 14 meters' walkway with normal speed. The walkway is marked on two meters and 12 meters. The data collected from the in-between 10 meters test will be used.
- **Time Up and Go Test (TUGT):** The participant is wore with three data acquisition modules and asked to stand up from a chair, walk 3 meters in a straight line, turn around, and then walk 3 meters back to sit down.
- **Dual-Task Walking (DTW):** The test aims at Parkinson's disease and stroke patients. Based on the 10WMT, the patient is required to calculate 100 keeps subtracting 2 as the walking process. Times of correct answers and wrong answers should be noted down.

2.4 Data Processing Module

The signal collected from the data acquisition module is wirelessly transmitted to the stationary computer. The accelerometer signal unit is converted to $^{m}/_{s^2}$, the gyroscope signal unit is converted to $^{rad}/_{s^2}$ and the magnetometer signal unit is converted to µT based on the range of data collection. Afterwards, the signals are filtered by a Butterworth band pass filter.

The algorithms are developed and tested in Matlab 2015b (www.mathworks.com), the data obtained and figures used in this paper are produced in this software as well. According to the engineering landing of the algorithms, the software which integrates all algorithms is developed by C# in Microsoft Visual Studio 2017 (visualstudio.microsoft.com). Specifically, there are three algorithm modules that correspond to the three test scenarios. Figure 2 describes the flow diagram for the developed gait analysis algorithm.

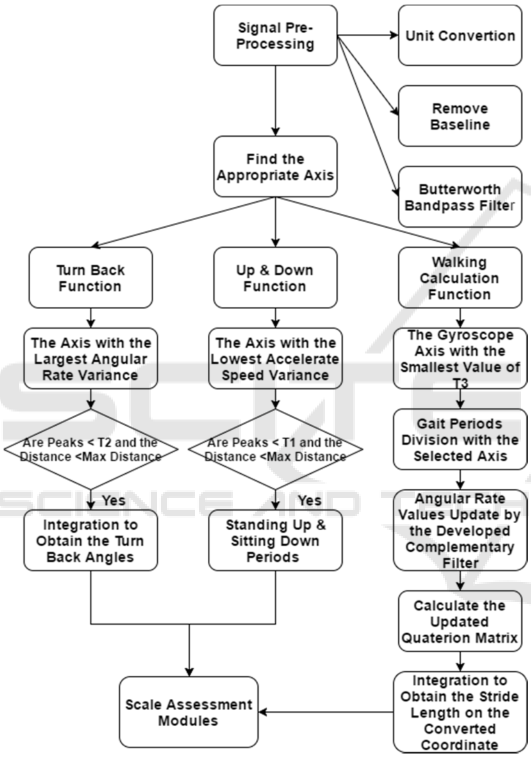

Figure 2: Flow diagram of the algorithm.

2.4.1 Up and Down Algorithm

The algorithm in this function corresponds with the up and go test scenario. Output features contain standing up time and sitting down time. The core part of the algorithm is to find out the suitable axis that contains enough information to figure out the standing up and sitting down periods. As participators are not required to wear data acquisition modules with a standard direction, which means the sensors might slide the location or skew with an angle, selecting the applicable axis can help us eliminate the effect caused by these issues. According to the up and down function, the algorithm is designed with the following steps,

- Find the Applicable Axis:

According to the physical movement situation of sitting down and standing up, the sensors should have vertical shifts. On the other hand, along with the sitting down and standing up process, body leans back and forward, thereby the angular velocity of forward axis changes. As a result, the changes of vertical accelerated speed and the forward angular velocity can be considered as features used to define the suitable axis.

When the variation of angular velocity is used as the feature, the suitable axis should be the axis with the maximum variance, which means the axis has maximum changes during the test process. If a window is added to the signal of the suitable axis, it can be found that the variance is higher during standing up and sitting down process. Considering that the algorithm should be applicable to Parkinson's disease and stroke patients who might have tremor on the forward direction, the axis with the lowest accelerate speed variance is selected to use.

- Interval Divisions:

The standing up and sitting down intervals are half sine waves at the beginning and the end of the test. Peaks on the axis are found by using a developed peaks finding algorithm. The threshold height value of peaks is set as E (the expectation of signal) + (weight value) x $\sqrt{2 * \text{V (the variance of signal)}}$; thus giving:

$$\mathrm{T1} = \mathrm{E} + 0.6 * \sqrt{2 * V} \tag{1}$$

The formula (1) comes from 3 sigma principle (Marilyn et al., 2007) and be modified according to actual signal condition. The maximum distance between two peaks is set as,

$$\text{Max distance} = (\text{mean}(\text{distance}))/2 \tag{2}$$

It is also necessary to confirm that the peak has the largest value within certain range, which is set as [-Max distance, Max distance]. The zero crossing points nearby the peaks are considered as the border of getting up and sitting down periods. The getting up and sitting down time can be obtained by calculating the length of two intervals.

2.4.2 Turn Back Algorithm

Output features of this function are turning time and turning back angle. The applicable axis of the gyroscope signal is found and output features are calculated based on this. The algorithm is designed with the following steps,

- Find the Suitable Axis:

The turning mainly happens around the vertical axis of the body. The angle around the vertical axis changes apparently thereby the variation of angular velocity is considered to be the feature used to define the axis. Actually, the axis we use here should be as same as the axis we use in the standing up and sitting down function. However, considering about the physical significance, the axis with the maximum angular rate variance is selected.

- Turning Back Interval Division:

The turning back interval might be a half sine wave, a half cosine wave, a whole sine wave or a whole cosine wave. This depends on how an individual turns. For example, if an individual turns back with an almost 360 degree angle, the interval should be a whole sine wave. To figure out the intervals turning back period during test process, firstly the threshold height value of peaks is set with the formula below,

$$\mathrm{T2} = \mathrm{E} + \sqrt{2 * V} * 1.5 \tag{3}$$

The maximum distance between two peaks and the certain range that contains one largest peak value are set as same as the standing up and sitting down function. The number of zero crossing points between two peaks should be two. The turning back angle is obtained by integrating the angular rate in the turning back period and the turning back time is the length of the turning period.

As a result, if there is a turning during the test process, and the turning angle is larger than 90 degree, the turning is considered as a real turning and counted.

2.4.3 Walking Algorithm

Walking algorithm function is called in all three test scenarios, which makes it the core part of the project. In the walking algorithm function, the output objects are stride length and relevant parameters such as stride speed and stride frequency. The gait time periods should be classified firstly and then output parameters can be calculated. The function can be divided into the following two sections,

- Gait Time Periods Classification:

Gait time periods can be divided into swing phase and stance phase roughly. It is common to use the variance of accelerometer values of the forward axis as the feature to classify gait periods. On account of there should be no significant change of the acceleration during the stance phase, the variance value in stance phase should be almost zero. On the other hand, during the swing phase, the variance value should fluctuate with a non-zero value. However, the classification method is limited in a series of conditions. For example, the threshold of the acceleration variance is nearly impossible to be applicable to all gait periods even though an adaptive threshold is used.

Considering about the disadvantages of previous methods, a developed method is designed to classify gait time periods precisely. Specifically, the developed method contains two parts,

Selection of Reference Axis:

The gyroscope data can be used to divide the gait time periods as stated by Koichi (Koichi et al., 2000). In the developed method, the appropriate gyroscope axis is selected with a new combined feature T3, which comes from a combination of features on time domain. The axis of gyroscope that we need is the one has the most obvious and periodic signal feature on the time domain. Specifically, the selected axis should have three typical time domain characteristics: the extent of the fluctuation of peak values is smaller, the number of peaks after filtered (with the method introduced in 2.4.1) is larger and the data of the axis is with good symmetry.

T3 is obtained by adding weights to above three features, which is shown below,

$$\begin{aligned}\mathrm{T3} = &\left(\frac{\mathrm{E}(\mathrm{difference}(\mathrm{peaks}))}{\mathrm{E}(\mathrm{peaks}) * \mathrm{Number}_{\mathrm{of}_{\mathrm{peaks}}}} + \frac{\mathrm{E}(\mathrm{difference}(\mathrm{valleys}))}{\mathrm{E}(\mathrm{valleys}) * \mathrm{Number}_{\mathrm{of}_{\mathrm{valleys}}}}\right) \\ &* \mathrm{ABS}\left(\mathrm{Number}_{\mathrm{of}_{\mathrm{peaks}}} - \mathrm{Number}_{\mathrm{of}_{\mathrm{valleys}}}\right)\end{aligned} \tag{4}$$

The axis with the smallest value of T3 is the axis of gyroscope used to classify gait time periods.

Gait Time Periods Classification:

Gait time periods are divided on the selected gyroscope axis by finding out appropriate peaks and zero crossing points. Peaks are found with the methods introduced in 2.4.1. During the stance period, the gyroscope value should pass through zero crossing points, therefore, the zero crossing points nearby peak values can be considered as borders of gait periods. With the developed method, gait time periods is divided as the figure below,

- Parameters Calculation:

Data on the geodetic coordinate (GC) can be

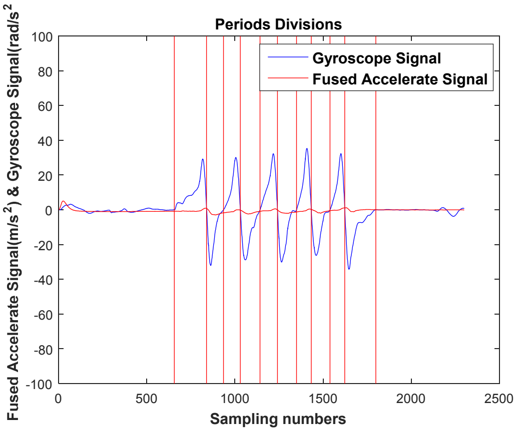

Figure 3: Divisions of gait time periods.

transformed from data on sensor coordinate (SC) via the transformation matrix R_{sc}^{gc} represented by quaternion. To obtain the updated and accurate quaternion matrix $[q_0, q_1, q_2, q_3]$, the data fusion algorithm is necessary. Normally speaking, there are several types of data fusion algorithms, such as Kalman filter, complementary filter and Mahony & Madgwick Filter. While there are limitations for the algorithms mentioned above, take Kalman filter as example, it needs significant modeling assumptions to reach its theoretical results (Reza, 2009). On the other hand, the generalized complementary filter is not as accurate as the Kalman Filter. Thus a developed complementary filter is designed.

As the aimed outputs do not require knowing the yaw angle, a six axes data fusion method is applied. What is confirmed is that in the GC, the accelerate data on two axes of horizontal plane should be zero and the value on vertical axis should be close to 1 (after normalization). According to the basic rationale of complementary filter, the updated gyroscope values can be shown as a fusion of previous gyroscope values and parameters calculated from the errors of acceleration values. A new error compensation model is designed in the developed algorithm and the steps are shown as below,

Calculation the Error Parameter:

The reference acceleration vector is obtained by multiply the acceleration vector [0, 0, 1] by the transformation matrix represented by quaternion. By doing the difference calculation of the reference acceleration vector and the acceleration vector collected from the sensor, the error parameter is obtained. It can be estimated that the error parameter can be used to support long time periods of time.

Data Fusion:

Considering wavelet transform can effectively describe the time domain characteristics on high frequency periods and the frequency domain characteristics on low frequency periods, it is selected to combine the gyroscope signal and the accelerate signal, instead of the traditional proportional-plus-integral (PI) control method. The selection of appropriate PI control parameters is difficult. On contrast, there are already a series of mature threshold setting methods of wavelet transform.

A window whose length is 50 is added to accelerate error signal and gyroscope signal to calculate appropriate filtered values. The updated angular rate values ($\omega_{x,y,z}$) are represented by the combination of low pass filtered angular rate values ($\omega_{x,y,z(lf)}$) and the weighted error parameters come from high pass filtered acceleration values ($error_{x,y,z(hf)}$). The formula is shown as,

$$\omega_{x,y,z} = \omega_{x,y,z(lf)} + error_{x,y,z(hf)} \tag{5}$$

Quaternion Update:

The updated quaternion (q_t) can be represented by the combination of previous quaternion (q_{t-1}) and updated gyroscope values (ω_t), which is shown in the following formula (James, 2006),

$$q_t = q_{t-1} + \frac{1}{2} q_t * \omega_t * \Delta t \tag{6}$$

The corresponding accelerate signal on GC can be obtained by multiplying the accelerate signal on SC by the transformation matrix which is composed by quaternion.

The transformed accelerate signal on x axis is shown as below,

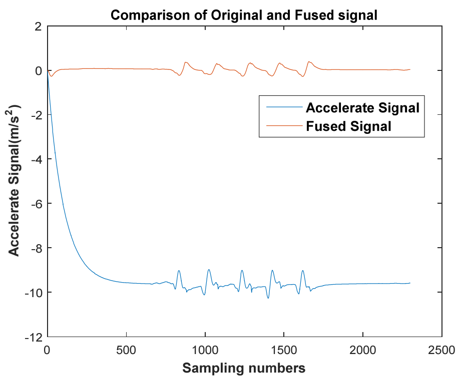

Figure 4: Original and fused accelerate signals on X axis.

3 RESULTS AND DISCUSSIONS

3.1 Performance of Up and Down Function

10 participants who signed the Informed Consent Form were randomly selected to do the TUGT test, which means the external factors such as height and weight were not considered. Each of them was asked to do the TUGT test for 5 times. The calculated outputs were recorded as the mean values of the 5 times' tests of each participant. The reference outputs were mean values recorded by a second chronograph. The comparison was shown in the following Bland-Altman figure,

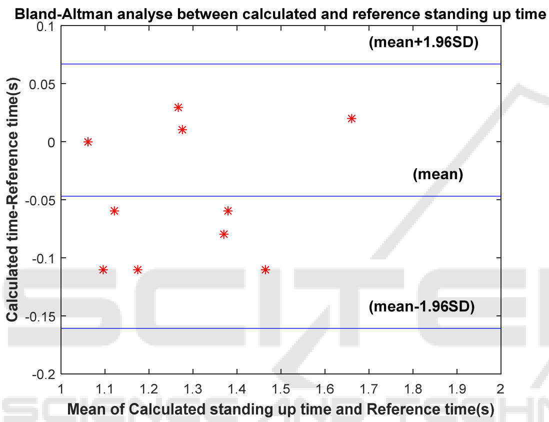

Figure 5: Bland-Altman figure of the standing up time.

The up and down time obtained by the two methods mentioned above showed a good consistency. However, the up and down time was not an absolutely objective value, the standard of border of up and down periods was without an authoritative standard. Moreover, there might be errors during recording process.

3.2 Performance of Turn Back Function

During the 10 groups of up and down tests introduced above, the turn back process was also filmed. The videos were replayed and the turn back time was recorded as reference. The comparison was shown in the following Bland-Altman figure, which demonstrated the consistency is good.

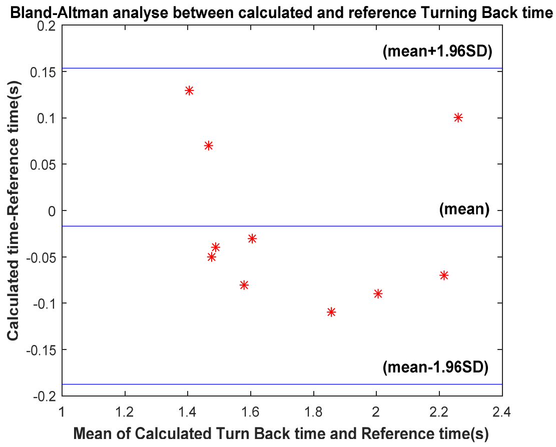

Figure 6: Bland-Altman figure of the Turning back time.

3.3 Performance of Walking Function

According to walking function, the outputs were based on the step length factor. A contrast test was designed to figure out the difference between the proposed method and gold standard. A Vicon device with the pressure trail was used to obtain relatively precise reference stride length values as gold standard. 10 Participants were asked to do the 10MWT test and the accurate rate was defined as the absolute value of 1- calculated values/recorded values. The comparison was shown as below:

Table 1: The comparison between calculated and recorded values of stride length.

Left / Right Leg	Mean Value of Stride Length (m)		Accurate Rate
	Calculated	Recorded	
1	1.55/1.86	1.5/1.73	89.6%
2	1.59/1.66	1.5/1.57	91.4%
3	1.51/1.41	1.53/1.53	95.4%
4	1.82/1.71	1.55/1.41	83.8%
5	1.04/1.65	1.00/1.48	92.9%
6	1.22/1.42	1.26/1.32	94.9%
7	1.16/1.48	1.25/1.35	92.0%
8	0.78/1.53	0.92/1.38	87.5%
9	1.43/1.29	1.29/1.32	94.0%
10	1.16/1.33	1.20/1.20	93.5%

The results showed the mean accuracy rate is around 91.5% and thus the error rate is around 8.5%. It is interesting to make a comparison with the result reported in (Benoît et al., 2015), obtained on a similar database collected from inertial sensors during walking process. On one hand, the error rate was around 5.5%, which got better results than the promoted algorithm. On the other hand, the promoted algorithm did not have a strict sensors wearing requirement.

4 CONCLUSIONS

This paper represented a system which could assess the body condition of normal people as well as Parkinson's and Stroke's patients based on the data collected from IMU placed on two ankles and the center of waist. New motion periods division method and data fusion method were discussed. The validation was conducted by comparing the calculated values with the reference values which were collected from camera videos and Vicon device. The results showed that the three functions processed the motion signal and calculated the output values precisely. At present, the system was tested by normal people, however, in the near future, the system can be applied to patients and help them recover from diseases.

REFERENCES

Hanson M, Powell H, Barth A, et al., 2009, Body area sensor networks: Challenges and opportunities, IEEE Computer, 42(1):58－65.

Mov Disord, 2003, Movement disorder society task force on rating scales for Parkinson's disease, The unified parkinson's disease rating scale (UPDRS): status and recommendations, 18:738.

Sebastian Madgwick, 2010, An efficient orientation filter for inertial and inertial/magnetic sensor arrays (internal report on his thesis and MARG).

Marilyn K. Hart, Ph.D. & Robert F. Hart, Ph.D, 2007, Statistical process control Techniques, Statit Software, Inc., 1128 NE 2nd Street, Corvallis, Oregon 97330.

Koichi S, Hikaru I, Yut Aka S, Non-restricted measurement of walking distance, Proceedings of 2000 IEEE International Conference on System, man, and Cybernetics. Nashville: IEEE, 2000: 1847-1852.

Reza Olfati-Saber, 2009, Kalman-Consensus Filter: Optimality, stability, and performance. Proceedings of the 48h IEEE Conference on Decision and Control (CDC) held jointly with 2009 28th Chinese Control Conference.

James Diebel, 2006, Representing Attitude: Euler Angles, Unit Quaternions, and Rotation Vectors, Stanford University, Stanford, California 94301–9010.

Benoît S, Mourad B, Jennifer D, Roger P-G, Christian G, et al., Implementation and Validation of a Stride Length Estimation Algorithm, Using a Single Basic Inertial Sensor on Healthy Subjects and Patients Suffering from Parkinson's Disease, Electronic Healthcare, 2015, 704-714.