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SCIENTIFIC PAPER

Development of wearable posture monitoring system for dynamic assessment of sitting posture

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Abstract

There have been increasing cases of people seeking treatment for neck and back pain. The most common cause of neck and back pain is due to long-term poor sitting posture. The most common poor sitting posture cases are humpback, and head and neck being too far forward. It is easy to cause neck and back pain and other symptoms. Therefore, the development of wearable posture monitoring system for dynamic assessment of sitting posture becomes both helpful and necessary. In addition to recording the wearer's posture when sitting with quantitative assessment, it is needed to execute real-time action feedback for correctness of posture, in order to reduce neck and back pain due to long-term poor sitting posture. This study completed an instant recording and dynamic assessment of position measurement and feedback system. The system consists of a number of dynamic measurement units that can describe the posture trajectory, which integrates three-axis gyro meter, three-axis accelerometer, and magnetometer in order to measure the dynamic tracking. In the reliability analysis experiment, angle measurement error is less than 2%. The correlation coefficient between correlation analysis and Motion Analysis (MA) is 0.97. It is shown that the motion trajectory of this system is highly correlated with MA. In the feasibility test of sitting position detection, it is possible to detect the sitting position from the basic action of the walking, standing, sitting and lying down, and the sensitivity reaches 95.84%. In the assessment of the sitting position, the information published by the Canadian Centre for Occupational Health and Safety was used, as well as the recommendations of professional physicians as a basis for evaluating the threshold of the sitting measurement parameters and immediately feedback to the subjects. The system developed in this study can be helpful to reduce neck and back pain due to long-term poor sitting posture.

Keywords Wearable · Dynamic measured unit · Feedback system

Introduction

In recent years, there have been increasing cases of people seeking treatment for neck and back pain. The most common cause of neck and back pain is due to long-term poor sitting posture. The amounts of time people sit in a day account for a large proportion of the day. Sedentary lifestyle is one of the important causes of skeletal muscle system diseases, and the risk of sedentary lifestyle is not fully understood compared to the risk of heavy labor activity [1]. Poor posture and sedentary lifestyle will increase the risk of lower back pain, arthritis, thrombosis, lumbar disc herniation, spinal deformity, cervical spur, body hypoxia, prostate problems and rectal cancer [2, 3]. Although the medical profession is not fully aware of the specific relationship between sedentary lifestyle and skeletal muscle system diseases, many studies have revealed the relationship between sedentary lifestyle and diabetic mortality [4]. The American Association for Cancer Research (AACR) surveyed 120,000 people live in 14 years. It was believed that sitting for 6 or more hours per day may increase the risk of death [5]. The angle between the thighs and the torso of the average person is almost 90° when sitting. This posture will cause the pelvis to tilt backward, and the pelvis will tilt forward when standing [6–8]. The pelvis, which is tilted back 30°, almost makes the bottom of the sacrum curved to a position parallel to the ground, which will make people unconsciously bend

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over [9–13]. Blood circulation is an important part of the oxygen and nutrients needed to transmit to the body. A sedentary lifestyle is a type of lifestyle with little or no physical activity, which will cause abnormal frequency of heartbeat, blood circulation and other symptoms [14]. The lymphatic system is part of the circulatory system and a vitally important part of the immune system [15]. Since the lymphatic system does not have a heart to pump it, it relies on muscle activity to promote the circulation of lymph nodes [16]. The main function of the lymphatic system is to remove waste products from tissues via the infiltration and circulation of the tissue fluid [17]. For example, our legs will be swollen after a long flight or train, because the body is in a relatively quiescent and sedentary state, and the posture is not correct, resulting in lymphatic obstruction, which leads to tissue fluid accumulation in the lower limbs, causing edema [18]. Slouching can reduce the chest and abdomen space, affect the function of the respiratory and digestive systems [19] and lead to an unbalanced body. Long-term slouching will make the cervical spine uneven, oppressing the stretching of the neck muscle. This posture develops habits, which will make the body exert excessive force, causing muscle tension and pain. The body may not be able to restore the natural posture, especially for children during their physical development period [20–22]. Quantitative life uses the input, state and performance parameters to express personal daily life [23]. The input refers to the external factors of body's absorption, such as digested food, air quality etc.; the state is a current characteristic, such as mood, skin conductance, oxygen saturation, etc. [24]; the performance is the behavior of the human body, divided into psychological and physical behavior. In this paper, the posture is quantified into walking, standing, sitting and lying. International research on walking, standing, sitting and lying are integrated into this study, including the distinction of action, the rehabilitation of posture, the assessment and feedback of actions, the types of sensors and the method of measurement, as shown in Table 1.

In the study of walking and standing, mainly for gait analysis, including pace, step frequency and bending angle. Through these parameters, it is possible to assess the subject's center of gravity, habits, rehabilitation. In the study of sitting, mainly for the assessment of poor posture caused by muscle soreness, the assessment can be accomplished by measuring the angle of the spine or the center of gravity and the posture of sitting can be corrected. In the study of lying, there are only few studies of the project, and mainly as a distinction between physical activities. Via these studies (Table 1), few researches were found that focused on walking, standing, sitting and lying at the same time.

Therefore, it is necessary to develop a wearable posture monitoring system for dynamic assessment of sitting posture. The system consists of a number of dynamic measurement units (DMU) that can describe the posture trajectory, which integrates three-axis gyro meter, three-axis accelerometer, and magnetometer in order to measure the dynamic track. The system can describe and distinguish between walking, standing, sitting and lying. These represent the basic activities of the body. In this study, the system to assessment of sitting posture was applied as the beginning of the system.

According to Table 1, the sensors used in the currently marketed products or published research are mainly divided into an inertial sensor, an accelerometer, an optical motion system, a gyroscope, a pressure sensor and an Electromyography sensor (EMG). The differences between our systems and listed products or published research are as follows:

i. Our system is a wearable system, not limited to the space of the venue, optical motion system and pressure sensor obviously do not apply.
ii. This study needs to use the three-axis rotation angle to record the motion track of the measured point. accelerometer, gyroscope and EMG obviously do not apply.
iii. The difference with the optical motion system is that our system is low in cost and short in calibration time.
iv. Our system uses inertial sensor, the listed products or the published research is mainly divided into timed up and go, respiratory effort monitoring system, sleeping position recognition system, recognition posture (lying, standing, sitting and walking). What sets us apart is the combination of recognizing four postures (lying, standing, sitting and walking) and assessing sitting posture.

Materials and methods

The purpose of this study is to develop a wearable posture monitoring system for dynamic assessment of sitting posture. The system consists of a number of DMUs (Fig. 1) that were developed by the authors. The DMU can describe the posture trajectory, which integrates three-axis gyro meter, three-axis accelerometer, and magnetometer in order to measure the dynamic track. The system needs to verify reliability and feasibility. To assure reliability, the DMU and the commercial Motion Analysis (MA) were used to measure the object's single-point motion track, and then correlation analysis of DMU and MA to determine whether there is a high degree of correlation. In the feasibility test of sitting position detection, the sitting position can be differentiated from the basic action of the walking, standing, sitting and lying, the feasibility of this system for physical activity measurement and long-term recording can be verified.

Table 1 Types of posture research methods

Time	References	Method	Classified				Remark
			Walking	Standing	Sitting	Lying	
1968	N. Azrin et al. [28]	Force sensor			V		Correctness of posture
1973	J. Morris et al. [54]	Accelerometer	V	V			Gait analysis
1974	B. J. G. Andersson et al. [25, 26]	Pressure sensor			V		Lumbar disc pressure
1985	J. Nilsson et al. [65]	Pressure sensor	V				Gait analysis
1990	A. Willemsen et al. [44]	Accelerometer	V	V			Joint angle and stride
1991	A. Willemsen et al. [47]	Accelerometer	V	V			Joint angle
1993	D. H. Watson et al. [27]	Inertial sensor			V		Relationship between head forward angle and headache
1996	G. Wu et al. [49]	Inertial sensor	V	V			Gait analysis
1996	R. Dai et al. [62]	Accelerometer	V				Gait analysis
1999	K. Tong et al. [59]	Gyroscope	V	V			Joint angle and stride
1999	K. Aminian et al. [39]	Accelerometer	V	V	V	V	Distinguish between different posture: walking, standing, sitting and lying
2000	R. Williamson et al. [50]	Inertial sensor	V				Joint angle and stride
2000	R. Williamson et al. [53]	Accelerometer, gyroscope	V	V			Joint angle and stride
2001	S. Okada et al. [30]	EMG		V		V	Rehabilitation system
2001	I. P. Pappas et al. [60]	Gyroscope, pressure sensor	V				Gait analysis
2001	M. Skelly et al. [64]	Pressure sensor	V				Gait analysis
2001	M. S. Wong et al. [29]	Orthotics			V		Prevention of scoliosis
2002	R. Mayagoitia et al. [34]	Accelerometer, gyroscope	V				Gait analysis
2002	K. Aminian et al. [57]	Gyroscope	V				Gait analysis
2002	T. Sakaki et al. [31]	EMG	V	V			Gait rehabilitation system
2002	R. Mayagoitia et al. [34]	Accelerometer, gyroscope	V				Gait analysis
2003	A. Mansfield et al. [42]	Accelerometer	V				Gait analysis
2003	P. Veltink et al. [61]	Accelerometer, gyroscope	V				Gait analysis
2003	M. Mathie et al. [40]	Accelerometer	V	V	V	V	Identification and classification of gait, sitting, standing, swing and fall
2004	I. Pappas et al. [66]	Gyroscope, pressure sensor	V				Gait analysis
2005	Y. Shimada et al. [46]	Accelerometer	V				Gait analysis
2005	A. Sabatini et al. [48]	Accelerometer, gyroscope	V				Gait analysis
2005	S. Lee et al. [51]	Inertial sensor	V	V			Joint angle and stride
2005	B. Coley et al. [56]	Gyroscope	V				Gait analysis
2005	D. Weber et al. [63]	Accelerometer	V				Gait analysis
2005	R. Riener et al. [32, 33]	Inertial sensor	V	V			Gait rehabilitation system
2006	J. Jasiewicz et al. [58]	Accelerometer, gyroscope	V				Gait analysis
2006	P. Grant et al. [41]	Accelerometer	V	V	V	V	Distinguish between different posture: walking, standing, sitting and lying
2007	K. O'Donovan et al. [55]	Inertial sensor	V	V			Joint angle
2007	D. Roetenberg et al. [35]	Inertial sensor	V	V			Joint angle and stride
2008	M. Duric et al. [45]	Accelerometer	V	V			Joint angle
2008	M. Duric et al. [52]	Accelerometer, gyroscope	V				Gait analysis
2008	Wai Yin Wonga et al. [70]	Accelerometer			V		Curvature of the spine
2009	K. Liu et al. [43]	Accelerometer	V	V			Joint angle and stride
2010	J. Rueterbories et al. [37]	Inertial sensor	V	V			Gait analysis
2011	T. Watanabe et al. [38]	Accelerometer, gyroscope	V	V			Joint angle
2012	Q. Li et al. [36]	Inertial sensor	V	V			Gait analysis

Table 1 (continued)

Time	References	Method	Classified				Remark
			Walking	Standing	Sitting	Lying	
2013	K. O'Sullivan et al. [72]	Photographs			V		Curvature of the spine
2014	F. Araújo et al. [71]	Sagittal X-rays		V			Curvature of the spine
2016	R. Zemp et al. [68]	Pressure sensor			V		Pressure distribution of seat and backrest
2016	K. Claeys et al. [69]	Optical motion capture systems		V	V		The angle of sensors
2016	A. Claus et al. [67]	Optical tracking system		V	V		Curvature of the spine
2017	H. Nguyen et al. [73]	Inertial sensor	V	V	V		Detection and segmentation of daily living activities during a Timed Up and Go task in people with Parkinson's disease
2017	C. H. Lee et al. [74]	Inertial sensor	V	V	V		Reliability of forward head posture evaluation while sitting, standing, walking and running
2017	J. E. Hernandez et al. [75]	Inertial sensor				V	Respiratory effort monitoring system
2018	O. S. Eyobu et al. [76]	Inertial sensor				V	A real-time sleeping position recognition system
2018	S. Hellmers et al. [77]	Inertial sensor	V	V	V		TUG test analysis
2019	U. Martinez-Hernandez et al. [78]	Inertial sensor		V	V		Identification of sit-to-stand and stand-to-sit

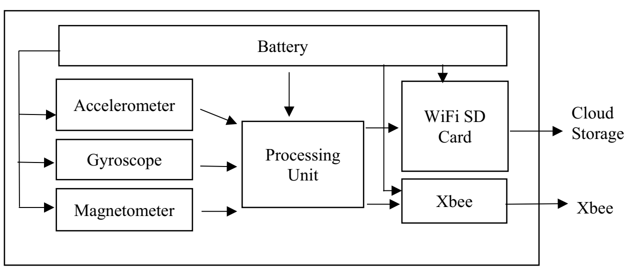

Fig. 1 The internal structure of the dynamic measurement unit. The accelerometer output signal is three-axis acceleration; the gyroscope output signal is three-axis angular velocity; the magnetometer output signal is three-axis magnetic field strength; the processing unit's output three-axis rotation angle; Xbee is used for wireless transmission, the signal is transmitted to the receiving end (PC); the WiFi SD Card is used as the storage unit

Reliability analysis

The experimental flow chart is shown in Fig. 2. The steps are described below.

Experimental group calibration

The three axes of the stereoscopic space are usually called XYZ axes, here the X-axis is the longitudinal axis, the Y-axis is the lateral axis, and the Z-axis is the vertical axis. Roll is defined as the DMU rotation left or right along the longitudinal axis. Pitch is defined as the DMU tilts up or down along the lateral axis. Yaw is defined as the DMU going left or right along the vertical axis (Fig. 3). The output signal of The DMU is Roll, Pitch, Yaw. When performing an accuracy analysis, the DMU requires a three-axis tilt test, which uses the angle of the inclinometer and the angle measured by the DMU for error analysis. The error should be less than 5%, otherwise the DMU will need to be adjusted until the expected results are obtained.

Control group

MA is the preferred action capture system in the market. The system consists of an Eagle digital capture lens, power hub, Ethernet switch and Cortex software, which can be extremely accurate in capturing complex action. After setting up the MA system, it must be calibrated first. A long 500 mm-pole with light balls on both sides of the pole (Spot A, B) are used and the pole will be swung. The movement trajectory in 60 s of the two light balls are recorded, and the distance between the 2 points are calculated, averaged, and compared with the original length (500 mm). The calibration is completed when the error is less than 5%.

Single dynamic trajectory test

Step

i. Place the DMU and the MA on the test pole at the same time. Schematic diagram shown in Fig. 4.
ii. Perform a series of motion tests (90 s).

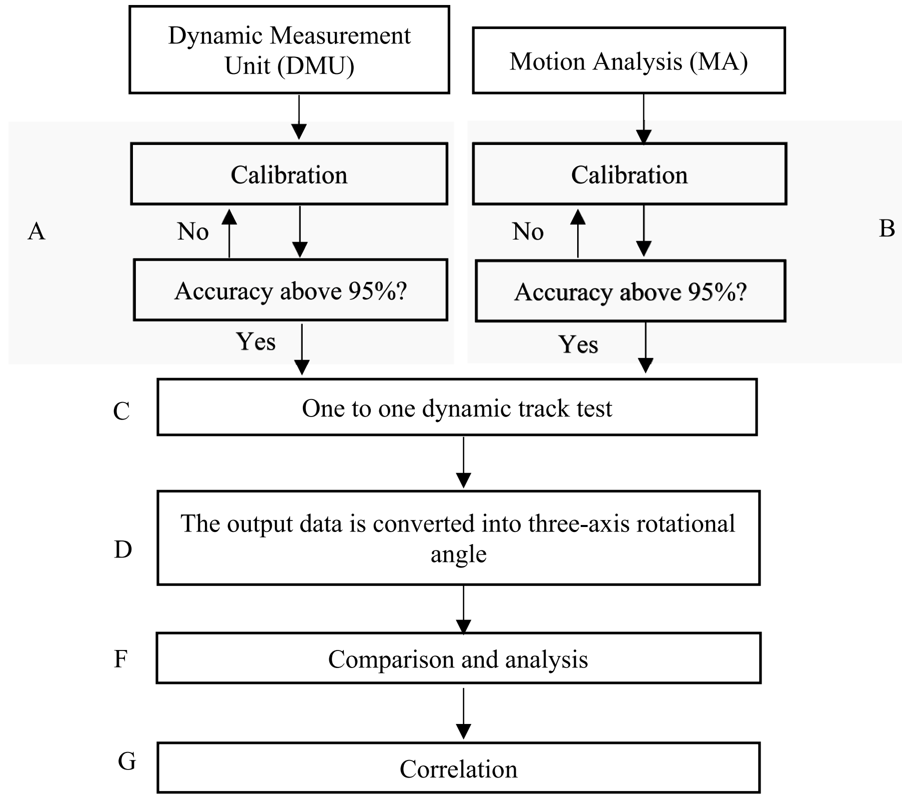

Fig. 2 The experimental flow chart of reliability analysis

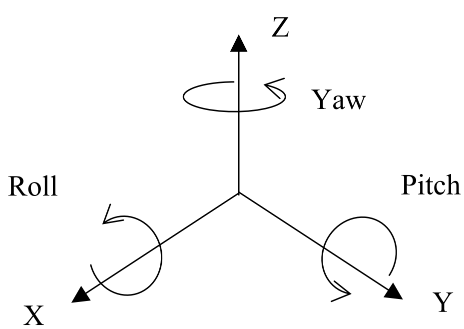

Fig. 3 Three angles on the coordinate axes

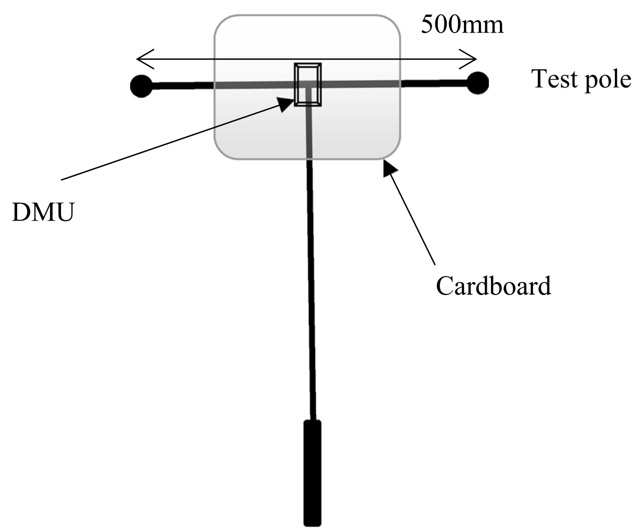

Fig. 4 The experimental schematic diagram of single dynamic trajectory test

iii. The output value of is converted.
iv. The correlation between total rotation angle of DMU and MA is calculated.

Comparison analysis

The comparison analysis uses the total rotation angle as the basis. The output value of the MA is the spatial coordinate of the three axes, and the output value of the DMU is the rotation angle of the three axes. Because each output value is to be compared with each other, they must be converted.

The first is the spatial coordinates of the MA to the rotation angle. Suppose one is given 2 points A and B on the test pole, the vector $\vec{AB}$ is $\left(B_X - A_X, B_Y - A_Y, B_Z - A_Z\right)$ at (t−1), the vector $\vec{A'B'}$ is $\left(B'_X - A'_X, B'_Y - A'_Y, B'_Z - A'_Z\right)$ at t. The schematic diagram shown in Fig. 5.

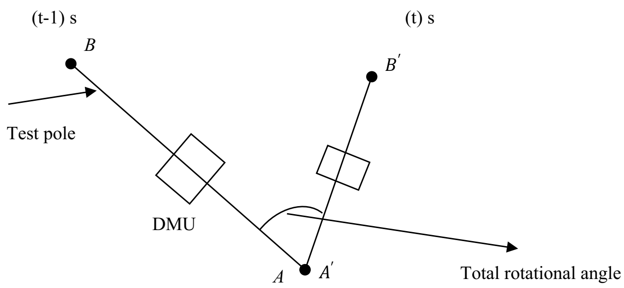

Fig. 5 The total rotation angle of the test pole

$$\text{MA}'\text{s total rotation angle } V_\theta = \cos^{-1}\left[\frac{\vec{AB}\cdot\vec{A'B'}}{\left\|\vec{AB}\right\|\cdot\left\|\vec{A'B'}\right\|}\right]. \quad (1)$$

The output value of the DMU is the rotation angle of the three axes (Roll, Pitch, Yaw), where the rotation angle at (t − 1) is $(A_{t-1}, B_{t-1}, C_{t-1})$, and the rotation angle at t is (A_t, B_t, C_t).

The total rotation angle of the DMU is $V_\emptyset$

$$= \left\|\left(A_t, B_t, C_t\right) - \left(A_{t-1}, B_{t-1}, C_{t-1}\right)\right\|. \quad (2)$$

Correlation

From Eqs. (1) and (2) we get $V_\theta \cdot V_\emptyset$. The correlation coefficient of A and B is obtained by Eq. (3). If the correlation coefficient is close to +1.0, then there is a strong positive linear relationship between MA and DMU.

$$\text{Correlation coefficient } r = \frac{\sum Z_x Z_y}{n} \quad (3)$$

Z_x and Z_y are the standardized z-values for MA and DMU. If correlation coefficient r is 1, the MA and DMU have a complete positive correlation. In other words, the data points from MA and DMU lie on a perfectly straight, positively-sloped line. If correlation coefficient r is − 1, MA and DMU have a complete negative correlation. In other words, the data points from MA and DMU lie on a perfectly straight, negatively-sloped line. If correlation coefficient r is 0, MA and DMU have no correlation.

Feasibility analysis of sitting posture

Selection of DMU position and judgment of action

In this experiment, two DMUs were placed in the subject's chest (nipple center, DMU C) and the lateral thigh (femoral center, DMU T) and the rotation angle (Roll, Pitch, Yaw) signal were analyzed to determine the current state of the subject (Fig. 6). When $Roll_c = -90° \pm 30°$ and $Roll_t = 0° \pm 30°$, the current state of action was determined as "Sitting". When $Roll_c = -90° \pm 30°$ and $Roll_t = -90° \pm 30°$, the current state of action was determined as "Standing". For lying, the subject has three types of lying positions, when $Roll_c = 0° \pm 30°$ and $Roll_t = 0° \pm 30°$, the current state of lying was determined as type 1 or type 3. When $Roll_c = (-150°$ to $-180°\cup)\cup(150°$ to $180°)$ and $Roll_t = (-150°$ to $-180°)\cup(150°$ to $180°)$, the current state of action was determined as type 2. No matter what kind of position, the current state of action was determined as "Lying". When $Roll_c = -90° \pm Roll_c(\text{t})$ and $Roll_t = -90° \pm Roll_t(\text{t})$, the current state of action was determined as "Walking". If the system cannot determine whether the current state of action is one of walking, standing, sitting or lying, the current state of action was determined as "Unidentified".

The subject participation

This experiment is mainly used to detect whether the system can recognize four basic physical activities (walking, standing, sitting, and lying) and assess sitting posture. Therefore, we choose a healthy male (age: 20–30 years old) as a system tester.

Measurement action and sampling frequency

The experiment took 20 min and the sampling rate of the DMU was set to 50 Hz. Four actions were taken, which are shown in Fig. 6, as a test, and each action was executed for about 300 s.

Signal filtering

In this study, the signal is a multi-to-one transmission, and multiple DMUs transmit the signal to the receiver. Noise was filtered using moving average. Moving average is a simple and smooth prediction method. Its basic idea is based on time series data, item by item, the average number of fixed sequence are calculated one by one. Moving average can smooth short-term fluctuations, which eliminates the noise caused by body shaking.

Data analysis and comparison

For DMU, the first task was to calibrate $Roll_c$ and $Roll_t$ Moving average was used to filter the noise, and the left and right ranks were set to five. The processed signals are defined as $Roll_{cf}$ and $Roll_{tf}$. We used 1 s as the basis for judging the interval of action state and calculated the median of each interval. The calculated value: $Roll_{cmed}$ is the median

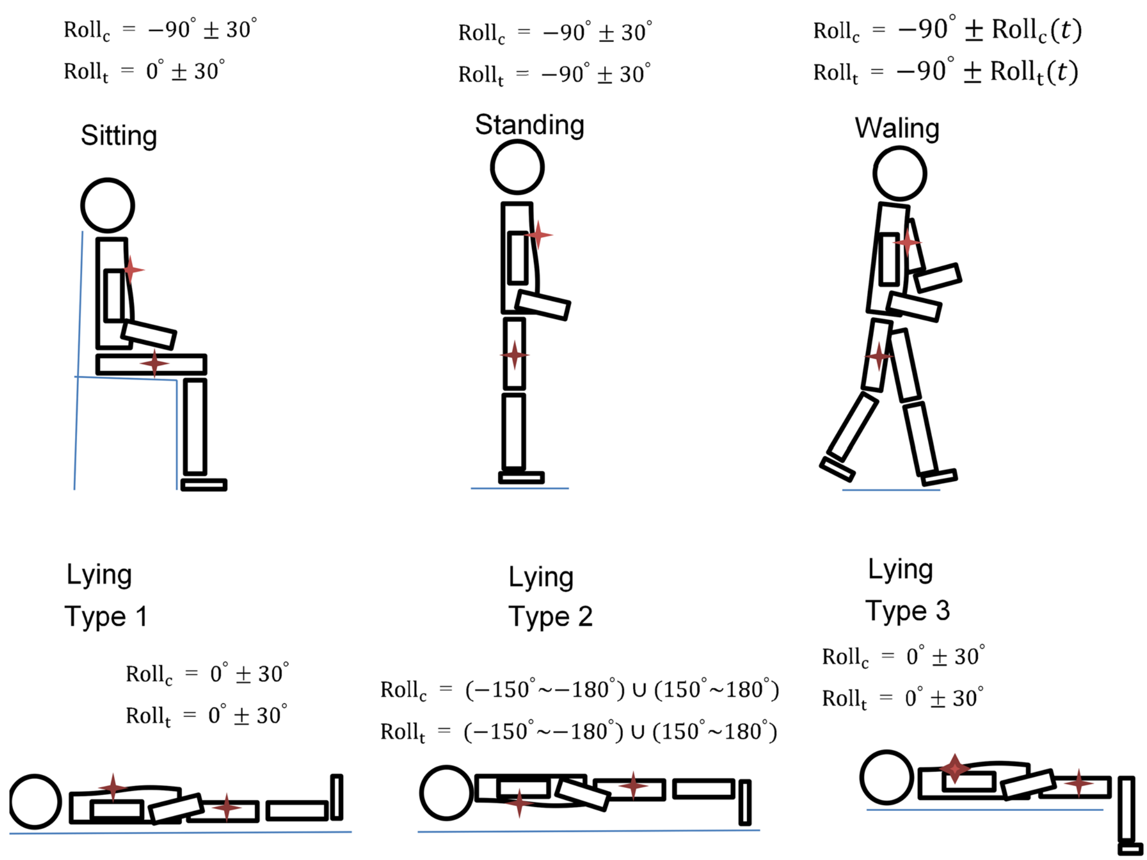

Fig. 6 The analysis diagram of judgment of posture

of $Roll_{cf}$ and $Roll_{tmed}$ is the median of $Roll_{tf}$. The judgment method is based in Sect. 2.2.1, to analyze the Roll_{cmed} and $Roll_{tmed}$, to distinguish between lying, sitting, standing, walking and unidentified (Fig. 7).

Sensitivity was used as the basis for the assessment of A value, which is the current measurement action (lying, sitting, standing, walking and unidentified).

$$Sensitivity\ S = \frac{Number\ of\ identical\ correct\ samples\ for\ A}{Total\ number\ of\ samples\ for\ A} \times 100\%. \quad (4)$$

Assessment of sitting posture

In the assessment of the sitting posture, we use the information published by the Canadian Centre for Occupational Health and Safety (CCOHS) organization and the recommendations of the professional physician as the basis for the study. After we have integrated, the proposed good "sitting posture" has the following:

i. To keep the joint angle: femur and back 90°–120°, Knee 90°–130°, Ankle 100°–120°.
ii. To keep the knee below the hip.
iii. The ankle is held in front of the knee.
iv. To keep the feet on the floor or foot pad.
v. Keep the upper body within 30° of the upright position.
vi. Do not be sedentary, it had better not to exceed 50 min.

We are based on the above 6 points as a basis, in accordance with the recommendations of professional physicians to assess the threshold of sitting parameters, and placement and number of DMU.

Results and discussion

Reliability analysis

Step A: DMU accuracy calibration

The inclinometer was used to do the calibration of the action. The calibration angle was selected in 0°, 45°, 90°, − 90°, − 45°. At each angle, five separate measurements were made. The error between the mean and the value of the inclinometer was within 2% (as shown in Table 2). This

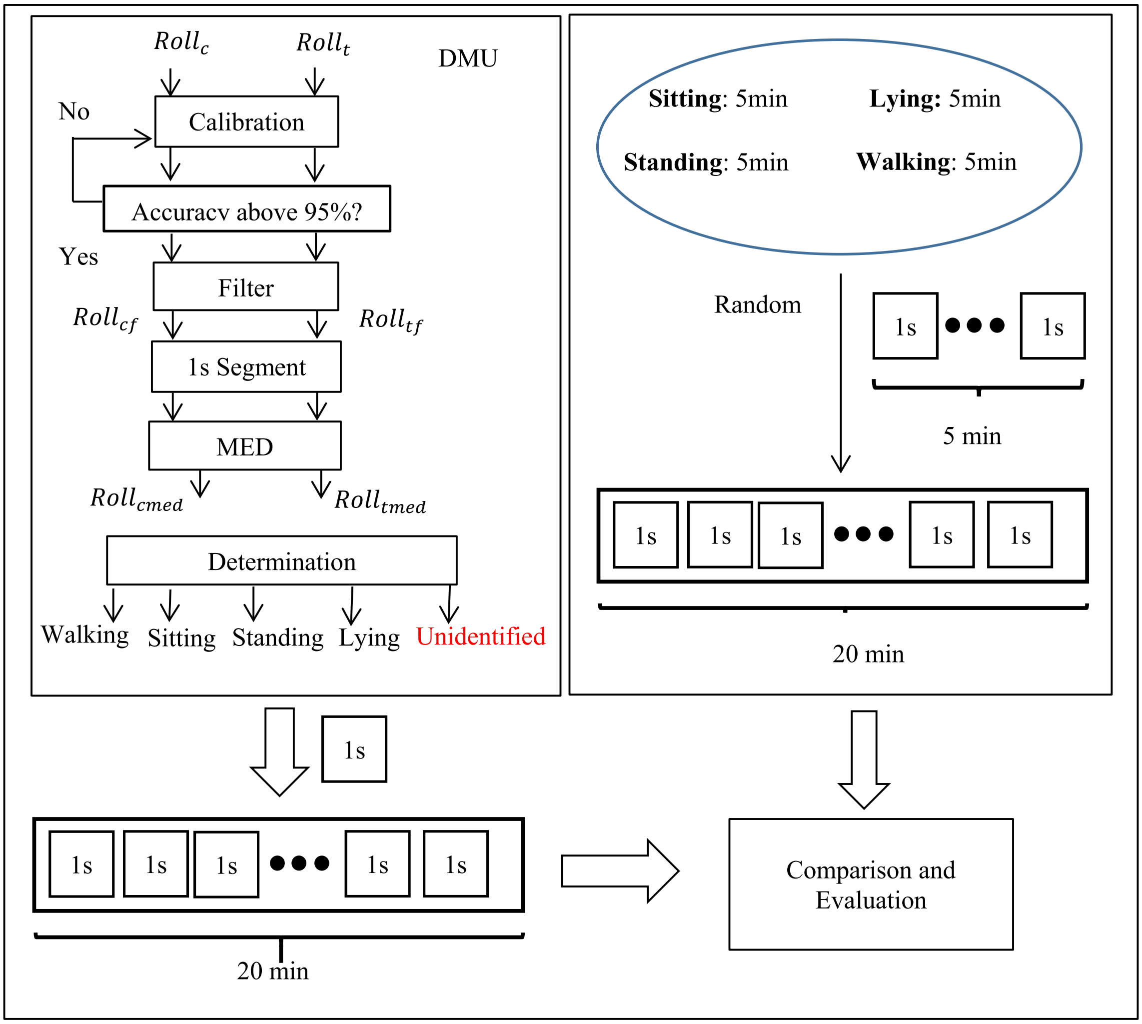

Fig. 7 The flow diagram of data analysis and comparison

shows that the accuracy of the DMU had reached more than 98%.

Step B: MA calibration

The test pole was used to calibrate, and the MA captured the distance between the two spots on the test pole. The error as compared to the actual length was calculated (500 mm) (Fig. 8). The error of 603 samples was within 1.5%. Table 3 shows some of the data results.

Step C

In step C, 15 experiments were done with 90 s for each experiment, where the sampling rate of the MA was 70 Hz and the sampling rate of the DMU was 50 Hz.

Steps D and E: comparison and relevance

V_θ and $V_\emptyset$ was a one-dimensional array, and the sampling rate of MA was 70 Hz, with each experiment was 90 s, so

Table 2 The calibration form of DMU

Inclinometer	0°	45°	90°	− 90°	− 45°	Error (%)
Roll	0.7	44.3	87	− 89.5	− 44	1.917
Pitch	− 1	45.8	91	− 89.3	− 45.2	1.028
Yaw	1.2	46	90.8	− 87	− 45.5	1.889

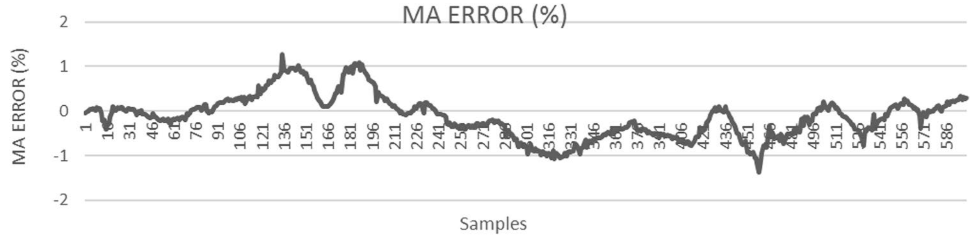

Fig. 8 The diagram of MA error rate detection, the horizontal axis is sample number and the vertical axis is the error rate

Table 3 The calibration form of MA

Front.head (spot A)			Rear.head (spot B)			Length (mm)
A_X (mm)	A_Y (mm)	A_Z (mm)	B_X (mm)	B_Y (mm)	B_Z (mm)	
630.460	− 305.17	1059.925	185.504	− 146.9	1223.45	499.776
627.081	− 306.937	1060.574	183.373	− 144.598	1223.702	499.841
623.991	− 308.811	1062.068	181.379	− 141.959	1224.171	500.023
591.671	− 310.071	1074.144	161.722	− 114.779	1237.802	499.779
231.292	746.798	1343.242	− 246.349	623.941	1386.663	495.096
966.691	− 109.504	1622.825	736.597	− 425.853	1309.021	501.491
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the V_{θ} array contained 6300 data. On the other hand, the sampling rate of DMU was 50 Hz, so the $V_{\emptyset}$ array contained 4500 data. In order to compare the data between the two, the V_{θ} array of MA was resampled to reduce the sampling rate to 50 Hz. Then low-pass filter was used to eliminate high-frequency noise and the cut-off frequency was set to 10 Hz. Lastly, moving average filter was used to smooth the data. Here, other objects or body touch usually causes the exception value to the DMU. The correlation between DMU and MA is shown in Table 4, and the average correlation is 0.97. Figure 9 is a comparison chart of the total average rotation angle of DMU and MA. The solid line represents the DMU and the dotted line represents the MA. The horizontal axis is the number of samples, with a total of 4500 data (90 s, 50 Hz). In the reliability experiment, the accuracy of the DMU in the angular measurement was verified. With the comparison of synchronization (Table 4 and Fig. 9), there is a high correlation between DMU and MA. It is shown that the DMU is synchronized with the MA on the trajectory of the measurement action. So multiple DMUs can be used to place a specific point on the body, to describe and construct the dynamic track of the body.

Table 4 The results analysis table of MDU and MA correlation analysis

Group	Correlation coefficient
1	0.984
2	0.945
3	0.953
4	0.969
5	0.991
6	0.989
7	0.984
8	0.899
9	0.958
10	0.978
11	0.953
12	0.986
13	0.971
14	0.978
15	0.965

Feasibility analysis of sitting posture

The system is designed to discriminate the sitting posture from other activities of daily life, such as walking, standing, sitting and lying. Tables 5, 6, 7 and 8 are the results of judgment of walking, standing, sitting and lying, Figs. 10, 11, 12 and 13 are the waveforms of lying, sitting, standing and walking, where the unit of the vertical axis is the angle in each figure.

For lying, $Roll_c$(Lying DMU C) $\subset 0° \pm 30°$ and $Roll_t$(Lying DMU T) $\subset 0° \pm 30°$ (Fig. 10). The action judgment of each interval is the same as the actual posture (Table 5), then the sensitivity of lying is calculated $S_{\text{lying}} = \frac{274}{274} \times 100\% = 100\%$.

In the part of sitting, most $Roll_c$(Sitting DMU C) $\subset -90° \pm 30°$ and $Roll_t$ (Sitting DMU T) $\subset -90^{\circ} \pm 30^{\circ}$(Fig. 11). From Table 6, it is clear that the result of the judgment of 28 1-s intervals is different from actual action. The rest of

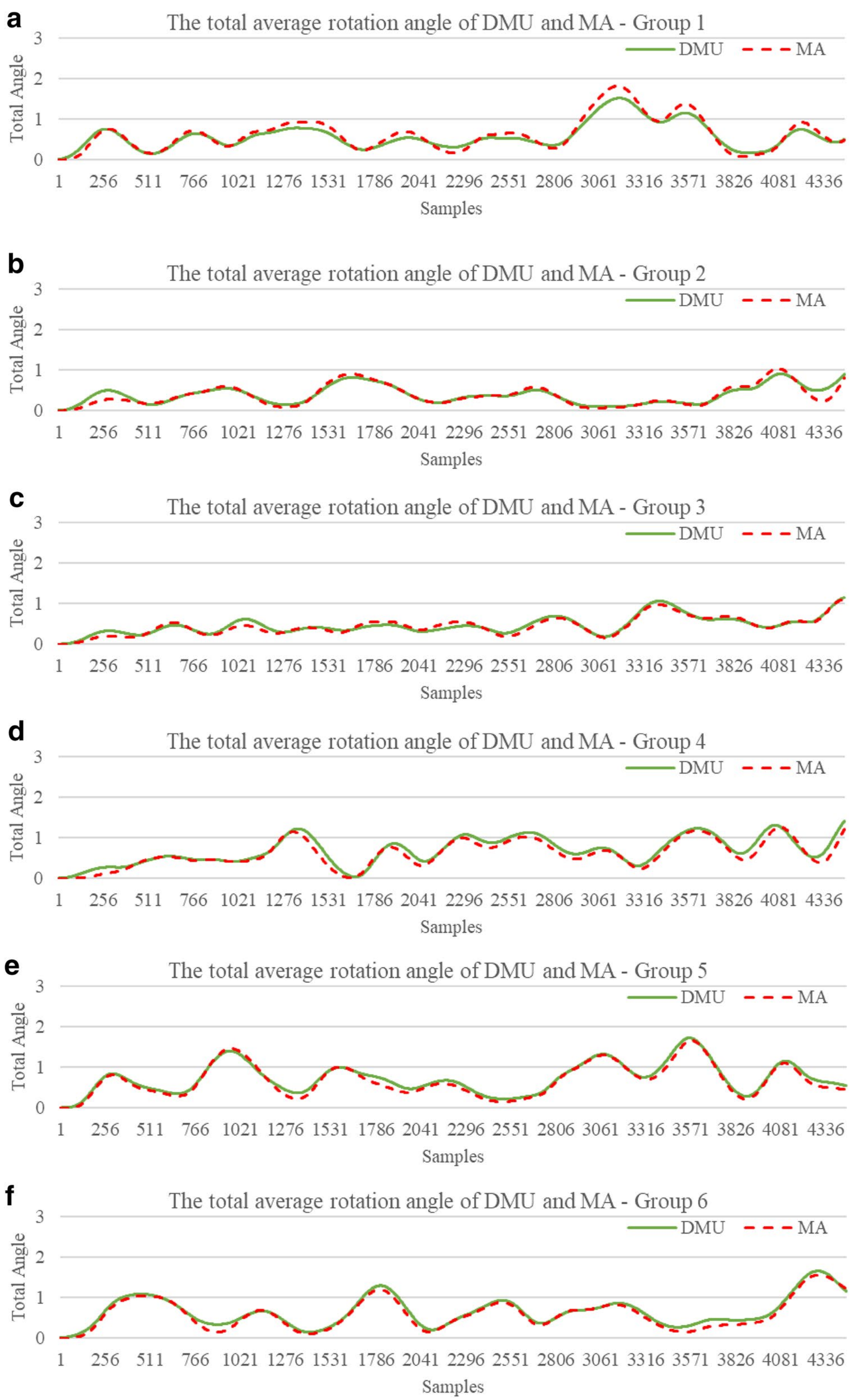

Fig. 9 The comparative analysis diagram of total average rotation angle of DMU and MA in Group 1 to Group 15, the horizontal axis is sample number and the vertical axis is the total average rotation angle in degrees

which, the posture judgment of each interval is the same as actual posture, then the sensitivity of sitting is calculated $S_{\text{sitting}} = \frac{274}{302} \times 100\% = 90.72\%$.

For standing, $Roll_c$(Standing DMU C) $\subset -90° \pm 30°$ and $Roll_t$(Standing DMU T) $\subset -90° \pm 30°$ (Fig. 11). The action judgment of each interval is the same as the actual

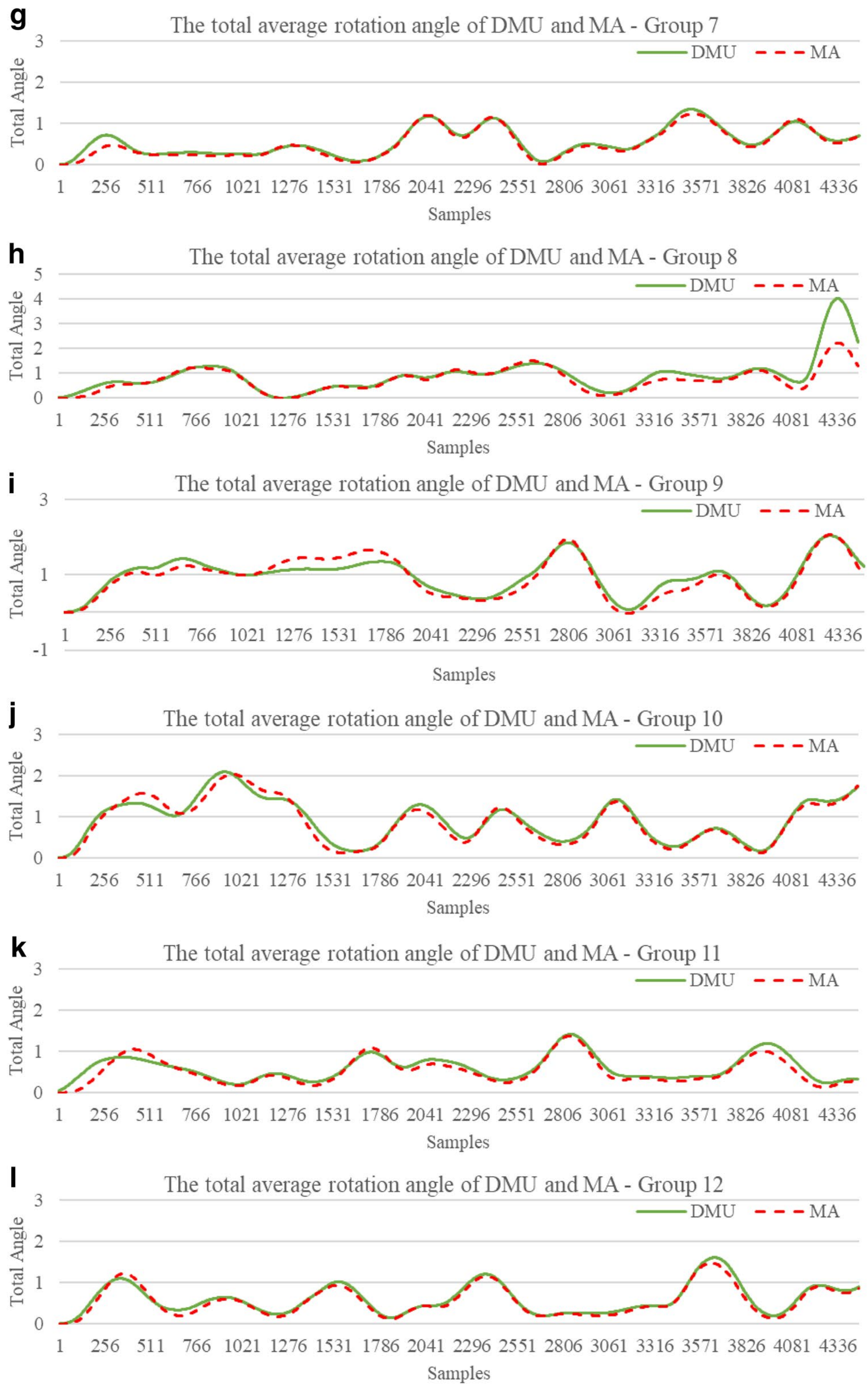

Fig. 9 (continued)

posture (Table 7), then the sensitivity of standing is calculated $S_{\text{standing}} = \frac{295}{295} \times 100\% = 100\%$.

In the part of walking, most $Roll_c$(Walking DMU C) $\subset\ -90° \pm Roll_c(t)$ and $Roll_t Roll_t$(Walking DMU T) $\subset\ -90°$ $Roll_t(t)$ (Fig. 13). From Table 8, it is clear that the result of the judgment of 19 1-s intervals is different from actual action. The rest of which, the posture judgment of each interval is the same as actual posture, then the sensitivity of walking is $S_{\text{walking}} = \frac{239}{258} \times 100\% = 92.64\%$.

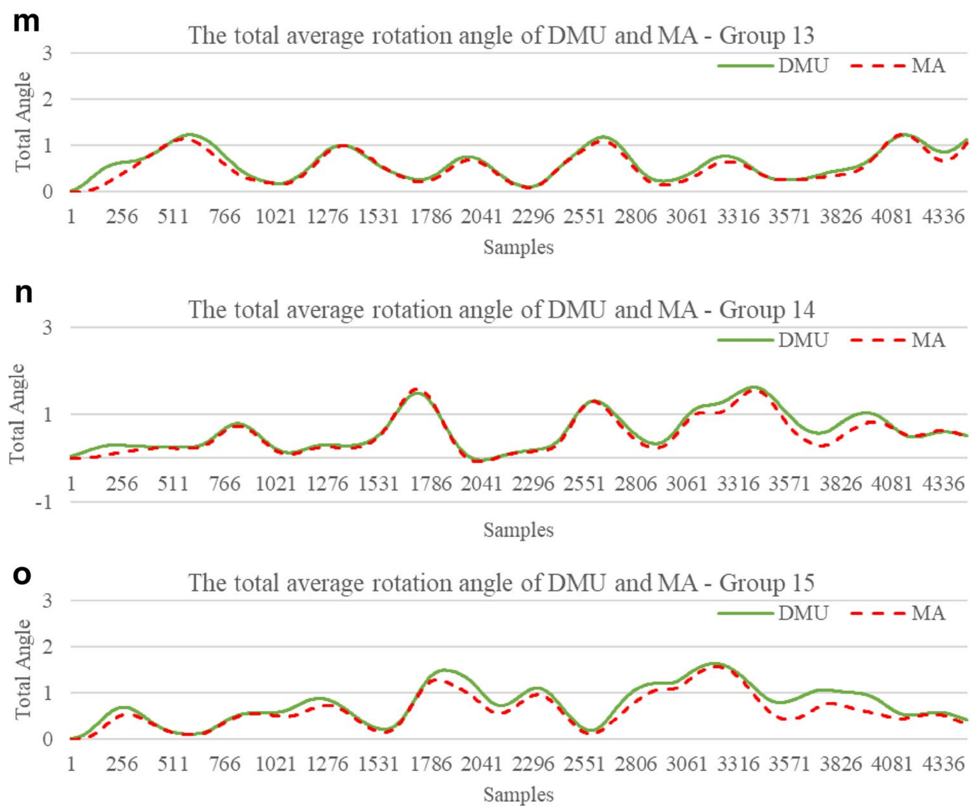

Fig. 9 (continued)

Table 5 The judgment results of lying posture

Interval	Lying DMU C (°)	Lying DMU T (°)	Judgment	Truth
1 s	2.05	−0.75	Lying	Lying
2–88 s	…	…	Lying	Lying
89 s	2.058	−0.86	Lying	Lying
90–180 s	…	…	Lying	Lying
181 s	2.922	2.002	Lying	Lying
182–272 s	…	…	Lying	Lying
273 s	0.9	−0.42	Lying	Lying
274 s	0.9	−0.43	Lying	Lying

Table 6 The judgment results of sitting posture. The "Unidentified" refers to the inability to judge whether the posture is one of the walking, standing, sitting or lying

Interval	Sitting DMU C (°)	Sitting DMU T (°)	Judgment	Truth
1 s	−106.591	−1.46	Sitting	Sitting
2–195 s	…	…	Sitting	Sitting
196 s	−119.799	−1.384	Sitting	Sitting
197 s	−120.285	−1.39	Unidentified	Sitting
198–223 s	…	…	Unidentified	Sitting
224 s	−122.581	0.066	Unidentified	Sitting
225 s	−116.936	−1.874	Sitting	Sitting
226–301 s	…	…	Sitting	Sitting
302 s	−87.622	−1.68	Sitting	Sitting

Table 7 The judgment results of standing posture

Interval	Standing DMU C (°)	Standing DMU T (°)	Judgment	Truth
1 s	−75.809	−88.08	Standing	Standing
2 s	−75.852	−88.373	Standing	Standing
3–99 s	…	…	Standing	Standing
100 s	−79.055	−84.206	Standing	Standing
101 s	−79.218	−83.701	Standing	Standing
102 s	−79.381	−85.324	Standing	Standing
103–294 s	…	…	Standing	Standing
295 s	−97.453	−75.312	Standing	Standing

The average sensitivity of all postures is $S_{average} = \frac{274+274+295+239}{274+302+295+258} \times 100\% = 95.84\%$. This shows that the system can differentiate the sitting posture from other activities of the daily life, such as walking, standing, sitting and lying.

Assessment of sitting posture

According to the information released by the CCOHS organization and the advice of professional physicians, we have developed a standard for assessing sitting posture. According

Table 8 The judgment results of walking posture. The "Unidentified" refers to the inability to judge whether the posture is one of the walking, standing, sitting or lying

Interval	Walking DMU C (°)	Walking DMU T (°)	Judgment	Truth
1 s	− 95.809	11.278	Unidentified	Walking
2–4 s	…	…	Unidentified	Walking
5 s	168.298	14.553	Unidentified	Walking
6–181 s	…	…	Walking	Walking
182 s	− 88.997	9.122	Unidentified	Walking
183–194 s	…	…	Unidentified	Walking
195 s	− 105.459	9.774	Unidentified	Walking
196–257 s	…	…	Walking	Walking
258 s	− 36.677	− 142.114	Walking	Walking

to the actual test of the system by the subject, we can evaluate the number and placement of sensors. It requires four DMUs, the placement points of which is the back (seventh thoracic, t7), thigh lateral (femoral center), calf lateral (tibia center) and head occipital bone. There are three rules of judgment for assessment of sitting posture, "to keep the joint angle", "to keep the upper body within 30° of the upright position" and "do not be sedentary exceeding 50 min". Each rule has its own threshold setting. When the threshold is exceeded, after the system has performed analysis, the program will give feedback to the subject.

The evaluation threshold and corresponding reminder feedback are as follows:

i. To keep the joint angle: femur and back (90°–120°), knee (90°–130°), ankle (100°–120°): The angle of the femur and the back can be measured by two DMUs (back and lateral thigh). The angle of the knee can be measured by two DMUs (thigh lateral and calf lateral). The angle of the ankle can be measured by the DMU placed on the calf lateral. When the angle is not within the threshold setting, the system will feedback the subject to correct the posture. The feedback part uses the horn sound to make a reminder. In this evaluation project, three short beeps will be issued when the evaluation angle is not within the threshold range.
ii. To keep the upper body within 30° of the upright position: It can be measured by two DMUs (back and head occipital bone). When the angle is not within the threshold setting, the system will feedback the subject to correct. The feedback part uses the horn sound to make a reminder. In this evaluation project, one long

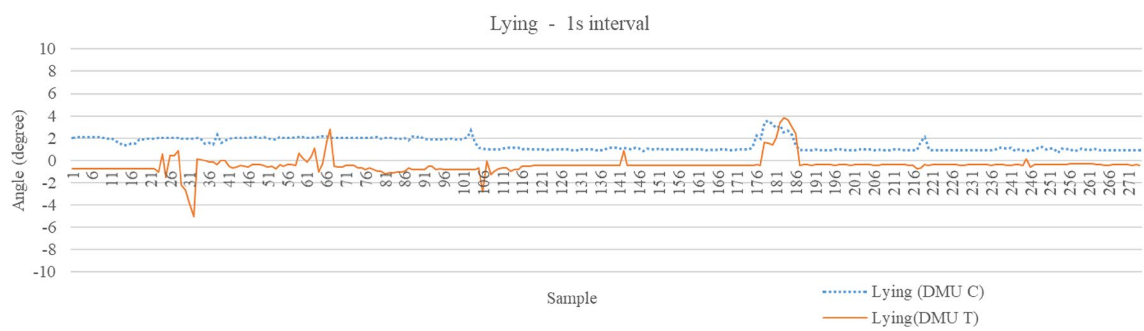

Fig. 10 The detection waveform of lying posture. The horizontal axis is sample number and the vertical axis is the values of $Roll_{cmed}$ and $Roll_{tmed}$ in degrees

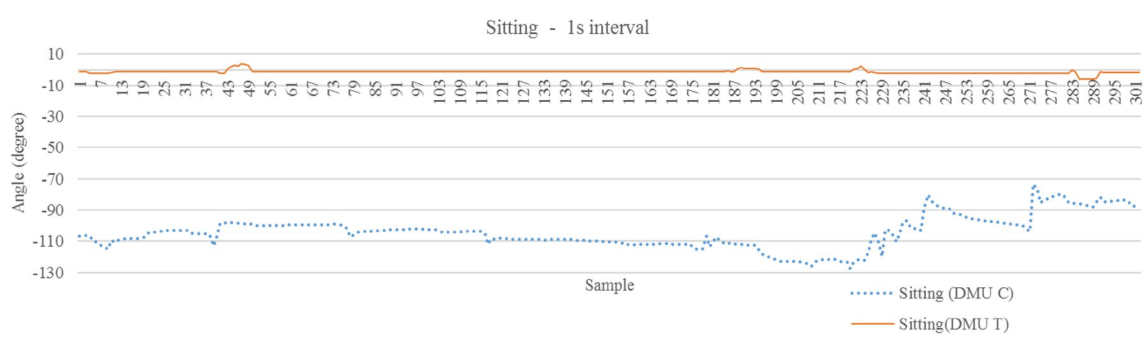

Fig. 11 The detection waveform of sitting posture. The horizontal axis is sample number and the vertical axis is the values of $Roll_{cmed}$ and $Roll_{tmed}$ in degrees

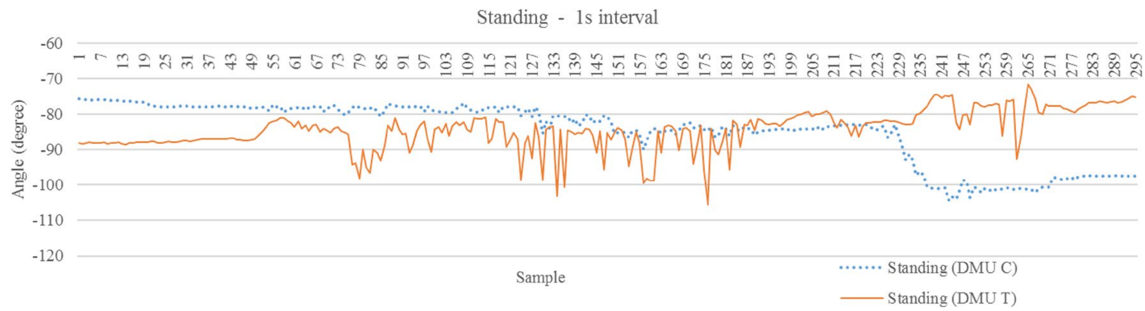

Fig. 12 The detection waveform of standing posture. The horizontal axis is sample number and the vertical axis is the values of $Roll_{cmed}$ and $Roll_{tmed}$ in degrees

Fig. 13 The detection waveform of walking posture. The horizontal axis is sample number and the vertical axis is the values of $Roll_{cmed}$ and $Roll_{tmed}$ in degrees

and two short beeps will be issued when the evaluation angle is not within the threshold range.

iii. Do not be sedentary, it had better not to exceed 50 min: If 50 min remain in the sitting posture, the system will immediately remind and advise the subject to move around. The feedback part uses the horn sound to make a reminder. In this evaluation project, three long beeps will be issued when the evaluation angle is not within the threshold range.

At present, the results of this part have completed the preliminary evaluation of the threshold setting of sitting posture and feedback reminder. However, people of different heights and weights may have different threshold settings. Therefore, it is necessary to measure more subjects in the future, analyze the differences between the subjects, and find the optimal threshold to improve the system.

Conclusions

At this stage of the research results, a real-time recording and dynamic assessment of position measurement and feedback system is completed. The system consists of a number of dynamic measurement units (DMU) that can describe the posture trajectory, which integrates three-axis gyro meter, three-axis accelerometer, and magnetometer in order to measure the dynamic track. In the reliability analysis experiment, angle measurement error is less than 2%, and the correlation coefficient between correlation analysis and MA is 0.97. It is proved that the motion trajectory of this system is highly correlated with MA. In the feasibility test of sitting position detection, the sitting position can be differentiated from the basic action of the walking, standing, sitting and lying, and the sensitivity is 95.84%. In the assessment of the sitting position, the information published by CCOHS and the recommendations of professional physicians was used as a basis to evaluate the threshold of the sitting measurement parameters to provide immediate feedback to the subjects, in order to reduce neck and back pain due to long-term poor sitting posture. For the future development, in order to allow the subjects to more easily understand the real information and interaction, human–machine interface (HMI) will need to be improved.

Future work

In the future, we have three main work items: the improvement of threshold setting, accuracy test for sitting posture feedback and human–machine interaction.

i. People of different heights and weights may have different threshold settings. Therefore, it is necessary to measure more subjects in the future, analyze the differences between the subjects, and find the optimal threshold to improve the system.
ii. After the improvement of the threshold setting, the accuracy test of sitting posture feedback is performed.
iii. At present, the human–machine interface of our system is mainly the beep of the speaker, although it is intuitive but lacks interest. For the current society, mobile phones are an indispensable 3C product for people. People are used to carrying them. Therefore, in order to make users more convenient and used to use the system, we will combine mobile phone software to enhance the human–machine interface.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. This article does not contain any studies with animals performed by any of the authors.

Informed consent Informed consent was obtained from all individual participants included in the study.

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