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The Influence of Treadmill on Postural Control

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ABSTRACT When people walk on a treadmill, significant differences exist in postural control if compared to walking on the ground. In this paper, a method combining linear and nonlinear analysis is proposed to evaluate the walking postural control ability. In this method, the movements of the upper body and the feet are analyzed separately, because these parts have more capacity to reflect the characteristics of people's gait. On this basis, the linear and nonlinear indicators of each part are analyzed, and the postural control ability is evaluated. The method is validated by three healthy subjects walking on both the treadmill and the ground. In treadmill walking case, the results show a smaller upper trunk acceleration (UTa) in the anterior-posterior (AP) direction. In the foot movement analysis, there are significant differences in the performance indexes related to the center of pressure (CoP) when people are walking on the treadmill and the ground. When walking on the treadmill, the velocity, acceleration, and jerk of the CoP in the AP direction are smaller than those in the ground walking case. Besides, when people walk on treadmills at uniform speeds, their feet accelerate is less in the vertical direction, and they have shorter stride length (SL) and longer stride time (ST). These results suggest that people have better postural control when walking on a treadmill. This method can be used as a means of assessing people's behavior when walking on various situations by evaluating their control posture ability.

INDEX TERMS Postural control, treadmill walking profile, upper trunk, foot analysis.

I. INTRODUCTION

The treadmill walking profile is very important in the research of gait analysis. In recent years, it has been widely used in the recovery of walking function of patients with gait disorders. Compared with the overground walking (OW), the treadmill walking (TW) has the advantages of small space requirement, easy observation of repetitive gait and controllable walking speed, which provides more opportunities for the research of gait [1]. However, a fixed speed treadmill usually cannot perfectly simulate a person's walking mode on the ground [2]. If the motion response of people on the treadmill is different from that on the ground, the transferability of recovery training from the treadmill to the ground will be affected. Also, there are differences in kinematics and space-time parameters between TW and OW profiles [3]. Among them, as an important indicator of walking stability, the differences of postural control ability between TW and OW deserve more attention. Postural control is the basis of an individual's ability to move and function independently [4]. Weak postural control ability will increase the risk of falling. Therefore, many researchers study the ability of postural control in gait analysis. If people have different postural control ability under TW condition and OW, which leads to the difference in postural control ability between these situations. When this is the case, the gait mode on the treadmill cannot be reproduced reliably on the ground walking process. Therefore, the walking training effect achieved on the treadmill is affected to a certain extent, when the ground walking is finally engaged. Moreover, OW shows greater variability in movement and less dynamic stability than TW [5], which introduces more challenges in transferring TW training to OW scenario.

The influence of the treadmill on people's postural control ability during walking is reflected in the changes of gait parameters and characteristics of the upper trunk caused by the treadmill. In the study of Liang Shi *et al.* [6], it is found that the treadmill can shorten the stride length (SL), increase the long-distance correlation of the stride intervals,

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and influence the gait rules in the swing stage. Also, the treadmill can increase the stability of the upper trunk. Similarly, it significantly reduces standing time and step-length during walking [7], [8]. Among the many gait parameters, the center of pressure (CoP) is a critical measure to access the ability of postural control [9]. The CoP is also considered as the most reliable output for postural balance control assessment [10]. Hsuan-Lun Lu *et al.* [11] studied the trajectories of the CoP and the center of mass (CoM) under the two conditions of OW and TW, and they also addressed the differences in people's balance control under such conditions. Among them, the root mean square (RMS) and moving velocity of CoP indicate the effectiveness of the postural control system and the effort to maintain the corresponding level of postural stability, respectively [12].

Furthermore, the speed of CoP and its higher derivatives also reflect postural control performance [13], [14]. In the foot analysis, SL, stride time (ST), variability in stride time and the acceleration of the foot in the vertical (V) direction during the swing phase can also reflect the walking stability [15].

The treadmill can make the gait pattern more stable, which is also reflected in the sample entropy (SE). John H Hollman *et al.* [16] found that healthy people had more stable gait patterns under TW than under OW. Among them, the difference between OW and TW in stride time and rhythm parameters is more significant, and the SE data of stride time in TW is lower, indicating that walking on a treadmill can hinder the variability of time and rhythm and that people's steps on the ground are more scattered than those on a treadmill. Other related studies have also shown that SE reflects the level of attentive and automated balance control. A lower entropy value indicates that postural control gets more attention, whereas higher entropy means the control is more like an automated process [17]–[19]. This allows us to analyze postural control by the SE, and to find the change of attention level of different parts of people walking in different environments from entropy. In addition to entropy, Lyapunov exponent (LyE) is another index of nonlinearity commonly used to quantify the stability of human movement [20]. The LyE represents the local dynamic stability during walking, and the larger exponent is, the worse the local dynamic stability is.

In the study of postural control, the movement of the upper trunk is also an important indicator. In some related studies, the activity analysis of the upper trunk has been widely used to measure the differences between the movement of patients and healthy people, including peak speed, swing angle, etc. [21], [22]. Regarding the influence of the upper trunk on postural control, Gimmon Yoav *et al.* reported that the transverse rotation of the upper trunk is an important indicator reflecting the ability of postural control [23]. Shawn M. O'Connor *et al.* [24] hold that the anterior-posterior (AP) stability during walking can be adjusted by controlling the anterior process of the spine.

The purpose of this study is to analyze the differences in people's postural control ability between TW and OW by using linear and nonlinear analysis methods on some gait parameters relevant to the postural control ability. This research provides a means for the evaluation of attitude control ability.

II. BACKGROUND

According to the related research, some appropriate gait parameters are determined to carry out the analysis of postural control ability.

A. UPPER TRUNK ANALYSIS

In the upper trunk analysis, Peter C. Fino *et al.* [25] found that in the case of mild neuropathy, fallers are significantly correlated with middle lateral (ML) sway frequency and jerk, by installing inertial sensors above the lumbar vertebrae of elderly women cancer survivors. Gimmon Yoav *et al.* [23] conducted micro-perturbation training on treadmill in the elderly and they found that the trained elderly increased the transverse rotation of the trunk by an average of 29% when walking on the treadmill. Michael H. Cole *et al.* [26] reported that PD patients with a history of falling have a larger trunk moement in the AP direction compared with PD patients without a history of falling and the normal elderly.

B. FOOT ANALYSIS

In the foot analysis, stride length and stride time directly reflect the state of walking, an important index in gait analysis, through the contraction of the thigh muscles during walking. The contraction then partly reflects the fatigue of the leg muscles during walking. In terms of SL, a larger length means more stretching of the muscles. A longer ST represents the lower frequency of muscle contraction during walking, and it also means a longer resting time. Shorter time tends to make walking more tiring. In this research, we adopt a uniform walking speed in both cases, which becomes an independent variable. At the same time, the fluctuation of gait cycles, also called gait variability, represents the flexibility and the adaptability under continually changing circumstances [27]. The coefficient variation (CV) of stride time reflects the overall distribution characteristics of the step time series and is quantified using mean and standard deviation [28]. Flora Ferreira *et al.* [29] also found that Vascular Parkinsonism patients with weaker posture control have higher variability in stride time compared to the control group. In the related research on SL, we find that the step size variability of healthy people is not significant under different conditions [30], so we do not need to calculate the coefficient of variation of stride length like stride time. Furthermore, the velocity of center of pressure and its higher derivatives also reflect postural control performance [13], [14]. Haylie L. Miller *et al.* [13] found, in their study on the moving velocity of center of pressure (CoPv) and the acceleration of center of pressure (CoPa), that children with autism and developmental disorders had poor attitude control abilities compared with typically developing children.

In terms of the jerk (derivative of acceleration), Alae Ammour *et al.* [31] and Martina Mancini *et al.* [32] found, in their study on handwriting in patients with Parkinson's disease, that compared with normal people, patients with worse handwriting control had higher wrist jerk values when writing. Joseph C. Grieco *et al.* [14] also observed the different paths of the CoP in children with the angelic syndrome and normal children by using pressure plates, and they found that the concerned children's jerk of center of pressure (CoPj) is higher than normal children. Lichen Zhang *et al.* [33] also demonstrated through the bricklaying experiment that skilled workers have the lowest jerk value, stable movement, and high motion control capacity. By contrast, third-year apprentices had the higher jerk values, indicating poor motion control. These studies show that higher jerk means a worse control ability. And it can be seen that as an indicator of control ability, it is often used in the research on the change of postural control ability caused by disease or fatigue. Similarly, the change of walking environment is also an important factor that changes the ability of postural control, so we can use jerk as a key feature to evaluate the control ability.

C. NONLINEAR ANALYSIS

The SE is a complexity measurement method of time series proposed by Richman [34], which reflects the complexity of time-series signals. The larger the SE is, the more complex the signals are and the lower the self-similarity is. In addition, the sample entropy also indicates the degree of attention. The smaller the entropy, the higher the degree of attention. And we also need to find out whether the reason for the difference in walking environment is caused by the change of attention to a certain feature.

The LyE describes the average exponential rate of convergence or divergence of initial values of the system after disturbance and was used to represent the local stability of the gait. A larger LyE means a faster divergence and a bigger dynamic instability.

III. RESEARCH METHOD

From the relevant research, it is noted that the acceleration of the upper trunk should be considered as one of the indicators for postural control. Meanwhile, for the foot analysis, the speed, acceleration, and jerk of CoP are relevant to people's ability to control posture while walking, and the higher jerk corresponds to the lower control ability. Similarly, the acceleration of one's foot in the V direction when walking can also be used to analyze postural control. For nonlinear analysis, the SE and the LyE can be used to analyze the differences in postural control.

This study will determine the differences in postural control ability between TW and OW by analyzing the upper trunk and foot. This includes the acceleration of the upper trunk (UTa), CoPv, CoPa, CoPj and Fa in the V direction, as well as the analysis of walking complexity and local dynamic stability in terms of the SE and the LyE by using the nonlinear analysis method.

To study postural control in different situations, we invited eight healthy subjects. Subjects are asked to walk on a treadmill and on the ground wearing inertial sensors and pressure detection insoles to collect the required gait data for analyzing.

A. SUBJECTS

In this study, to reduce the effects of unrelated factors, healthy participants are selected without walking disorders, neurological diseases or other diseases that affected walking. Each subject was informed of the experiment. Also, before the experimental data collection started, each subject was familiar with the process of data collection in advance, including how to walk, how long to walk and when to start or stop. Before the treadmill test, all subjects were trained on the treadmill (Yijian, Hangzhou, China) to ensure that each subject was adapted to the treadmill used in the experiment, so as not to cause sudden changes in the walking environment to interfere with the experiment. The information about the subjects is shown in the Table 1.

TABLE 1. Subjects Information

	age	weight	height	BMI
Subject 1	25	80	180	24.69
Subject 2	24	65	165	23.88
Subject 3	22	64	166	23.23
Subject 4	23	68	175	22.20
Subject 5	23	87	175	28.41
Subject 6	21	84	173	28.06
Subject 7	23	67	175	21.88
Subject 8	31	78	174	25.76

The weight's unit is kg. The height's unit is cm.

B. EXPERIMENTS

1) INSTRUMENTS

In this study, the acceleration of the upper trunk and the acceleration of the foot in the V direction is measured by wearable inertial measurement units (IMU). With wireless and wearable technology, these sensors are small, light and inexpensive, without the grueling setup times of traditional motion capture systems. Besides, it has the advantages of long battery life and freedom from space limitations [35], [36].

Each wearable inertial measurement unit adopts STM32F103C8T6 as the main controller and meets the processing speed requirements of data collection in this study. The inertial sensor uses a 9-axis sensor MPU-9250 to collect the acceleration, gravity acceleration and geomagnetic data of the subjects in three directions when they are moving. The ellipsoid fitting technique is then be used to correct the data towards higher accuracy, by eliminating the errors caused by temperature drift and other factors. In terms of wireless data communication of the inertia measurement unit, nRF24L01

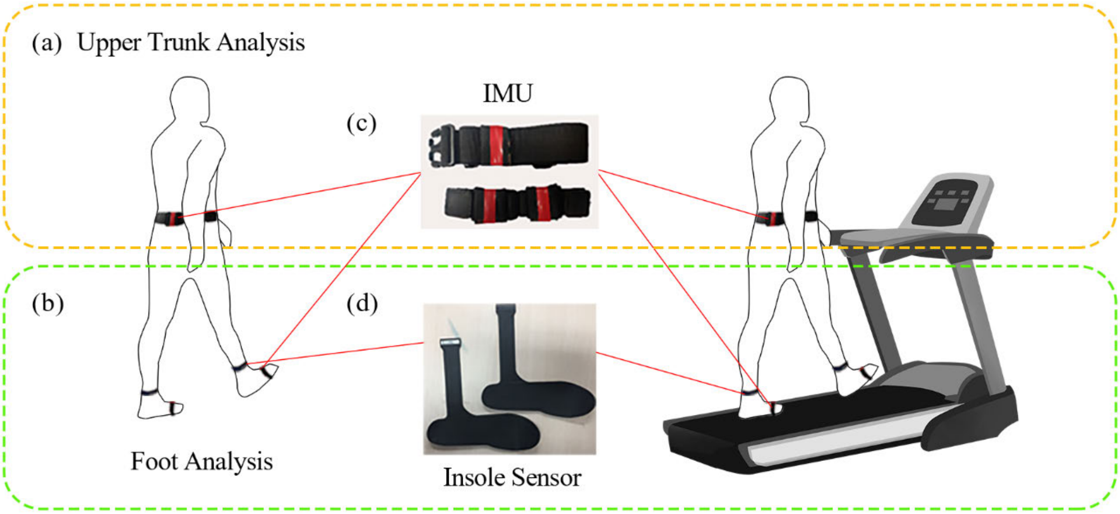

FIGURE 1. (a) Upper trunk analysis. An inertial detection unit is wearing on the back to measure the acceleration of the upper body while walking on the ground (left) and the treadmill (right). (b) Foot analysis. Wear an inertial measurement unit and an insole sensor on each foot to collect the foot's acceleration in the vertical direction and the pressure center during walking. (c) Inertial measurement unit (IMU), consisting of STM32F103C8T6, MPU-9250 and nRF24L01. (d) Insole sensor for the measurement of the center of pressure.

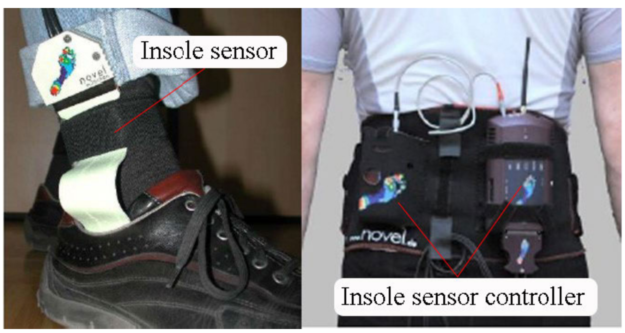

FIGURE 2. Insole sensor for in-shoe wear (left). Insole sensor controller and storage device (right).

is selected as the wireless data transmission module, which has a small size and lightweight. The selected solution meets the requirements of data acquisition speed without affecting walking. Three such units are worn on each subject's back, left foot and right foot. Data from three directions of each sensor are transmitted to the computer for subsequent analysis, at the rate of 200 samples per second in real-time when the subject walks.

The CoP data when subjects walk is measured by insole sensors (Pedar -X, Novel, Munich, Germany). The insole sensors are placed in the shoes of the subjects, in a proper position, to detect the right plantar pressure distribution. Compared with force-measuring plates or force-measuring tables, the use of the insole sensor enables the data collection without spatial limitation, and it can be applied to the CoP data collection during walking under various conditions, which meets the experimental requirements.

The insole sensor collects the distribution of plantar pressure at a frequency of 100Hz during the subject's walking, including the position of the plantar pressure center of the left foot and the right foot and the amount of pressures at each moment. The starting or stopping of data collection by the insole sensor will be controlled by the computer via Bluetooth transmission. The CoP data of subjects measured during walking will be stored in SD card. These data can be read by Pedar software (Novel, Munich, Germany), for subsequent analysis and calculation.

2) EXPERIMENT LAYOUT

After each subject has worn the device, the OW test is performed on a 420-meter straight lane without obstacles. Each subject must walk following a straight line and look ahead visually to eliminate the influence of other irrelevant factors. The OW test will obtain the acceleration of each subject's upper torso during walking, the acceleration, the position and pressure of the plantar pressure center of both feet. Besides, we will calculate the average walking speed of the subjects during the OW test, which will be used to set the speed of the treadmill during the TW test.

Each subject was trained to walk on the treadmill in advance to get used to the machine before the TW test. Each subject was required to walk on the treadmill for five minutes to complete the TW test, which was roughly the similar time the subjects walked during the OW test. In the TW test, the treadmill will run at a constant speed at the rate each subject made during the OW test. During TW walking, each subject shall not hold the handrail of the treadmill, look in front of the treadmill, and watch the treadmill screen to avoid interference from other factors.

After all the tests are completed, the collected data are stored in a computer and processed by Python to calculate various characteristic parameters needed for experimental analysis.

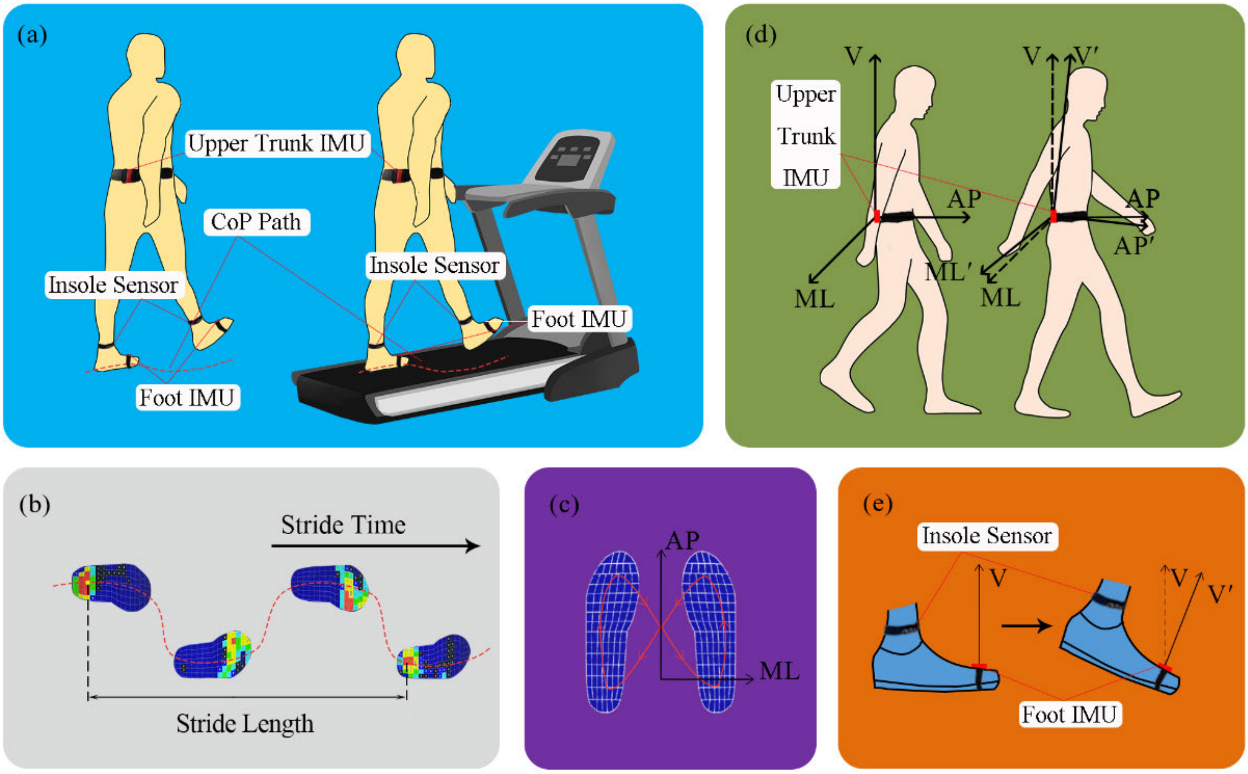

FIGURE 3. **(a) The path of the center of pressure when people travel under both conditions. (b) Schematic diagram of step length and stride time of each step during walking. (c) Change the curve of the center of pressure collected by the insole sensor. (d) A change in the position of the upper trunk, which can cause a change in acceleration, while walking. (e) The change in the vertical acceleration of feet as one walks.**

C. LINEAR FEATURES

1) STRIDE LENGTH(SL)

The SL is an important feature in the analysis of human gaits [37], [38]. From the SL during walking, we can see the stretching condition and activity range of leg muscles during walking, which is of great reference significance for this study. In this experiment, the SL is calculated as follows:

$$SL = \frac{L}{S_n} \tag{1}$$

where SL is the stride length; L is the distance traveled by subjects in OW or TW tests; S_n is the number of steps taken. Since the data measured by the insole sensor are the position and pressure magnitude of the CoP, and the timestamp of the samples, the appropriate pressure threshold is selected for filtering according to the interference value greater than 0N between the two zero pressures, as well as the obvious sudden large increase or decrease pressure value when falling and lifting. After comprehensive analysis, the pressure threshold of this experiment is 90N in OW and 25N in TW. The reason is that the sampling interval is very short compared with the walking process, so this method can also achieve good results. Therefore, we reserved the samples with CoP pressure greater than the threshold, while the points less than the threshold are considered as interferences or the foot did not touch the ground completely, which are set to zero.

Therefore, we take the point where the CoP pressure of one foot is greater than the threshold for the first time as the starting point of the step, and the point where the CoP pressure of the other foot is greater than the threshold for the first time as the endpoint of the step (and also as the starting point of the next step). The number of steps obtained by the above method is taken as the total number of steps in a test and used for further calculation.

2) STRIDE TIME(ST)

The ST reflects the rhythm of people's stride, and the longer ST means the people have longer muscle relaxation time in one-step walking. In the previous analysis, we learned that if people are more tired during walking, it will affect the control of posture, so the research on ST is particularly important [30]. According to the step starting and ending point obtained above, we can get the ST as follows:

$$ST = \left(T_{end} - T_{start}\right)/100 \tag{2}$$

where ST is the step time, T_{start} and T_{end} represent the time stamp at the beginning and the ending of each step, respectively. Since the insole sensor reads data at a frequency of 100Hz, one can divide the result by 100 to get the step time of each step.

3) ROOT MEAN SQUARE(RMS)

The RMS reflects the effectiveness of the postural control, with a lower value corresponding to higher effectiveness [12]. Meanwhile, the RMS is related to the force and the fatigue degree of the muscle contraction [39]–[41].

$$RMS = \sqrt{\frac{1}{N}\sum_{k=1}^{N} x_k} \tag{3}$$

where x is the sample to be calculated, and N is the number of samples.

4) COEFFICIENT OF VARIATION(CV)

The CV is calculated as follows:

$$CV = \frac{Std}{Mean} \times 100 \tag{4}$$

In this study, we calculate the CV of ST. Where, Std is the standard deviation of the ST in samples, and $Mean$ is the mean of the ST.

5) UPPER TRUNK ACCELERATION(UTA) AND FOOT ACCELERATION(FA)

The UTa and the Fa in V direction can be obtained by the inertia measuring unit. When the subject is walking, the acceleration, angular velocity and magnetic field data measured by the sensor are sampled at a rate of 200Hz. After the undersampling, the data of the accelerometer and the magnetometer are calibrated using the ellipsoid fitting based on the least square method [42]. All the resulting acceleration data will be filtered by a low pass Butterworth filter (4 order, 3Hz, zero-phase filtering). To eliminate the effect of walking speed, all accelerations are taken as their RMS [43].

6) CoP FEATURES

The CoP path obtained by the insole sensor is shown in the Figure 4. The paths of CoP are obtained from the insole sensors, so we use its derivatives with respect to time as the CoPv, CoPa, and CoPj.

Since the collected COP path coordinate points are discrete, but the sampling time interval is relatively short, it is feasible to use the difference to approximate the derivative, to obtain the instantaneous values, and then take the average value to obtain the required index.

The CoPv can be obtained as follows($t = 0.01$s):

$$CoPv_{i\_ML} = (p_{i+1\_ML} - p_{i\_ML})/t \tag{5}$$

$$CoPv_{i\_AP} = (p_{i+1\_AP} - p_{i\_AP})/t \tag{6}$$

$$\overline{CoPv_{ML}} = \frac{1}{n-1}\sum_{i=1}^{n-1} CoPv_{i\_ML} \tag{7}$$

$$\overline{CoPv_{AP}} = \frac{1}{n-1}\sum_{i=1}^{n-1} CoPv_{i\_AP} \tag{8}$$

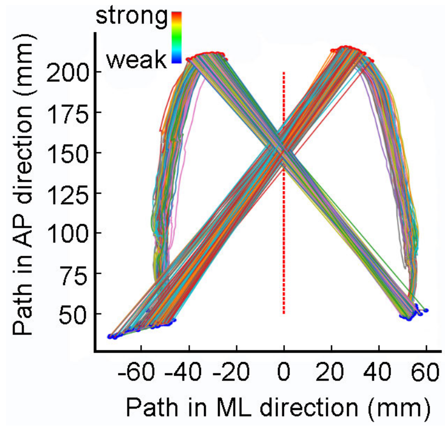

FIGURE 4. CoP path obtained by insole sensor.

where n is the number of coordinate samples in the collected CoP path. p_{i_ML} is the i-th coordinate point of the CoP path in the ML direction. p_{i_AP} is the i-th coordinate point of the CoP path in the AP direction. $CoPv_{i\_ML}$ is the i-th instantaneous velocity of CoP in the ML direction. $CoPv_{i\_AP}$ is the i-th instantaneous velocity of CoP in the AP direction. $\overline{CoPv_{ML}}$ is the average velocity of CoP in the ML direction. $\overline{CoPv_{AP}}$ is the average velocity of CoP in the AP direction.

The calculation of CoPa is as follows:

$$CoPa_{i\_ML} = (CoPv_{i+1\_ML} - CoPv_{i\_ML})/t \tag{9}$$

$$CoPa_{i\_AP} = (CoPv_{i+1\_AP} - CoPv_{i\_AP})/t \tag{10}$$

$$\overline{CoPa_{ML}} = \frac{1}{n-2}\sum_{i=1}^{n-2} CoPa_{i\_ML} \tag{11}$$

$$\overline{CoPa_{AP}} = \frac{1}{n-2}\sum_{i=1}^{n-2} CoPa_{i\_AP} \tag{12}$$

where $CoPa_{i\_ML}$ is the i-th instantaneous acceleration of CoP in the ML direction. $CoPa_{i\_AP}$ is the i-th instantaneous acceleration of CoP in the AP direction. $\overline{CoPa_{ML}}$ is the average acceleration of CoP in the ML direction. $\overline{CoPa_{AP}}$ is the average acceleration of CoP in the AP direction.

One gets the CoPj as follows:

$$CoPj_{i\_ML} = (CoPa_{i+1\_ML} - CoPa_{i\_ML})/t \tag{13}$$

$$CoPj_{i\_AP} = (CoPa_{i+1\_AP} - CoPa_{i\_AP})/t \tag{14}$$

$$\overline{CoPj_{ML}} = \frac{1}{n-3}\sum_{i=1}^{n-3} CoPj_{i\_ML} \tag{15}$$

$$\overline{CoPj_{AP}} = \frac{1}{n-3}\sum_{i=1}^{n-3} CoPj_{i\_AP} \tag{16}$$

where $CoPj_{i\_ML}$ is the CoP's i-th instantaneous jerk in the ML direction. $CoPj_{i\_AP}$ is the CoP's i-th instantaneous jerk in the AP direction. $\overline{CoPj_{ML}}$ is the average jerk of CoP in the ML direction. $\overline{CoPj_{AP}}$ is the average jerk of CoP in the AP direction.

D. NONLINEAR FEATURES

1) SAMPLE ENTROPY(SE)

SE is a nonlinear dynamic parameter used to quantify the regularity and unpredictability of time series fluctuations. It can measure the complexity of time series by measuring the probability of generating new patterns in signals. And the SE is calculated as follows:

$$X(i) = [x(i), x(i+1), \ldots, x(i+m-1)] \tag{17}$$

$$\begin{aligned} d_{ij} &= d[X(i), X(j)] \\ &= \max_{0\leq k\leq m-1}[|x(i+k) - x(j+k)|] \end{aligned} \tag{18}$$

$$B_i^m(r) = \frac{1}{N-m} B_i(r) \tag{19}$$

$$B = \frac{1}{N-m+1} \sum_{i=1}^{N-m+1} B_i^m(r) \tag{20}$$

$$A = \frac{1}{N-m} \sum_{i=1}^{N-m} A_i^{m+1}(r) \tag{21}$$

$$SE = -\ln \frac{A}{B} \tag{22}$$

where $\{x(n)\}$ is the original time series sampled at equal intervals of length n. $X(i)$ is a set of m-dimensional space vectors constituted by $\{x(n)\}$. In this study, $m = 2$, $1 \leq i \leq N-m+1$. d_{ij} is the distance between the vector $X(i)$ and $X(j)$. When a vector $X(i)$ is given, B_i is the number of all vectors which distance compared $X(i)$ is less than the tolerance r. The value of r is $0.2std$ of the $\{x(n)\}$. $B_i^m(r)$ is B_i divided by the total distance $N-m$. The $B_i^m(r)$ of all the vectors divided by the total number of vectors $N-m+1$ is defined as B. Change the dimension m of $X(i)$ into $m+1$, and repeat the equations 17 - 20 to get A. Then the SE is the negative of the logarithm of A divided by B.

2) LYAPUNOV EXPONENT(LYE)

One gets the LyE is as follows ($l = 6$):

$$Y(t) = [y(t_0), y(t_0+T), \cdots, y(t_0+(l-1)T)] \tag{23}$$

$$d_i = e^{\lambda_i t} d_i(t_0) \tag{24}$$

$$\ln d_i(t) = \lambda_i(t) + \ln d_i(t_0) \tag{25}$$

where $Y(t)$ is the delay vector that has l elements. $y(t_0)$ is the initial point. $d_i(t)$ is the distance between the two delayed vectors and the maximal Lyapunov exponent λ is the greatest slope of $\ln d_i(t)$ with respect to t.

E. STATISTICAL ANALYSIS

In this article, the SPSS 25 (IBM, Armonk, NY, USA) is used to compare the data characteristics between OW and TW conditions by the paired t-test (N=8). Following the rule suggested by Cohen [44], the values of 0.2, 0.5, and 0.8 represents small, medium and large effects, respectively.

IV. RESULTS AND DISCUSSION

According to the above experimental scheme and feature calculation methods, the results are analyzed based on the above-mentioned key features.

We will analyze the results from the aspects of trunk analysis and foot analysis, and evaluate the posture control ability of people walking under TW and OW conditions.

A. UPPER TRUNK ANALYSIS

The linear and nonlinear indices of the upper trunk in the three directions are shown in the Table 2-3.

TABLE 2. Linear Features of Upper Trunk

N=8		OW	TW	T-test
		Means±std	Means±std	p
UTa	ML	0.41±0.12	0.82±0.29	**0.002**
	V	0.79±0.19	0.92±0.28	0.069
	AP	1.18±0.19	0.97±0.34	0.072

UTa = Upper trunk acceleration.
The Uta's unit is m/s².

TABLE 3. Nonlinear features of Upper Trunk

N=8		OW	TW	T-test
		Means±std	Means±std	p
SE	ML	0.17±0.03	0.17±0.02	0.755
	V	0.18±0.01	0.18±0.01	0.614
	AP	0.18±0.01	0.18±0.02	0.180
LyE	ML	0.03±0.01	0.02±0.00	**0.045**
	V	0.01±0.01	0.02±0.00	**0.002**
	AP	0.01±0.01	0.02±0.00	**0.000**

SE = Sample entropy, LyE = Lyapunov exponent.

According to the results of the acceleration analysis of the three directions of the upper body, the UTa in the AP direction is higher in the case of OW (OW:1.18 ± 0.19, TW:0.97 ± 0.34, p = 0.072) and the acceleration in the ML direction is higher when walking on the treadmill (OW:0.41 ± 0.12, TW:0.82 ± 0.29, p = 0.002). The results are similar to those of other researchers.

As an important feature of the trunk analysis, the AP direction of people walking on the treadmill has a lower acceleration. Besides, people show greater acceleration and better local stability in the ML direction, which shows that people do adjust the posture through the lateral movement of the spine to keep the stability of the AP directions when walking. In addition, the LyE in other directions are slightly lower in the case of the ground. The reason for this may be that the trunk rotates laterally to adjust posture continuously And the comparison of all the directions in the upper trunk analysis is shown in the Figure 5.

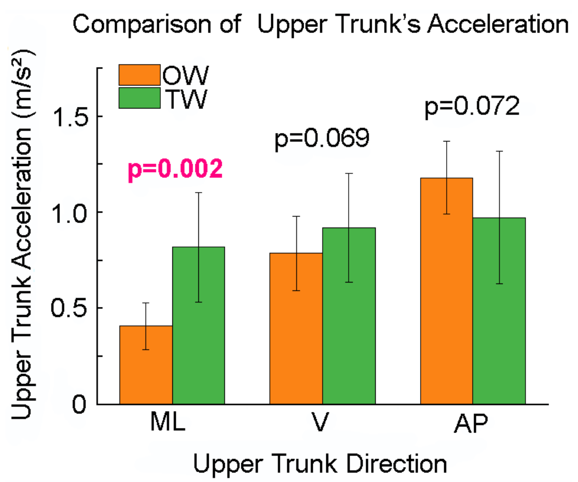

FIGURE 5. Comparison of the UTa in OW and TW.

TABLE 4. Linear Features of Foot

N=8		OW	TW	T-test
		Means±std	Means±std	p
SL		1.42±0.09	1.22±0.19	**0.015**
ST		1.06±0.06	1.18±0.05	**0.000**
CV of ST		1.81±0.52	3.04±1.86	0.080
Fa	V	2.48±0.81	2.16±0.57	0.405
Fj	V	159.75±57.54	147.07±132.53	0.759

SL = Stride length, ST = Stride time, CV = Coefficient of variation, Fa = Foot acceleration, Fj = Foot jerk.
The SL's unit is m. The ST's unit is s. The Fa's unit is m/s^2. The Fj's unit is m/s^3.

TABLE 5. Nonlinear Features of Foot in V Direction

N=8		OW	TW	T-test
		Means±std	Means±std	p
SE	V	0.21±0.04	0.22±0.03	0.487
LyE	V	0.03±0.00	0.03±0.00	0.209

SE = Sample entropy, LyE = Lyapunov exponent.

B. FOOT ANALYSIS

1) FOOT ACCELERATION, STRIDE LENGTH AND TIME

Regarding the foot movement in the vertical direction, its acceleration and jerk in the case of OW are both greater than these in the case of TW (OW:2.48 ± 0.81, TW:2.16 ± 0.57, p = 0.405; OW:159.75 ± 57.54, TW:147.07 ± 132.53, p = 0.759). This phenomenon also represents better posture control when walking on a treadmill.

On average, people walking on treadmills have shorter stride lengths, longer stride times and the difference is significant in statistics. It is important to note that since the test uses the same walking speed in both cases, but under the same walking speed, the pace of people on a treadmill has a smaller SL (OW:1.42 ± 0.09, TW:1.22 ± 0.19, p = 0.015) and longer ST (OW:1.06 ± 0.06, TW:1.18 ± 0.05, p = 0.000). Different from the conclusion of J. H. Hollman *et al.* [1] and L. Shi *et al.* [6], we believe that when people walk on a treadmill they have larger coefficient variation of stride time, smaller steps and longer time to rest, but it may causes higher rhythm and a higher level of fatigue when walking on the ground which leads to poor posture control.

TABLE 6. Linear Features of CoP

N=8		OW	TW	T-test
		Means±std	Means±std	p
CoP	ML	34.93±2.18	35.80±1.81	0.296
	AP	109.45±8.15	106.77±11.43	0.372
CoPv	ML	31.84±6.21	29.43±8.78	0.132
	AP	303.59±32.52	246.31±33.85	**0.000**
CoPa	ML	3.19±0.58	2.92±0.87	0.113
	AP	30.57±3.34	24.62±3.46	**0.000**
CoPj	ML	330.95±56.33	293.80±88.47	0.060
	AP	63.03±6.30	54.80±7.34	**0.000**

CoPv = CoP's velocity, CoPa = CoP's acceleration, CoPj = CoP's jerk.
The CoPv's unit is mm/s. The CoPa's unit is m/s^2. The CoPj's unit is m/s^3.

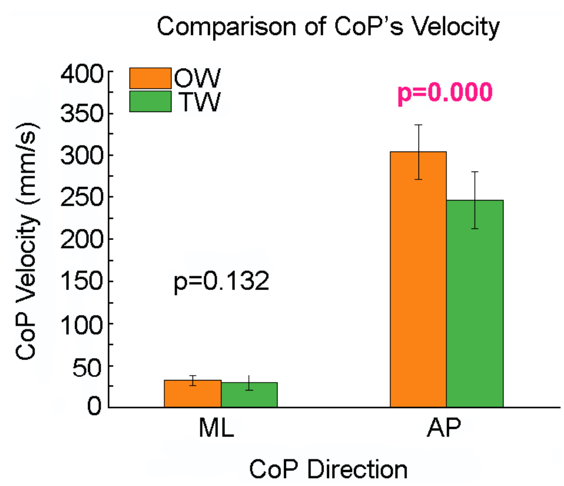

FIGURE 6. Comparison of CoP's velocity between OW and TW.

2) CoP CORRELATION FEATURES

The characteristics of the velocity, acceleration and jerk of the CoP between TW and OW conditions are shown in the Table 6. And the comparison of CoPv, CoPa, and CoPj in the two cases is shown in Figures 6-8.

In the CoP analysis, we find that in the case of OW, COPv, CoPa and CoPj in the AP direction are all bigger than those in the case of TW (OW:303.59 ± 32.52, TW:246.31 ± 33.85, p = 0.000; OW:30.57 ± 3.34, TW:24.62 ± 3.46, p = 0.000; OW:63.03 ± 6.30, TW:54.80 ± 7.34, p = 0.000).

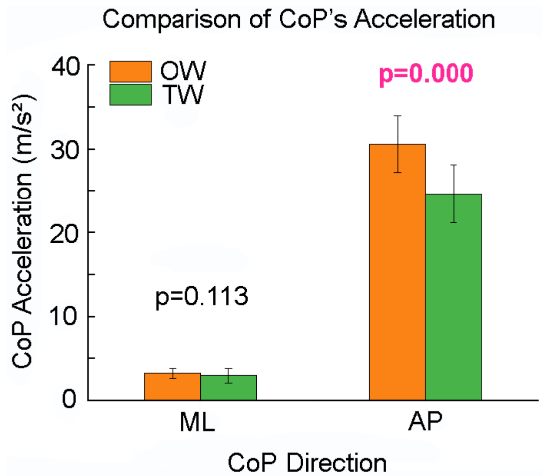

FIGURE 7. Comparison of CoP's acceleration between OW and TW.

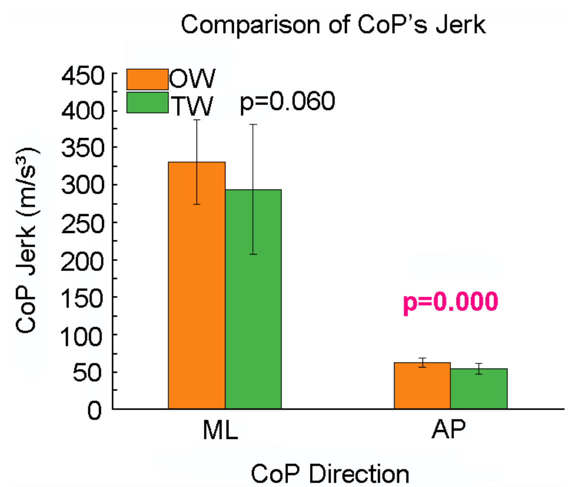

FIGURE 8. Comparison of CoP's jerk between OW and TW.

It can be seen from these results that the treadmill walking has a significant influence on the CoP, and the differences between the two cases are mainly reflected in the component of the CoP in the AP direction. This means that people got more effective posture control when walking on a treadmill. At the same time, a higher control ability is reflected in the AP direction as the action direction, while in ML direction, the characteristics of OW and TW are basically the same, that is, the treadmill does not significantly affect people's walking characteristics in ML direction.

Nonlinear analysis of the CoP position is shown in Table 7, where the SE and the LyE are depicted. The SE represents the regularity of the CoP distribution, and also indicates people's attention to walking. The smaller SE indicates that people paid more attention to their pace, while the larger SE indicates that people did not care about their walking path, in another word, walked more freely.

From the SE and LyE of the CoP, one finds that there is no significant difference between two conditions, which means that people don't pay more attention to the feet movement when walking on the treadmill, and the difference in control ability is caused by upper trunk movement rather than feet.

TABLE 7. Nonlinear features of CoP

N=8		OW	TW	T-test
		Means±std	Means±std	p
SE	ML	0.06±0.00	0.06±0.00	0.368
	AP	0.06±0.00	0.06±0.00	0.558
LyE	ML	0.01±0.01	0.01±0.01	0.353
	AP	-0.01±0.01	-0.01±0.01	0.999

SE = Sample entropy, LyE = Lyapunov exponent.

C. NONLINEAR FEATURES SUMMARY

The comparison of all the nonlinear features in the postural control ability analysis is shown in the Figure 9. The motion regularity, attention, and local stability during walking are demonstrated.

The coordinate axis on the left side of the graph is a variety of nonlinear features, and the coordinate axis above is sample entropy. The values of gray box (OW) and red circle (TW) in the figure correspond to the coordinate axis. The axis at the bottom of the graph is Lyapunov exponent, and the values of blue diamond (OW) and yellow star (TW) in the figure correspond to the coordinate axis.

As can be seen from Fig. 9, there is no significant difference in the sample entropy of upper trunk acceleration in three directions in the two cases, while Lyapunov exponent shows significant difference. And there is no significant difference in the sample entropy and Lyapunov exponent between the two directions of CoP, and nor does foot acceleration in V direction. The reason for this result, as mentioned above, when people switch from the ground to walking on a treadmill, their attention is not on their feet, but on the use of upper trunk movements to adjust.

D. CONTROL CAPABILITY ASSESSMENT

Some representative indicators are selected to visually demonstrate the differences in postural control ability under OW and TW conditions. Since all the indicators involve in this paper represent better ability by smaller values, the following evaluation method is adopted.

$$\delta = \frac{MIN}{\bar{x}} \times 100 \tag{26}$$

where, MIN is the minimum value obtained in the case of OW and TW for all indicators to be evaluated, and $\bar{x}$ is the RMS value of indicators to be evaluated in the case of OW or TW. When assessed using this method, the group with greater postural control will have higher δ values.

In this experiment, we selected the five characteristics of CoPv, CoPa, CoPj, Uta in AP and Fa in vertical direction to evaluate the postural control ability. Combined with the above calculation methods, the postural control ability in

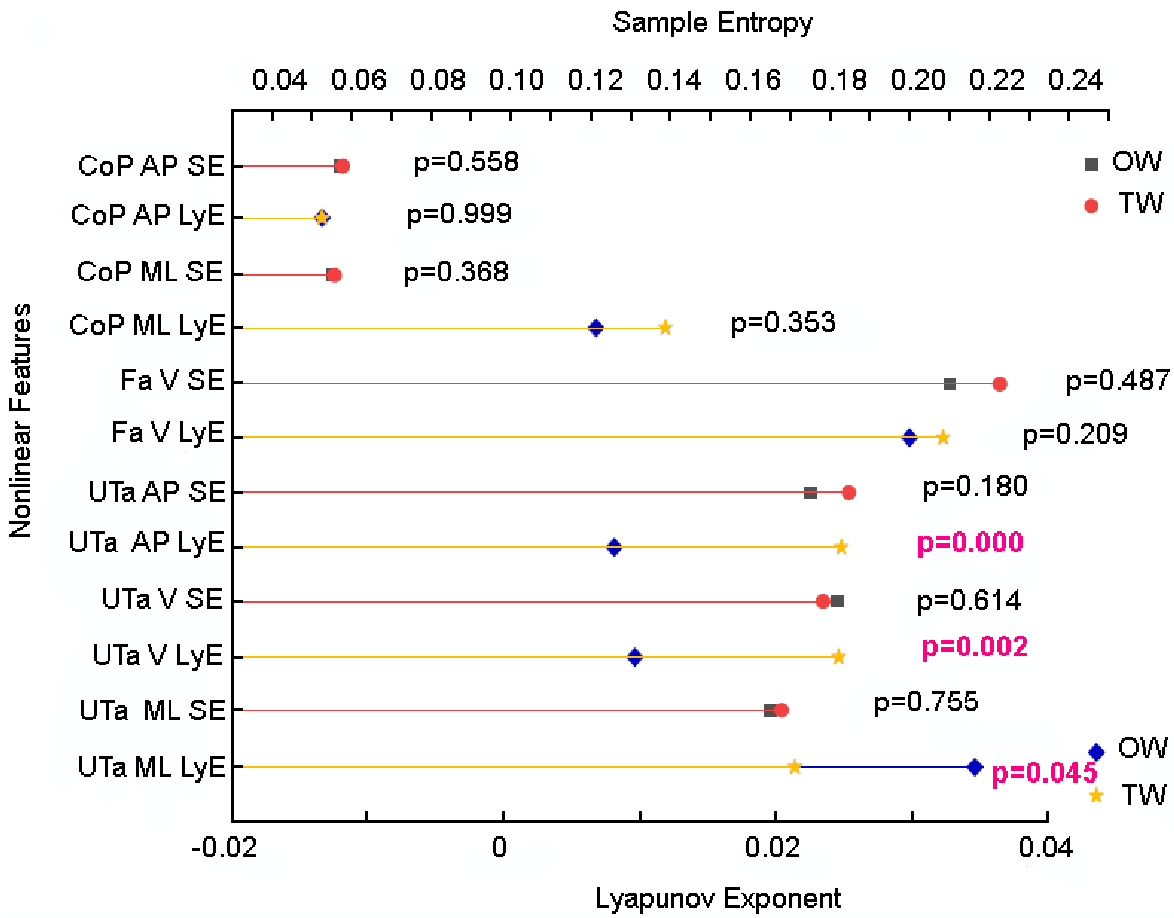

FIGURE 9. Comparison of nonlinear features between OW and TW.

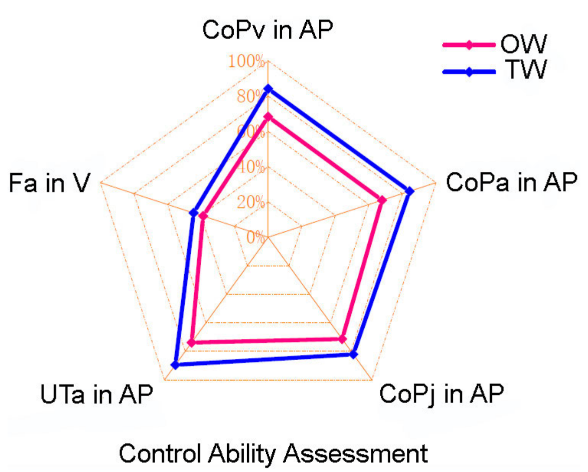

FIGURE 10. Assessment of posture control between OW and TW situations.

two situations is obtained. The specific situation is shown in the Figure 10. By averaging the scores obtained under these five characteristics, we find that people's average scores are 64.06% in the OW case and 76.89% in the TW case. From the above analysis, one finds that people got better posture control when walking on the treadmill.

V. CONCLUSION

This paper developed a method base on linear and nonlinear analysis to assess the postural control ability of people walking on the treadmill and on the ground. The whole idea of the method boils down to the differential analysis of linear and nonlinear characteristics of treadmill walking to evaluate the postural control ability in different states. The variance analysis of this assessment was done using the paired t-test of the indicators, to test the significance level of the differences. The indicators analyzed were divided into the upper trunk and the feet. The results suggested that people got better postural control when walking on a treadmill than on the ground.

In this experiment, we adopted a uniform walking speed in two cases, to integrate the differences of the SL and the ST, and made a comprehensive comparative analysis according to the experimental results. It was observed that people have shorter SL and longer ST when walking on treadmills, which makes walking on treadmills has slower rhythm than walking on the ground. The results of this comprehensive analysis suggested that people may more tired when walking on the ground, which also leads to weaker posture control in such situation.

It should be noted that in the CoP analysis, whether it is CoPv, CoPa or CoPj, the differences between TW and OW were mainly reflected in the AP direction instead of the ML direction. This indicated that the motion trajectory of the CoP on the AP direction can better reflect the postural control ability of forwarding movement and that people adjusted the marching state by changing the step in such direction. The reason for the larger correlation features of COP was also related to the fact that people are more tired when walking on the ground, therefore worse posture control ability. Also, when walking on a treadmill, the feet showed bigger stability in the vertical direction. At the same time, in the analysis of the upper trunk, we find that the movement of the torso in the ML direction is a way for people to control their posture, and when people walk on the treadmill, the acceleration in the AP direction is smaller. After comprehensive analysis and evaluation, although the upper trunk exhibits slightly unstable in the ML and V direction, this paper confirmed that people have better posture control when walking on the treadmill.

Linear and nonlinear analysis methods were used to identify representative indicators for the assessment of postural control ability. The main goal of further research is to analyze people's postural control under other conditions.

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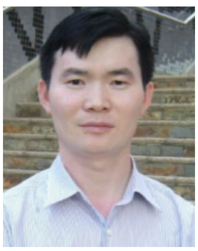

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