Multidimensional Evaluation Model of Elderly People's Balance Ability
Based on 3D Monitoring Points

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Abstract. With the aging of the population becoming more and more serious, the falls of the elderly have gradually become the focus of academia. We build a multidimensional model to evaluate the walking balance ability of the elderly so as to help them correct their postures and prevent possible falls. From the perspective of the state of gravity center, gait and body features, some indicators such as envelope area of gravity center shifting and stride length are extracted to assess the stability of old people's walking. Then entropy weight method is introduced to build the evaluation model. Finally, the validity of the model is proved by empirical analysis.

Introduction

Balance ability is the overall performance of the integration and coordination of a body's multiple tissues. If any part of the body comes across problems, it may cause effect to the balance ability of the body. From literature reviews we know that there exists two main factors affecting the balance ability of the elderly, the height of gravity center and the area of bearing surface. Decreasing the height of gravity center and increasing the area of bearing surface are both effective ways for the people to maintain balance[1]. From a physiological point of view, balance ability is mainly related to vision, gender, age, height, weight and other physical features.

On the basis of the analysis above, we extract 25 indicators that affect body balance ability, they are as follows, state of gravity center (including envelope area of gravity center shifting, swaying degree of gravity center and acceleration of gravity center), gaits (represented by stride length) and body features (including BMI and age).

Extraction of Indicators

State of Gravity Center

Firstly, the gravity center of the whole human body can be synthesized by the 42 monitoring points. Then state of gravity center can be measured by envelope area of gravity center shifting, swaying degree of gravity center and acceleration of gravity center.

Determination of Gravity Center. A random sampling test[2] is made by deploying 42 monitoring points on the body of the elderly subjects. See the layout of the points indicated in the following pictures. The data contains the coordinates of these 42 monitoring points of each subject.

In terms of synthesizing human gravity center, it is necessary to determine the gravity center’s coordinates of each body part. According to the research of Zhang Chunhong[3], human body can be divided into 14 body parts, they are head, trunk, left upper arm, right upper arm, left lower arm, right lower arm, left hand, right hand, left thigh, right thigh, left leg, right leg, left foot, right foot. We can
synthesize the gravity center of each body part first. According to the research of Vaughan C L\cite{4}, the distance from the front point of a body part to its gravity center divided by the length of the whole body part is a fixed ratio. Based on that, the coordinates of each body part’s gravity center can be calculated.

According to the research of Yang Zhifang\cite{5}, the trail of the gravity center of the whole body is determined by the weight and coordinates of each body part. The weight ratios of different body parts are as follows.

<table>
<thead>
<tr>
<th>Different parts of body</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>0.044</td>
<td>0.037</td>
</tr>
<tr>
<td>Trunk</td>
<td>0.479</td>
<td>0.487</td>
</tr>
<tr>
<td>Upper Arm (Both sides)</td>
<td>0.053</td>
<td>0.051</td>
</tr>
<tr>
<td>Lower Arm (Both sides)</td>
<td>0.030</td>
<td>0.026</td>
</tr>
<tr>
<td>Hand (Both sides)</td>
<td>0.018</td>
<td>0.012</td>
</tr>
<tr>
<td>Thigh (Both sides)</td>
<td>0.200</td>
<td>0.223</td>
</tr>
<tr>
<td>Leg (Both sides)</td>
<td>0.107</td>
<td>0.107</td>
</tr>
<tr>
<td>Foot (Both sides)</td>
<td>0.038</td>
<td>0.030</td>
</tr>
</tbody>
</table>

Then the trail of the gravity center of the whole body can be calculated by the following formula.

\[
r_{com} = [x_{com}, y_{com}, z_{com}] = \sum_{i=1}^{N} \frac{m_i r_i}{M}
\]  

\[
r_i = [x_i, y_i, z_i]
\]

represents the shifting trail of the body part \(i\), \(m_i\) represents the weight of the body part \(i\), \(M\) stands for people’s weight, \(N=14\). \(x\), \(y\) and \(z\) are three axes of spatial rectangular coordinate system.

**Envelope Area of Gravity Center Shifting.**Envelope area of gravity center shifting refers to the area covered by the swaying trajectory of the human body's gravity center.

A fast approximation algorithm\cite{4} for the envelope area of the gravity center is proposed by An Meijun(2011). The algorithm conduct a virtual rotation of all the points to find the most peripheral point, then connect those points to work out the envelope area of gravity center shifting. The formulas are as follows.

\[
P = (X, Y)
\]
\[
\alpha = \frac{\omega}{180} \times \pi \tag{3}
\]
\[
A = \begin{bmatrix}
\cos(\alpha) & -\sin(\alpha) \\
\sin(\alpha) & \cos(\alpha)
\end{bmatrix} \tag{4}
\]

\[P' = A \tag{5}\]

In the formula above, \(\alpha\) is the rotation angle, \(P'(x', y')\) is the point got by the rotation of \(P(x, y)\), matrix \(A\) is a rotation transformation matrix.

In the process of calculating the extremum by changing the rotation angle, it is possible that the extremum points repeat. When calculating the envelope area of the gravity center, the repeated points can only be used once. As shown in the figure below, the blue curve connects the most peripheral points to obtain the envelope area. In the next step, the area of the irregular shape will be calculated.

![Figure 2. Envelope area of gravity center shifting.](image)

Under these circumstances, every vertex’s coordinates is known, then we can divide the area into \(N-2\) triangles. If the three sides’ lengths of a triangle are \(a\), \(b\) and \(c\), the square of each triangle can be figured out using the formulas below. Finally the envelope area of gravity center shifting is the sum of all these triangles’ area.

\[T = \frac{a+b+c}{2} \tag{6}\]
\[A = \sqrt{T \cdot (T - a) \cdot (T - b) \cdot (T - c)} \tag{7}\]

**Swaying Degree of Gravity Center.** When the gravity center sways left and right in the process of advancing, the swaying degree of gravity center is defined as the deviation from the forward path of the gravity center. The forward route can be simulated by fitting a regression curve according to the projection distribution of the landing point on the horizontal plane (XOY plane). According to the physiological characteristics and human walking characteristics, it is considered that the heel firstly touches the ground when people are walking. Therefore, the monitoring point 37 of the left heel and 36 of the right heel are selected as the projection points when people are walking on the ground. It can be shown in the following figure.
Once we know the path people walk along, the vertical length between the projection point and the regression line can be figured out. The swaying degree of gravity center equals the product of the maximum length and the minimum one. The formula is as follows.

\[ S_{\text{minmax}} = \min(\text{Length}_i) \cdot \max(\text{Length}_i) \]  

(8)

It can be assumed that the bigger the \( S_{\text{minmax}} \) is, the bigger the degree of gravity center swaying is, that is to say, the balance ability of human body is poorer.

**Acceleration of Gravity Center.** Acceleration is a vector representing the degree of velocity change per unit time. Generally speaking, acceleration is an instantaneous concept, its unit is \( \text{m/s}^2 \). When the point Q is moving in general space, the change of velocity vector divided by the time it passes through is called the average acceleration in the time of \( \Delta t \). The formula is as follows:

\[ a = \frac{\Delta v}{\Delta t} = \frac{v(t+\Delta t)-v(t)}{\Delta t} \]  

(9)

The displacement of the gravity center is a spatial curve composed of discrete points, but due to the short monitoring interval, the average acceleration between the two points can be approximately regarded as the instantaneous acceleration of the previous point.

**Gait**

Gait is represented by the indicator stride length, the measurement of stride length is the length of each step out, that is to say, the distance between the projection points of the heel monitoring points (left heel point 37, right heel point 36) at different time intervals on the horizontal plane. The illustration is shown in the following picture.
Due to that the normal stride length is about 150-160 cm, so this indicator needs to be processed through the formulas below.

\[
SL' = \begin{cases} 
SL - 160, & SL > 160 \\
150 - SL, & SL < 150 \\
0, & \text{else}
\end{cases}
\]

(10)

**Body Features**

**BMI.** Due to that BMI has a normal value, greater or less than the normal value means poor physical fitness, so normalization by mean value method is adopted to make the indicators dimensionless, the formula is as follows.

\[
r_i' = \frac{r_i}{\bar{r}_i}, i = 3
\]

(11)

In the formula above \( r_i \) is the unprocessed indicator's value and \( r_i' \) is the value which is processed. \( \bar{r}_i \) is a reference value of ordinary Chinese which equals 22.

**Age.** Age is a significant factor influencing the balance of people and the function of various organs of the elderly body gradually decreases with the increasing of age, resulting in sluggish sensation, sluggish action and poor response. The correlation between balance ability and age is a complex curve. The decrease of the dynamic balance function in the elderly happens when the body movement function decreases. So, it’s assumed that the greater one’s age is, the worse the balance ability.

**Multidimensional Assessment Model**

We apply min-max normalization method, making dimensionless treatment for all the indicators above. Due to that they are all cost-type indexes, the unified formula is as follows.

\[
r_i' = \frac{\max - r_i}{\max - \min}, i = 1, ..., 6
\]

(12)

Then based on the data, entropy weight method is introduced to give each indicator a weight to build up the multidimensional assessment model. The indicators and their weights are illustrated in the following table.

<table>
<thead>
<tr>
<th>General objective</th>
<th>First-grade Index</th>
<th>Second-grade Index</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>multidimensional assessment model</td>
<td>State of Gravity Center</td>
<td>Envelope Area of Gravity Center Shifting</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>Swaying Degree of Gravity Center</td>
<td>Acceleration of Gravity Center</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>Acceleration of Gravity Center</td>
<td>Stride Length</td>
<td>0.22</td>
</tr>
<tr>
<td>Body Features</td>
<td>BMI</td>
<td></td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>Age</td>
<td></td>
<td>0.21</td>
</tr>
</tbody>
</table>

Then the balance assessment model is built as the following.

\[
\text{BalanceAbility} = 0.08 \cdot \text{EAGCS} + 0.24 \cdot \text{SDGC} + 0.06 \cdot \text{AGC} + 0.22 \cdot \text{SL} + 0.18 \cdot \text{BMI} + 0.21 \cdot \text{AGE}
\]

(13)

In order to test the effectiveness of the model, the feet trails of people with different balance abilities are visualized to make a comparison. We can see from the left picture below that the foot
trails are not stable and regular, conversely, the right picture indicates much more stability. That means the model we set up is viable and credible.

Figure 6. Comparison of foot trails between those with different balance ability.

Summary
By extracting the features of old people’s walking, a multi-dimensional model is built to assess the balance ability of the elderly. According to that, we can find out the reasons of poor balance abilities. Based on that, personalized suggestions can be put forward for each old person to improve his balance and prevent falls.

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References