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ANALYSIS OF STABILITY OF THE HUMAN GAIT

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Analysis of the gait stability of a man moving along an even surface with a constant velocity is presented. The stability criteria applied to biped robots, namely: the Zero Moment Point (ZMP) and the Ground projection of the Center Of Mass (GCOM) have been employed in the investigations. The analysis has been carried out on the basis of measurement data obtained from the human gait recorded with a digital camera.

Key words: human gait, stability criteria

1. Introduction

The human walking is a complex activity, which consists of four main tasks: the initiation and termination of a locomotion movement, generation of a continuous movement, maintenance of the equilibrium, and adaptability to meet any changes in the environment. The maintenance of the equilibrium is one of the most important activities for two main reasons. Firstly, the center of mass is located in a considerable distance from the support area, and secondly, for a major period of the walking cycle, the body is supported by a single limb with the center of mass outside the base of the support. In older people, up to 70% falls occur during locomotion. Differently from previous approaches dealing with the balance of the static posture only, this paper presents a study of stability of the human gait during the walking process. The analysis makes use of the concept of the Zero Moment Point (ZMP) and the Ground projection of the Center Of Mass (GCOM) previously used to define the control and stability of biped robots.

2. Stability criteria

Both biomechanics and robotics use some criteria needed to estimate the amount of stability. There are two main types of such criteria, namely:

- static stability criteria (GCOM),
- dynamic stability criteria (ZMP).

Support area

The support area in the single-support phase is approximately equal to the area of a single foot. In the double-support phase, the area is much wider and becomes a convex hull of two-feet areas, as shown in Fig. 1.

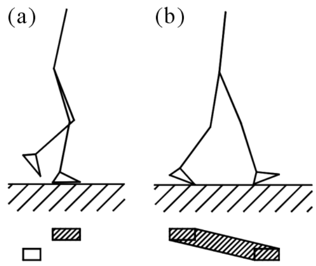

Fig. 1. Support polygon during single-support phase (a) and double-support phase (b)

GCOM criterion

The biped/human gait is said to be statically stable and a human posture is said to be balanced if the gravity line from its center of mass falls within the convex hull of the foot support area (support polygon) (Goswami, 1999). If the GCOM point is beyond the support polygon, it is equivalent to the presence of an uncompensated moment acting on the foot, which causes it to rotate around the point on the polygon boundary.

By *the static stability margin* one means a distance of the GCOM from the edge of the support polygon, measured along a current vector of motion of the gravity center

$$
\begin{aligned}
x_{GCOM} &= \frac{\sum_{i=1}^{n} M_{xi}}{\sum_{i=1}^{n} F_{xi}} = \frac{\sum_{i=1}^{n} m_i x_{ci}}{\sum_{i=1}^{n} m_i} \\
y_{GCOM} &= \frac{\sum_{i=1}^{n} M_{yi}}{\sum_{i=1}^{n} F_{yi}} = \frac{\sum_{i=1}^{n} m_i y_{ci}}{\sum_{i=1}^{n} m_i}
\end{aligned}
\tag{2.1}
$$

where m_i is the mass of the ith body, x_{ci}, y_{ci} – location of the center of mass of the ith body.

ZMP criterion

The Zero Moment Point (ZMP) is a point on the ground where the total moment generated due to gravity and inertia equals zero (Goswami, 1999; Vukobratovic *et al.*, 1990). The ZMP of a biped robot must be inside the convex hull of the foot support area to ensure stability of the walk without falling down (Goswami, 1999; Vukobratovic *et al.*, 1990). The ZMP is also known as the Center Of Pressure (COP).

Finally, we can obtain each component of the ZMP in the form of equation (2.2)

$$\begin{aligned} X_{zmp} &= \frac{\sum_{i=1}^{n} m_i(\ddot{z}_i - g_z)x_i - \sum_{i=1}^{n} m_i(\ddot{x}_i - g_x)z_i - \sum_{i=1}^{n}(\dot{T}_y)_i}{\sum_{i=1}^{n} m_i(\ddot{z}_i + g_z)} \\ Y_{zmp} &= \frac{\sum_{i=1}^{n} m_i(\ddot{z}_i - g_z)y_i - \sum_{i=1}^{n} m_i(\ddot{y}_i - g_y)z_i + \sum_{i=1}^{n}(\dot{T}_x)_i}{\sum_{i=1}^{n} m_i(\ddot{z}_i + g_z)} \end{aligned} \tag{2.2}$$

where $(\dot{T}_x)_i$, $(\dot{T}_y)_i$ denote x, y components of time derivatives of the ith body angular momentum.

The dynamic stability margin is the distance between the ZMP and the support polygon boundary measured along the actual ZMP velocity vector.

3. Investigations

The investigations comprised the following stages:

- assumption of a simplified model of the human body and its association with anthropometrical data,
- recording of a trajectory of some selected points on the human body during walking (with the help of a digital camera),
- generation of an input data file for a program for the gait stability analysis on the basis of the digital data recorded,
- writing a computer program for evaluation of the gait stability according to the ZMP and GCOM criteria,
- calculations and visualization of the obtained results.

In Figs. 2a,b, a simplified kinematic model of the human body in the form of a 6-element kinematical chain is presented. The element that substitutes the pelvis is massless. The upper part of the body is represented by element 3, whose mass is equal to the sum of masses of the head, chest and upper limbs. The legs are without feet, elements 1, 5 replace shanks, whereas elements 2, 4 replace thighs. The mass of elements 1, 5 is equal to the mass of feet and shanks. The segments are made of rods of a constant density and are connected by means of spherical joints. Each segment is treated as a rod with the center of mass located in the geometrical center of the rod. It is assumed that the center of mass of each element is positioned in the middle of its length.

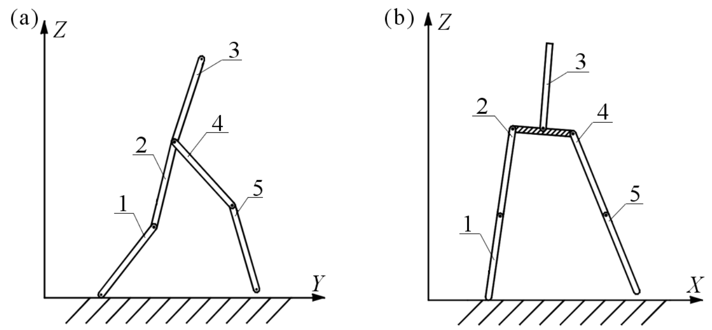

Fig. 2. Model view in sagittal plane (a) and frontal plane (b)

4. Recording of trajectories of the gait

Two digital cameras positioned perpendicularly with respect to each other were used for recording the gait trajectories. They traced the path of markers that contrasted with the surrounding and were placed on the body of the walking man. The time of shuttle opening was fixed at 1/1000 s, the shots were made at the speed of 25 exposures per second. A small part of the film showing the central portion of the path was employed in the analysis. In order to minimize the deformations, the object was filmed from a long distance by means of telephoto lens.

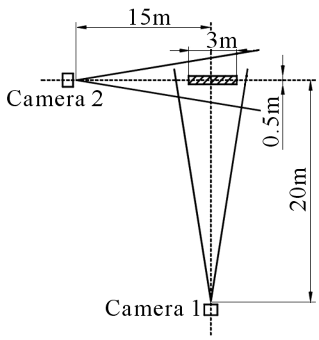

Fig. 3. Arrangement of two-camera system

Conversion of the recorded gait trajectories into a digital data file

Further examination was conducted with a computer program for analysis of images that allows for spatial reconstruction of the objects recorded with two cameras at least. The relevant markers on the human body were associated with the markers in the program. The data concerning the position of the markers, obtained by automatic tracing of the marked points, were recorded in a text file.

Program for analysis of the gait stability and data filtration

The program for analysis of human gait trajectories was written by means of the MATLAB calculation package. This package contains a high-level language interpreter that allows for implementation of numerical algorithms and now constiutes a standard in scientific and technical computations as well as in visualization of their results.

In order to calculate accelerations in individual points of the kinematic chain, the recorded data should be pre-filtered. It is done with low-pass filters that cut off higher harmonics of the signal. It can also be done by means of interpolating B-spline cubic functions.

5. Results of calculations

The stability of the human gait can be analyzed in two perpendicular planes: the sagittal (anterior-posterior) plane and the frontal (medial-lateral) one. The stability of the human body in one plane only is not sufficient to assume that the human gait is stable. The recorded walking process (Fig. 4) was analyzed separately in three stages: the standing stage, transitional stage and walking stage, and in the before mentioned planes.

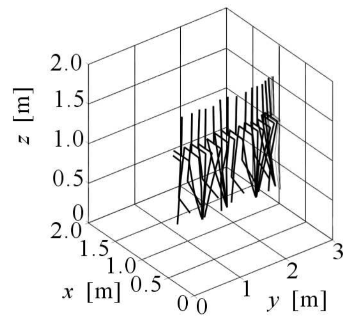

Fig. 4. Recorded walking process

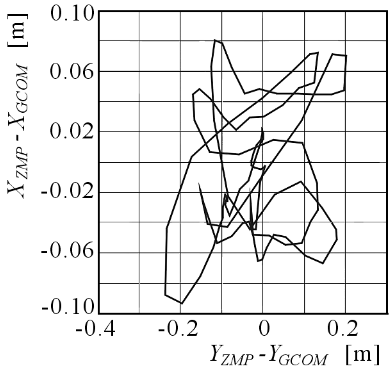

Fig. 5. Stabilogram recorded during walking stage

On the basis of the results obtained from the calculations, it is concluded that:

- trajectories of the GCOM and ZMP are situated within the convex hull of the foot support area,
- locations of characteristic points of the trajectories (common points of the GCOM and ZMP, the maxima and the minima of both trajectories) are symmetric and evenly distributed,
- the delay between the maximum of the ZMP with respect to the maximum of the GCOM has a constant value,
- the amplitude of the body displacement in the sagittal plane is 10 times higher than displacements recorded in the frontal plane. However, because the maximum dimension of the supporting polygon in the anterior-posterior direction is larger than the dimension of this polygon in the medial-lateral direction (foot length is much larger than its width), the stability is maintained.

6. Concluding remarks

Currently there is not any uniform standard in biomechanical laboratories that is applied in investigations of the human gait stability. The measurement procedure presented in this paper is based on methods that are employed by designers of biped robots. It is an alternative to the platforms recording the background reaction forces that have already been used for 50 years.

The investigations conducted and the experience gathered have allowed for formulation of postulates concerning the modification of the method for the

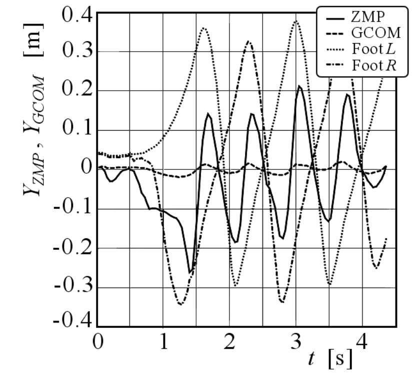

Fig. 6. Trajectories Y_{GCOM}, Y_{ZMP} – sagittal (anterior-posterior) plane

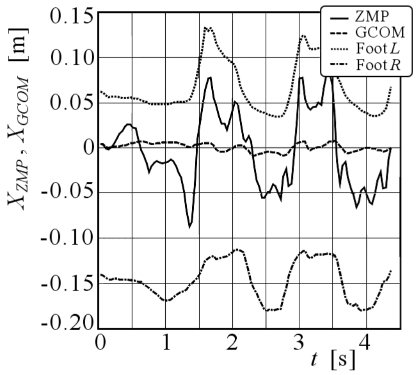

Fig. 7. Trajectories X_{GCOM}, X_{ZMP} – frontal (medial-lateral) plane

gait stability analysis. It seems that connection of two criteria of the stability evaluation, namely the ZMP and the GCOM, with two ways of recording, that is to say, by means of pressure sensors and an optical method, can significantly increase the accuracy of measurements, and consequently, the reliability of estimations made.

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Analiza stabilności chodu człowieka

Streszczenie

Artykuł przedstawia analizę stabilności chodu człowieka poruszającego się po równej poziomej powierzchni. W badaniach wykorzystano dwa kryteria stateczności: ZMP(*Zero Moment Point*) i GCOM (*Ground projection of the Center Of Mass*) stosowane w odniesieniu do robotów dwunożnych. Analizę przeprowadzono na podstawie zarejestrowanych za pomocą kamer cyfrowych danych dotyczących trajektorii wybranych punktów.

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