Commun Nonlinear Sci Numer Simulat 16 (2011) 2313–2318

Contents lists available at ScienceDirect

Commun Nonlinear Sci Numer Simulat

journal homepage: www.elsevier.com/locate/cnsns

Changes in the gait characteristics caused by external load, ground slope and velocity variation

Jerzy Mrozowski *, Jan Awrejcewicz

Department of Automation and Biomechanics, Technical University of Lodz, Poland

ARTICLE INFO

Article history:
Available online 6 May 2010

Keywords:
Human gait
Locomotion characteristics

ABSTRACT

The complexity of the human gait manifests itself by lots of parameters that can evoke different changes in the walking manner. They can be divided into two groups: inherent, like anthropometric features or peculiar psychomotor type, and those related to the external conditions. The aim of the paper is to analyze the influence of three parameters, i.e. external load, ground slope and gait velocity, on the locomotion characteristics and the gait stability. Within the framework of investigations for different values of the mentioned parameters a film registration of the trajectories of selected kinematic nodes during some gait cycles has been carried out. The obtained data was a subject of numerical calculation aimed at extracting the essential properties of the principal gait characteristics.

1. Introduction

Walking is a dynamic process which involves so many of the body's systems and requires them to be so accurately coordinated that providing a comprehensive description of it would appear impossible. The research carried out therefore focuses on selected aspects of walking, based on needs reported by orthopaedic surgeons, physiotherapists, bioengineers, representatives of the footwear industry, sports competitors, trainers, and people from many other walks of life (see [1,2,4–6]).

The aim of the present work is to investigate the effect of three parameters, namely speed of walking, ground slope and external load, on the characteristics and stability of a person's walk. To achieve this, a fairly widespread method was used, whereby fragments of the action of walking are recorded on a film. The data so obtained are subjected to kinematic analysis, carried out on a simplified mathematical–physical model using a specially written computer program.

2. Investigations

Human body may be discussed as a collection of elements bound on the edges with joints [8]. They constitute a kinematic chain made up of bones (passive locomotive system) activated by muscles (active locomotive system). For the research purposes, many different simplified human body models are used, allowing to carry out the observation and analysis of human movements.

For the purposes of present study the model was assumed consisting of 11 mass elements and two massless elements, representing the shoulder girdle and the pelvic girdle (Fig. 1). Despite the substantial degree of simplification, such model seems to be adequate for the evaluation of walking characteristics. Element 1 substitutes the head and the neck, 2 and 6 – the arms, 3 and 7 – the forearms, 4 and 8 – the tights, 5 and 9 – the shanks, 10 – the trunk and 11 – the backpack (external

* Corresponding author. Address: Stefanowski St. 1/15, 90-924 Lodz, Poland.
E-mail address: jmrozow@p.lodz.pl (J. Mrozowski).

1007-5704/$ - see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.cnsns.2010.04.059

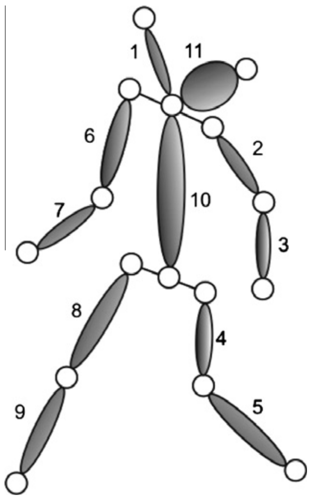

Fig. 1. Scheme of the human body model.

load). While modelling legs, the feet were not isolated – such simplification is justified by the accepted study methodology as well as the used walking stability criteria. The size and mass distribution of model elements are adequate to their real size and mass distribution in human body.

During the course of the study the transitory location of GCOM (Ground projection of the Centre Of Mass) and ZMP (Zero Moment Point) points on a support plane was determined. While walking, these points change their location as some factors change (e.g. walking phase, speed, ground properties etc.) likely to influence – directly or indirectly – the stability. Until the moment, when the point described in terms of a given criterion leaves the support zone, it can be said that the stability is maintained. Each fall of the GCOM or ZMP points trajectory out of this zone's borders means stability loss.

A natural way to gain data describing a human gait is its video recording. This relatively simple and convenient method allows the acquisition of the most essential geometric and kinematic parameters which can be exploit as a base for further investigations. During the research project realisation a recording was performed using two digital camcorders set perpendicularly to each other, at the distances of approx. 4.2 m (x axis) and 5.2 m (y axis) from the object, with the recording speed of 25 fps (frames per second). In order to facilitate the subsequent synchronisation of the pictures from both camcorders, at the beginning of each film the flash from the camera flash lamp was generated (Fig. 2).

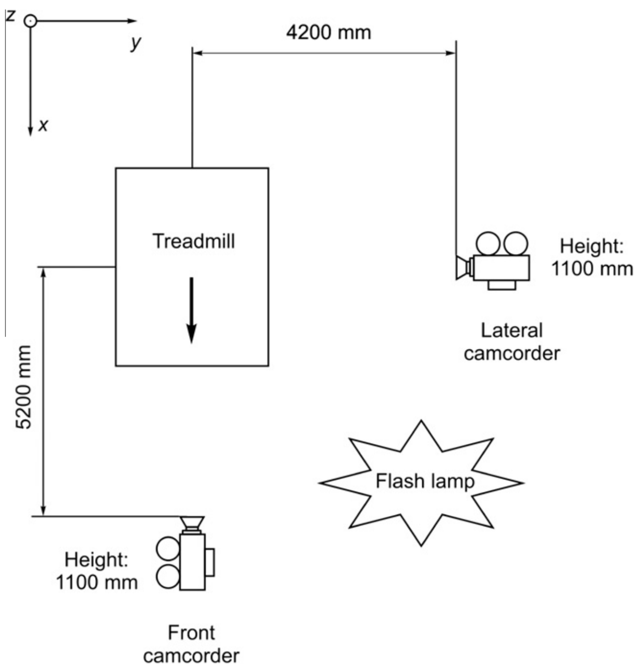

Fig. 2. Scheme of the measurement stand.

Fig. 3. Video recording of the walking process (a) without an external load – horizontal surface (b) with an external load (backpack) – horizontal surface (c) without an external load – downhill surface.

At the prepared research site, the video recording of walking was conducted, for different combinations of the speed, ground inclination and external load. Before the recording started, the markers (table tennis balls) were attached to the examined person's body. They were fixed to the kinematic nodes taking part in locomotion, i.e. in the rotation axes of glenohumeral joint, elbow joint, hip joint, knee joint and ankle joint (see Fig. 3).

The movement recording with the use of digital camcorders had been saved as *.AVI files, which were later subjected to analysis by the SimiMachIX software. That software makes possible the real-time observation of the recorded movement. As a result, the digital record of the trajectory of the selected kinematic nodes was obtained, which take part in walking. On such basis, it was possible to determine the speed and acceleration of the individual segments as well as a whole body.

The human walking stability is one of the essential elements in locomotion quality evaluation. Any of its disorders badly influence the effectiveness of locomotion and cause the increase in the energy consumption. There are numerous criteria of human walking stability. In the present paper only two of them were used, applied mainly for robots stability evaluation – GCOM and ZMP [3,7].

3. Numerical results

Figs. 4 and 5 show the results of projection of the body's overall centre of mass onto the floor in the frontal plane (y axis). These graphs show that a highly stable walk is maintained for that plane in the double support phase. On each of them the reserve of stability in this phase lies in the range of approximately 5–10 cm from the left or right edge of the polygon of support. Of particular note is the clearly visible tendency during the swing phase for the overall centre of mass to become closer to the foot being the supporting foot during that stage.

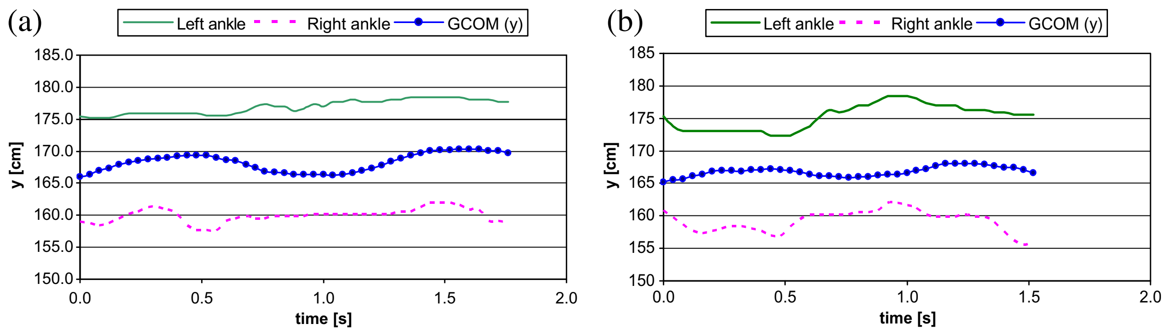

Fig. 4. Deviation of GCOM point in the frontal plane (y coordinate) (a) velocity of 4 km/h, (b) velocity of 6 km/h.

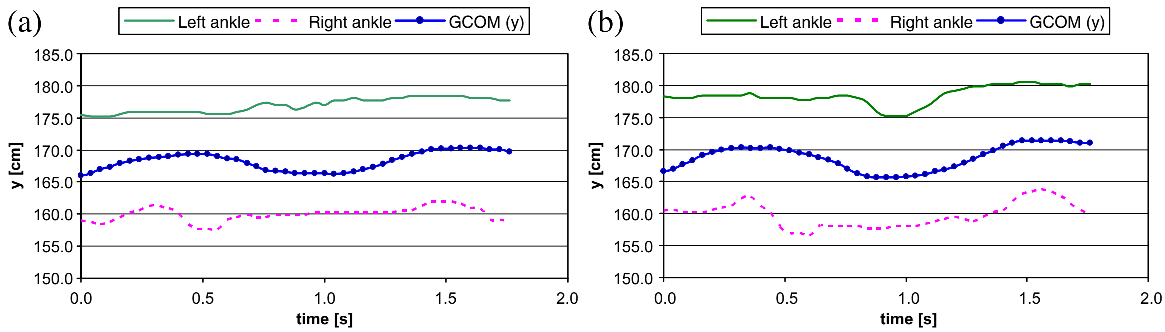

Fig. 5. Deviation of GCOM point in the frontal plane (y coordinate) during walking at a velocity of 4 km/h (a) without an external load and (b) with an external load of 20 kg.

Fig. 6 shows the value of the z coordinate of the momentary position of the body's overall centre of mass, namely its rising and falling in particular phases of walking.

For walking with a load (Fig. 6b) there is a clear lowering of the body's overall centre of mass by approximately 4 cm under the effect of the load placed on the subject in the form of a rucksack weighing approximately 20 kg. In this case the vertical oscillation of the overall centre of mass lies in the range 167–171 cm.

Figs. 7 and 8 show the momentary value of the y coordinate of the ZMP in the frontal plane. As in the case of the GCOM, the ZMP also tends to ''rock'' to the sides, but for ZMP these divergences are decidedly greater. During the double support stage the overall centre of mass is transferred towards the leg which will be the supporting leg in the swing phase. This is particularly visible for a walking speed of 4 km/h. For a speed of 6 km/h (Fig. 7b) the amplitude of the lateral divergences of the ZMP is significantly smaller.

Fig. 9 presents the influence of ground inclination on the ZMP trajectory. As the ground slope increase some peaks of ZMP oscillations, proving a momentary loss of stability, can be observed.

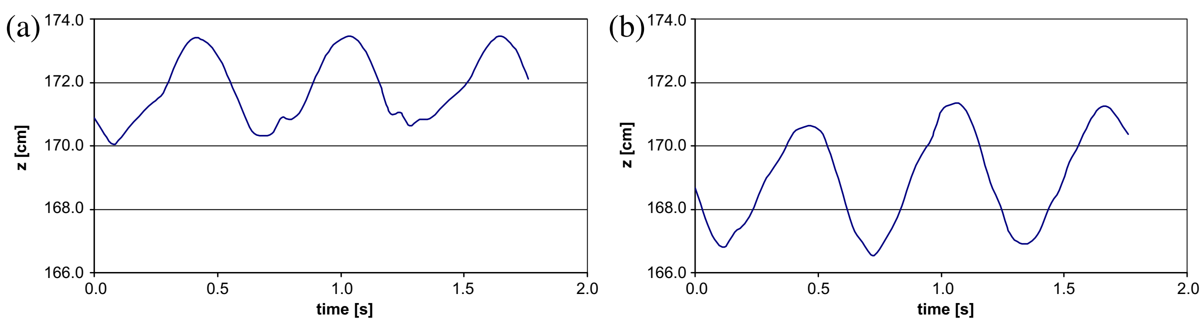

Fig. 6. Vertical position of COM (Centre of Mass) during walking at a velocity of 4 km/h on a horizontal surface (a) without an external load and (b) with an external load of 20 kg.

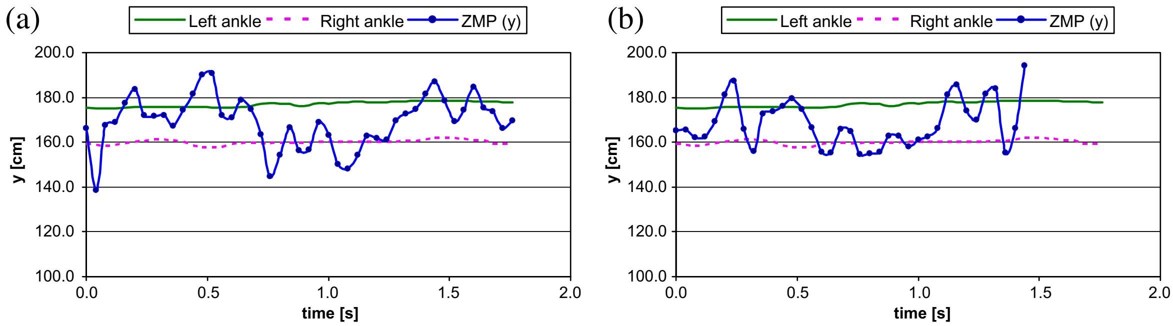

Fig. 7. Deviation of ZMP in the frontal plane (*y* coordinate) (a) velocity of 4 km/h, (b) velocity of 6 km/h.

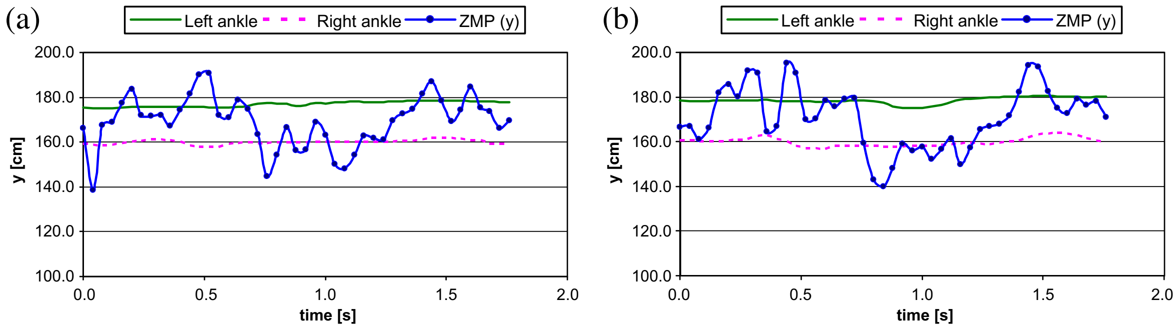

Fig. 8. Deviation of ZMP in the frontal plane (*y* coordinate) during walking at the velocity of 4 km/h (a) without external load and (b) with the external load of 20 kg.

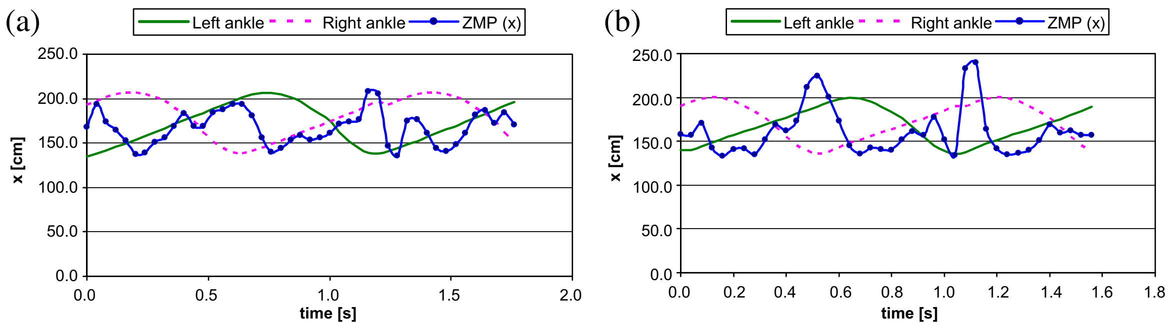

Fig. 9. Changes of ZMP location in the sagittal plane (*x* coordinate) during walking at the velocity of 4 km/h (a) on a horizontal surface (b) on a downhill surface.

4. Conclusions

Based on the experiments carried out, the following conclusions can be formulated:

- Momentary loss of stability in the sagittal plane (the *x* axis), when the overall centre of mass moves forward of the polygon of support, occurs in the swing phase when the back leg becomes the front leg. This instability (measured in terms of the distance of GCOM and ZMP from the edge of the polygon of support) increases as the speed of walking increases. Analysis of the behaviour of the ZMP also showed that as speed increases, the momentary loss of stability occurs somewhat earlier, namely in the final phase of double support.
- As walking speed increased, an increase in length of step was observed. Moreover a decrease was observed in the amplitude of movements of the overall centre of mass in the frontal plane (*y* axis), which indicates an increase in locomotive stability. It should be pointed out that as the speed of walking approaches a speed at which running begins, the characteristic of the GCOM in the frontal plane approaches a straight line. This indicates that walking becomes more stable in that plane as speed increases.

- An increase in external load causes a lowering of the overall centre of mass. It would appear that this is due to a decrease in the radius of physiological curves of the spine and in the height of intervertebral discs. For a load of approximately 20 kg, a significant lowering of the overall centre of mass, by around 4 cm, was recorded.
- As speed increases, the lowering of the overall centre of mass can be noticed only at the boundary between walking and running (6 km/h); in the case of the test subject the lowering amounted to only 1 cm. However the amplitude of movements of the overall centre of mass in the z axis was constant regardless of the style of walking, amounting to approximately 4 cm.
- The ZMP course analysis reveals that in the case of downhill walking at the moment preceding initial contact of the front leg (end of the swing phase) a substantial momentary "backward" loss of stability in the sagittal plane (x axis) takes place. We can find that during the descending movement an increase of ground slope cause a backward displacement of the centre of mass.

Summarizing the above conclusions we can confirm the accuracy of one of the definitions of walking, which states that it is a cyclic process of momentary loss and recovery of stability. Both criteria (GCOM and ZMP) for the sagittal plane showed that there exist such periods in the walking cycle for which the points GCOM and ZMP are outside the polygon of support, which indicates that the walker momentarily loses balance. In the case of the frontal plane such a tendency was observed, including in the double support phase, only in relation to the ZMP criterion, which is evidence of the greater accuracy of that determinant of stability in dynamic conditions. In this case, for each style of movement, the overall centre of mass moves from one side to the other relative to the subject.

In the light of the above conclusions, it would appear to be of interest to investigate how a load which is asymmetric in the frontal plane would affect the size and nature of divergences of the ZMP, for example when a load is placed on one arm.

Because the subject taking part in our tests was a woman, it would be interesting to supplement the results by comparing them with those obtained for tests using a man as subject. Moreover, in order to achieve a full analysis, it would be desirable to investigate how the stability of walking depends on physical parameters of the subject, such as height and weight.

References

[1] Hreljac A. Preferred and energetically optimal gait transition speeds in human locomotion. Med Sci Sports Exercise 1993;25(10):1158–62.
[2] Inman VT, Ralston HJ, Todd F. Human walking. Baltimore/London: Williams & Wilkins; 1981.
[3] Mrozowski J, Awrejcewicz J, Bamberski P. Analysis of stability of the human gait. J Theor Appl Mech 2007;45(1):91–8.
[4] Murray MP, Drought AB, Kory RC. Walking patterns of normal men. J Bone Joint Surgery 1964;46A(2):335–60.
[5] Murray MP. Gait as a total pattern of movement. Am J Phys Med 1967;46(1):290–333.
[6] Perry J. Gait analysis: normal and pathological function. Thorofare, NJ: Slack, Inc.; 1992.
[7] Vukobratović M, Borovac B. Zero-moment point – thirty five years of its life. Int J Humanoid Rob 2004;1(1):157–73.
[8] Winter DA. Biomechanics and motor control of human movement. John Wiley & Sons; 2004.