Gait Pattern Generator for Control of a Lower Limb Exoskeleton

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Abstract

The aim of the study was to propose a relatively simple central pattern generator (CPG) model, which can be used to control a lower limb exoskeleton. The mentioned generator and the simulation model of the human gait were developed based on experimental observations of the healthy volunteer's gait recorded using a motion tracking system. In order to reproduce the correct movements of the exoskeleton segments, time series of angles in the joints corresponding to the hip and knee joints were calculated based on tracing the trajectories generated by the CPG and the inverse kinematic relations. The proposed model can be implemented to control the lower limb (extremity) exoskeleton and assist various types of gait abnormality in patients with different motor dysfunction by means of changing the parameters of the control system. The presented experimental data, the developed gait simulation model, and the results of numerical simulations can be treated as guidelines for further improvement of the proposed model and its application in the exoskeleton control system. Although the study is mainly focused on rehabilitation applications, the proposed model is general and can be used also for other purposes such as control of bipedal and multi-legged robots.

Keywords: human gait, exoskeleton, central pattern generator

1. Introduction

Impaired locomotion is a common phenomenon observed especially in highly developed societies. This applies to both young people and the elderly. Among young people, dysfunctions result mainly from traffic accidents and sports injuries. In turn, older people often have weakened lower limb muscles as well as suffer from osteoarthritis or osteoporosis. Regardless of the reasons, dysfunctions of the locomotion system are serious consequences not only from the medical point of view, but they also affect the social sphere by limiting the mobility and social activity of a large number of people.

It has been shown that rehabilitation of a dysfunctional human locomotion system can be improved by external stimulation of muscular and nervous systems by using the lower limb exoskeleton [1-5]. The design of such a device must meet many requirements regarding mechanical strength, control, stability or kinematic and dynamic biocompatibility with a human lower limb [6-9]. Although several decades have passed since the first lower limb exoskeleton was made, this issue is still the subject of study in many research centers.

In the present work, an attempt was made to develop a simulation model of human gait based on an experimental study of real gait, conducted with a motion capture system. The applied approach is a biologically inspired method of gait generation [10]. In contrast to many methods used in the literature [11-13], this work presents a relatively simple way of controlling the movement of lower limbs by using the concept of a so-called central pattern generator (CPG). The first CPG model was proposed in the 1980s by Cohen et al. who studied the dissection of a lamprey spinal cord [14]. Since then, researchers have been using CPG algorithms to control different biologically inspired walking robots. The outcomes of the study, including experimental data, the developed gait simulation model, and the results of numerical simulations, can be used as guidelines for further improvement of the proposed CPG model and its applications in the exoskeleton control system.

2. Experimental observations

The study was started by observing the gait of a healthy volunteer by using an OptiTrack motion capture system, which has been successfully used, for instance, to track the human movement during the falling process [15]. The linear and angular positions of individual characteristic points and body segments were registered by 3D tracking of 37 passive markers distributed on the volunteer's body according to the OptiTrack Baseline protocol (see Fig. 1).

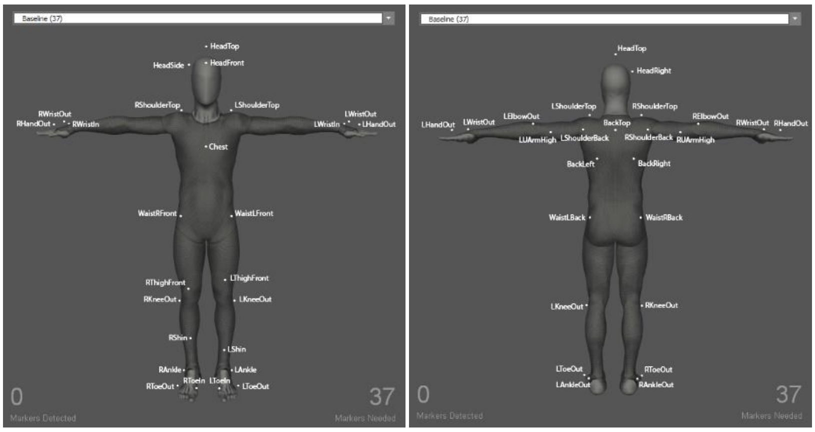

Figure 1. Thirty seven reflective markers distributed on the subject's body

Based on the positions of markers, the system reconstructed the human body segments and visualised their movement during the walking process. Figure 2 shows the configurations of the volunteer’s body at different stages of gait.

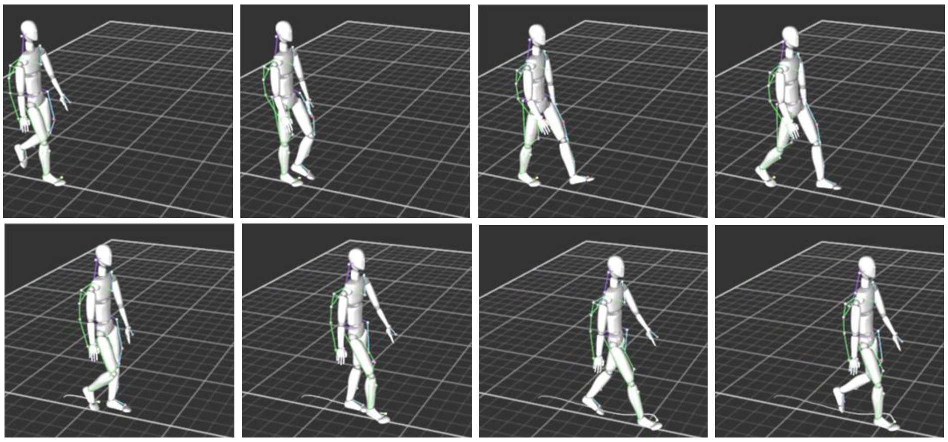

Figure 2. Subject's body at different stages of gait recorded by a motion capture system

3. Kinematics of the human lower extremity

Figure 3 schematically shows the configuration of a single human lower limb. The global coordinate system Oxz is fixed to the ground, whereas the centre of the local coordinate system $O'x'z'$ has the coordinates $O'(x, L)$ with respect to the global coordinate system (the parameter L stands for the distance between the joint $j1$ and the ground in a standing position). Links l_1, l_2, and l_3 connected by rotary joints ($j1$, $j2$, and $j3$) can be considered as a kinematic scheme of a prototype of a lower limb exoskeleton. The segment l_3 can be treated as the basis of the human foot. Therefore, in this model, the pivot point (joint $j3$) was chosen at the point of contact of the human lower limb (heel) with the ground, and not, as usually, in the ankle joint.

Unfortunately, the positions of the markers do not correspond to the exact positions of individual human joints. This mainly applies to the hip joint and it is a certain difficulty in the research being carried out. Therefore, in our investigations, the approximate location of rotary joints (especially hip joints) relative to individual markers has been estimated based on the OptiTrack Baseline protocol and the anatomical structure of the human upper limb.

The function $h(t)$ is a time-varying vertical fluctuation of the hip joint (pivot point of the whole lower limbs). $H(t)$ denotes the fluctuations of the position of the joint $j1$. The definitions of angles $\theta_1(t)$, $\theta_2(t)$, and $\theta_3(t)$ are also given in Fig. 3.

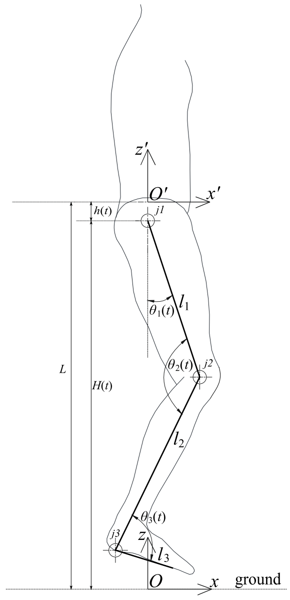

Figure 3. Biomechanical model of the human lower extremity

It should be emphasized that the main task of the lower limb exoskeleton is to stimulate movements in the hip and knee joints, and to a lesser extent in the ankle joints. Therefore, in this paper, we are most interested in obtaining times histories of the angles $\theta_1(t)$ and $\theta_2(t)$ which correspond to the mentioned human hip and knee joints.

Forward kinematics describing the relationship between the coordinates $x'(t)$ and $z'(t)$ of the supporting point of the leg (heel) as a function of angles $\theta_1(t)$ and $\theta_2(t)$ is given as

$$\begin{cases} x'(t) = l_1 \sin\theta_1(t) - l_2 \sin\alpha(t), \\ z'(t) = -h(t) - l_1 \cos\theta_1(t) - l_2 \cos\alpha(t), \end{cases} \tag{1}$$

where $\alpha(t) = \pi - \theta_1(t) - \theta_2(t)$. In turn, inverse kinematics, which gives the dependence of articulated variables $\theta_1(t)$ and $\theta_2(t)$ as a function of Cartesian variables, has the form

$$\begin{cases} \theta_1(t) = \operatorname{atan}\left(\dfrac{-x'(t)}{z'(t)+h(t)}\right) + \operatorname{acos}\left(\dfrac{l_1^2 + [x'(t)]^2 + [z'(t)+h(t)]^2 - l_2^2}{2l_1\sqrt{[x'(t)]^2 + [z'(t)+h(t)]^2}}\right), \\ \theta_2(t) = \operatorname{acos}\left(\dfrac{l_1^2 + l_2^2 - [x'(t)]^2 - [z'(t)+h(t)]^2}{2l_1 l_2}\right). \end{cases} \tag{2}$$

In our model, $h(t)$ has the same values for both the left and the right lower limb (it has been confirmed by experimental observations with a motion capture system). However, the angles in the joints *j*1, *j*2, and *j*3 are not the same for both lower limbs. Namely, the angles $\theta_{1\mathrm{A}}(t)$, $\theta_{2\mathrm{A}}(t)$, $\theta_{3\mathrm{A}}(t)$ correspond to the right limb, whereas the angles $\theta_{1\mathrm{B}}(t)$, $\theta_{2\mathrm{B}}(t)$, $\theta_{3\mathrm{B}}(t)$ correspond to the left limb. The angles $\theta_{3\mathrm{A}}(t)$ and $\theta_{3\mathrm{B}}(t)$, fluctuations $h(t)$ of the right and left lower limb, as well as movements of the upper limbs during gait were estimated on the basis of data obtained from the motion capture system.

4. The proposed CPG model

The approximate representation of the trajectory of the supporting points of both lower limbs, which can be possibly implemented in the exoskeleton control system, was based on the central pattern generator. The proposed CPG model is based on the sine function in the form as presented below

$$X_{\mathrm{A}}(t)=\begin{cases}-\dfrac{1}{\pi}\,\mathrm{modulo}(\omega t,\pi) & \text{for}\quad 0<\mathrm{modulo}(\omega t,2\pi)\le\dfrac{\pi}{2},\\ -\dfrac{1}{2}+\dfrac{1}{\pi}\,\mathrm{modulo}\left(\omega t-\dfrac{\pi}{2},\pi\right) & \text{for}\quad \dfrac{\pi}{2}<\mathrm{modulo}(\omega t,2\pi)\le\dfrac{3}{2}\pi,\\ \dfrac{1}{2}-\dfrac{1}{\pi}\,\mathrm{modulo}\left(\omega t-\dfrac{3}{2}\pi,\pi\right) & \text{for}\quad \dfrac{3}{2}\pi<\mathrm{modulo}(\omega t,2\pi)\le 2\pi,\end{cases}\tag{3}$$

$$Z_{\mathrm{A}}(t)=\sin\left(\omega t-\frac{\pi}{2}\right)\cdot J\left(-\sin\left(\omega t+\frac{\pi}{2}\right)\right),\tag{4}$$

$$X_{\mathrm{B}}(t)=-X_{\mathrm{A}}(t),\tag{5}$$

$$Z_{\mathrm{B}}(t)=\sin\left(\omega t+\frac{\pi}{2}\right)\cdot J\left(-\sin\left(\omega t-\frac{\pi}{2}\right)\right),\tag{6}$$

where $J\left(-\sin\left(\omega t-\frac{\pi}{2}\right)\right)$ and $J\left(-\sin\left(\omega t+\frac{\pi}{2}\right)\right)$ are classical unit step functions:

$$J\left(-\sin\left(\omega t-\frac{\pi}{2}\right)\right)=\begin{cases}1 & \text{if}\quad -\sin\left(\omega t-\dfrac{\pi}{2}\right)>0,\\ 0 & \text{if}\quad -\sin\left(\omega t-\dfrac{\pi}{2}\right)\le 0,\end{cases}\tag{7}$$

$$J\left(-\sin\left(\omega t+\frac{\pi}{2}\right)\right)=\begin{cases}1 & \text{if} \quad -\sin\left(\omega t+\frac{\pi}{2}\right)>0,\\ 0 & \text{if} \quad -\sin\left(\omega t+\frac{\pi}{2}\right)\leq 0.\end{cases} \tag{8}$$

$X_{\mathrm{A}}(t)$, $X_{\mathrm{B}}(t)$, $Z_{\mathrm{A}}(t)$, and $Z_{\mathrm{B}}(t)$ are non-dimensional variables of the proposed CPG model. Variables $X_{\mathrm{A}}(t)$, $X_{\mathrm{B}}(t)$ are responsible for control of the leg's mechanism the in *x*-direction, whereas variables $Z_{\mathrm{A}}(t)$ and $Z_{\mathrm{B}}(t)$ control the leg's mechanism in the *z*-direction. The subscript A corresponds to the right leg, while the subscript B corresponds to the left leg.

The periodic orbits of the presented CPG model are shown in Fig. 4. The orbit presented on the left part of the Fig. 4 corresponds to the right leg, while the orbit shown on the right corresponds to the left leg. As can be seen from the formulas (3) – (6), the periodic orbit in the space of variables $X_{\mathrm{A}}(t)-Z_{\mathrm{A}}(t)$ is in antiphase with respect to the orbit in the space of variables $X_{\mathrm{B}}(t)-Z_{\mathrm{B}}(t)$ (the phase shift equals π). Therefore, both periodic orbits shown in Fig. 4 are the same.

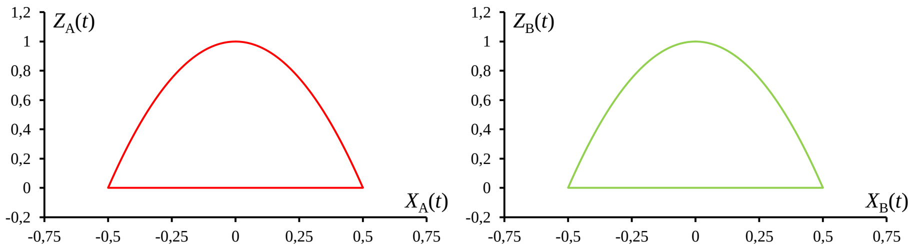

Figure 4. Phase trajectories of the proposed CPG to control the exoskeleton system

The variables of the proposed CPG model cannot be directly used to control an exoskeleton. However, by changing the frequency, as well as the appropriate scaling of the presented orbits and their conversion into the workspace of the exoskeleton mechanism, it is possible to precisely control the parameters of a single stride. The variables of the CPG model can be converted to the workspace of the exoskeleton mechanism (in local coordinate system $O'x'z'$) in the following way

$$x'_{\mathrm{A}}(t)=l_{stride}X_{\mathrm{A}}(t), \tag{9}$$

$$z'_{\mathrm{A}}(t)=h_{stride}Z_{\mathrm{A}}(t)-L, \tag{10}$$

$$x'_{\mathrm{B}}(t)=l_{stride}X_{\mathrm{B}}(t), \tag{11}$$

$$z'_{\mathrm{B}}(t)=h_{stride}Z_{\mathrm{B}}(t)-L, \tag{12}$$

where l_{stride} and h_{stride} are the length and height of the single stride, respectively. A similar approach has been presented and used on the example of a hexapod robot walking with tripod gait in [16].

5. Numerical Simulations

The gait simulation model was developed in the Scilab environment. Values of the parameters l_{stride} and h_{stride} were estimated based on the experimental observation with the capture motion system ($l_{stride} = 0.6$ m and $h_{stride} = 0.1$ m). Phase trajectories of the joint *j*3 (both for the left and the right leg) in the local coordinate system $O'x'z'$ are presented in Fig. 5.

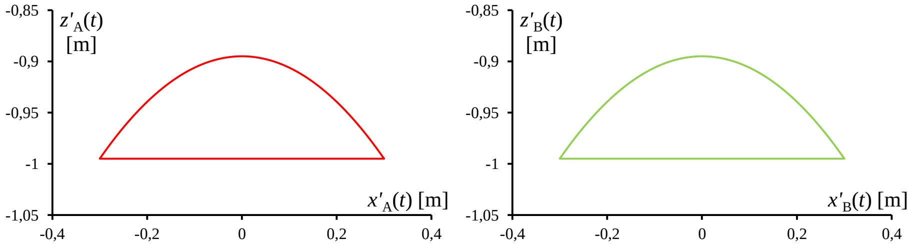

Figure 5. Phase trajectories of the joint *j*3 in the local coordinate system $O'x'z'$

Figure 6 shows exemplary configurations of the human body at different stages of one complete gait cycle. They were captured at regular time intervals for the human gait model controlled using the proposed CPG model. As can be seen, the presented numerical simulations reflect the configurations of the human body during normal gait (see Fig. 2) satisfactorily.

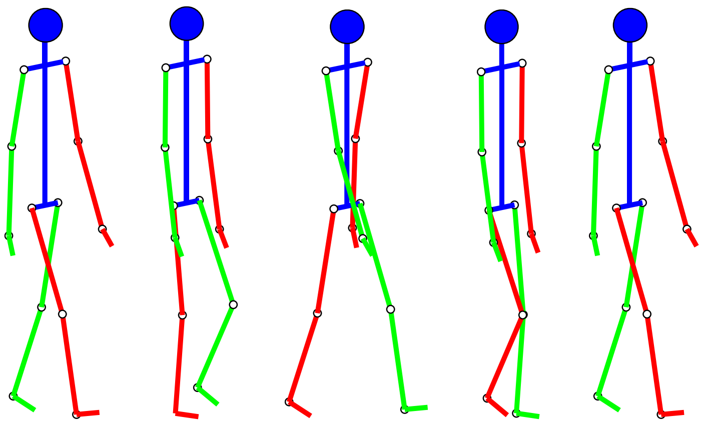

Figure 6. Snapshots of a walking human, plotted in Scilab at regular time intervals

Figure 7 presents a comparison of experimental results obtained by the motion capture system with the results of numerical simulations with the use of the proposed CPG model. For the comparison, fluctuations of the joint $j1$ (which are the same for both legs) in both the direction of movement and the vertical direction (in the global coordinate system) were selected. Apparently, it was impossible to obtain a close match between the simulation and experimental results in the entire range of the registered experimental data. This is primarily due to the non-repeatability of human movements, as opposed to the simulation model. Nevertheless, it can be seen that both the experimental and simulation results are characterized by similar time courses. Namely, the position $x(t)$ of the joint $j1$ changes linearly (constant walking speed) in the direction of movement, while the fluctuations $H(t)$ of the position of the joint $j1$ are periodical with a small amplitude (about 0.04 m), depending on the gait phase.

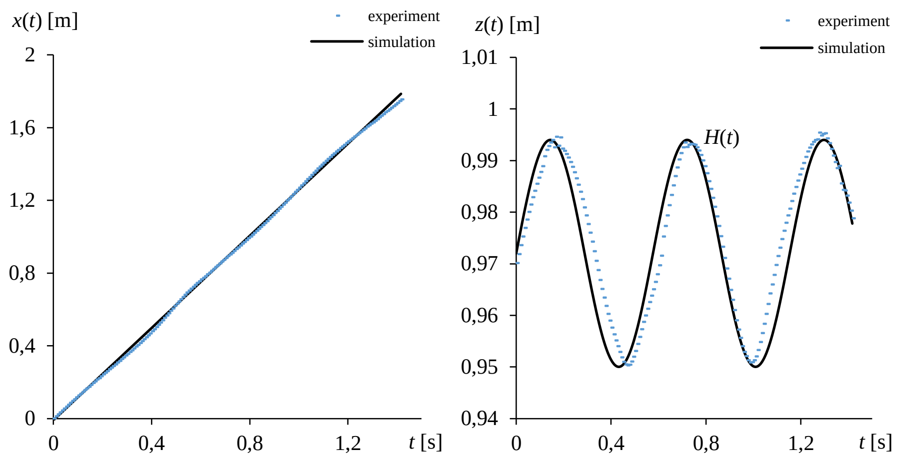

Figure 7. Experimental vs. numerical fluctuations of position of the joint $j1$ in the forward direction (left) and the vertical direction (right)

6. Conclusions

In the paper, a simulation model of human gait has been developed based on experimental observations conducted with the motion capture system. A relatively simple gait model using a central pattern generator has been proposed, which can be potentially used to control the lower limb exoskeleton. The paper contains some information useful for control of a lower limb exoskeleton, with respect to their dynamic balance and the behavior of the system. The experimental data, the developed gait simulation model, and the results of numerical simulations can be treated as guidelines for further improvement of the proposed CPG model and its application in the exoskeleton control system. Last but not least, it should be noted that although preliminary research was mainly focused on rehabilitation applications, due to the general nature of the study, it is possible to use it also for other purposes such as in control systems for specialized bipedal robots and others.

It should be noted that new tools will be developed in the future to encompass all the needs of the final project of a human lower limb exoskeleton.

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