

The control algorithm of the lower limb exoskeleton synchronous gait

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Abstract. In this article a study of algorithms for human movement in the lower limbs exoskeleton is presented. Human-machine system is considered, the classification of the existing exoskeletons by type of power distribution, the features of stable motion of the mechanism are presented. The law of the necessary trajectory of the center of mass of the exoskeleton is shown in the sagittal and frontal planes to maintain stability. The synchronous motion scheme of the centre of mass and the foot is described.

1 Introduction

A human’s gait in the exoskeleton is one of the most difficult locomotion. That’s why it is a very significant problem. There are a great amount of papers concerning bipedal gait [2, 3, 6, 7, 12-16, 22]. However, in the majority of cases the gait is considered in a single sagittal plane, thus limiting the application sphere of the results obtained for exoskeleton applications. The thing is that the locomotion in the exoskeleton is similar to the quasi-static gait. That’s why the locomotion modeling should be considered in respect to the spatial kinematics, since the motion takes place both in the sagittal and frontal planes. This approach to the locomotion modeling appears only in some papers [1, 3, 7, 13, 15, 18, 21].

The locomotion research in the paper is done with relation to the quasi-static locomotion modeling with the help of kinematics approaches, while the inverse kinematics problem is solved by approximation methods. The obtained results, concerning the determination of the rotation angles of the exoskeleton links for different positions of the foot taking into account the position of the center-of-mass projections are used for the development of the control algorithms of a person’s locomotion in the exoskeleton. The special attention is focused on experimental researches, which were carried out on the prototype of the exoskeleton.

One of the most important moments, that requires the adequate mathematical description is the locomotion of a person in the skeleton on uneven surface. The creation of the locomotion control algorithm, taking into account the recognition of a surface irregularities, and the formulation of the conditions for the gate on the basis of “intellectual foot”, opens completely new possibilities for the creation of the lower-limb exoskeletons, which provide a confident, steady locomotion of a person across rough terrain. So that, this monograph is first of all devoted to the problems, concerning the modeling of a person’s locomotion in the

exoskeleton, taking into account the interaction of the feet with the supporting surface. Besides, much attention is paid to the energy distribution in the human-exoskeleton system. An energy criterion is offered, it allows the estimation of the power inputs from the actuators, taking into consideration the human muscles work.

2 Exoskeleton classification

A person in the exoskeleton can be described a human-machine system. The cooperation of this system elements is many-sided. Different criterion can be used for quantities analysis of the interference of a human and an exoskeleton. Let’s consider in detail only one of them, that allows the estimation of the power inputs level from both the person and the machine, while doing one of the exercises, for instance at verticalisation, walking and so on.

Figure 1 shows the classification of exoskeletons by the criterion of power inputs in the human-machine system. Let’s choose three different classes of exoskeleton systems.

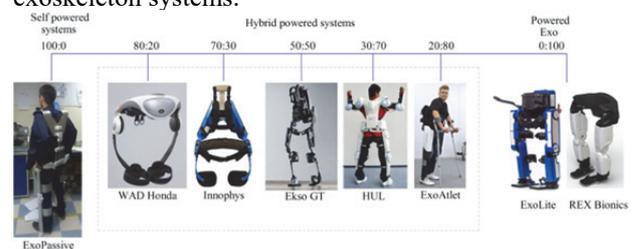


Fig. 1. The classification of exoskeletons by energy distribution.

The first class is self-powered systems (SPS), the second is hybrid systems, driven by both a human and the exoskeleton drives (hybrid powered systems (HP)), and the third is the systems set in movement only by exoskeleton drives, the so-called Powered Exoskeleton (PE).

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As noted earlier many researches are devoted to the bipedal gait analysis, and the results were published in many papers [5, 7, 8, 20-22]. Both theoretical and experimental methods for locomotion study were developed. The kinematic and dynamic aspects of the movement are thoroughly considered. Basically, these papers describe the motion of bipedal robots in the sagittal plane. This approach is valid only for a fairly fast walk, in which the inertia forces become significant.

At the same time, a human gait in the exoskeleton, especially at the very beginning, is extremely slow and has been studied insufficiently. This is due to the fact that such a movement should occur both in the sagittal and frontal planes. The kinematics of such a motion is quite complicated, so the mathematical modeling of the spatial motion of two-legged robots is presented only in several works due to considerable difficulties [1-8, 21]. The mathematical description of the slow (quasi-static) gait of a human in an exoskeleton, according to our analysis, is not present anywhere.

Besides, special attention should be paid to the formulating of conditions that ensure a stable vertical position of the patient during movement, and this becomes possible if the patterns of movement of the feet and the center of mass of the exoskeleton with the patient are studying.

3 The gait description

For mathematical modeling of a person's gait in an exoskeleton, it is necessary, on the one hand, to analyze and establish kinematic connections between the movement of exoskeleton links during walking, and on the other, to study the nature of the motion of the center of mass and to investigate the interaction of the feet of the exoskeleton with the supporting surface.

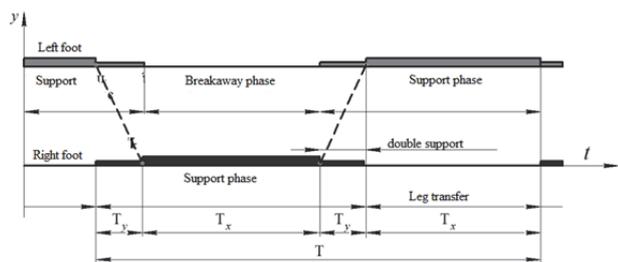


Fig. 2. The scheme of the interaction of the feet with the supporting surface in instants of time.

Let us consider the scheme of the interaction of the feet with the supporting surface at different instants of time, for this we use the diagram shown in Figure 2, such a diagram in the biomedical literature is called apodogram [20, 21]. A thin line indicates the the absence of the contact mode of one or another foot with a support. A wide line indicates the mode when the foot contacts the support. From the podogram you can see that the locomotor cycle (step) consists of two two-support and two single-support phases.

The two-support phase is the period of step T_y , during which both legs are in contact with the supporting surface and the center of mass is transferred from one

foot to the other and a single-support phase is the period of step T_x , during which the transfer is carried out, starts from the moment of detachment of the foot from the support surface and finishes at the moment when the same foot contacts the support surface, at the same time the center of mass is transported along the supporting foot. The time of step T determines the rhythm of walking and is determined by the formula:

$$T = 2T_x + 2T_y \quad (1)$$

We will assume that walking begins with a two-support phase, when the feet are located symmetrically with respect to the longitudinal axis. Figure 3 shows the scheme for the exoskeleton feet moving along the longitudinal axis Ox along the support surface.

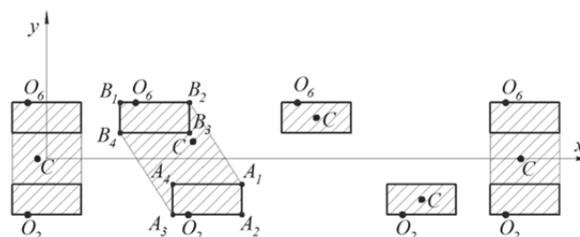


Fig. 3. The scheme for the exoskeleton feet moving along the longitudinal axis Ox along the support surface.

Here we use following annotation: $A_1A_2A_3A_4$ are the boundaries of the right foot, $B_1B_2B_3B_4$ are the boundaries of the left foot, O_2, O_6 are the ankle joints, C is the projection of the center of mass on the reference plane. In the two-support phase, the dimensions of the supporting surface are determined by the points $A_1A_2A_3B_2B_3B_4$, and in the single-support phase by the dimensions of the foot.

To visualize the position of the exoskeleton at different instants of time, we can consider both the spatial image of the exoskeleton in the 3D model format, and the projection of the exoskeleton on the frontal and sagittal planes, the so-called 2D models. Figures 4 and 5 show flat images of the exoskeleton for the movements sequence in the frontal and sagittal planes.

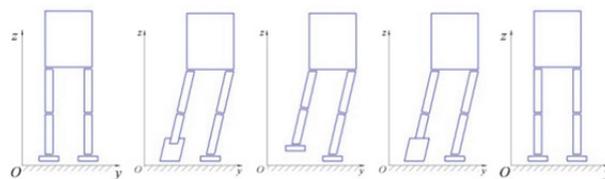


Fig. 4. The scheme of the exoskeleton weight transfer in the frontal plane.

The distinctive feature of such a gait is that the movement begins in the frontal plane and the weight is transferred to the left foot by the work of the ankle and hip joint drives.

After the center of mass is transferred to the left leg, a one-support phase begins, at which the transfer of the right foot is carried out through the movement of the links of both the right and left legs. This phase is completed after the right foot contacts the support surface. After this,

two-support phase begins, at which the center of mass is transferred to the right foot. Then all the movements are repeated. The left foot is moved forward by the length of the step, the center of mass moves along the right foot and at the moment of the left foot contacts the support surface is transferred to the left foot.

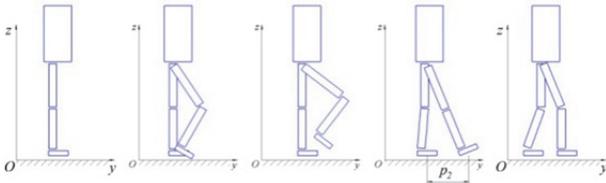


Fig. 5. The scheme of the transfer of the exoskeleton weight in the sagittal plane.

This step corresponds to the so-called "quasi-static gait". The name suggests that the exoskeleton is statically stable in every intermediate position of the mechanism.

In order to formulate conditions that ensure a stable gait, we choose three points of the exoskeleton. These points include the center of mass of the exoskeleton "C" (CME) and the "Ai" points of the feet, where $i = 2$ for the right foot and $i = 6$ for the left foot.

Let's introduce the parameters that determine the gait and define the motion of the foot: L is the length of the step, determined by the distance between the point of one foot at the previous and following steps; y_m is the maximum deviation of the point "A" of the foot from the longitudinal axis of symmetry, T is the execution time of one step, H is the maximum height of the lift of the foot. The position of the points "Ai", at any time is determined by parametric equations:

$$\begin{cases} z_{Ai} = z_{Ai}(t) \\ x_{Ai} = x_{Ai}(t) \\ y_{Ai} = y_{Ai}(t) \end{cases} \quad (2)$$

The position of the center of mass projections (point "C") in a fixed coordinate system is given by the corresponding equations:

$$\begin{cases} z_C = z_C(t) \\ x_C = x_C(t) \\ y_C = y_C(t) \end{cases} \quad (3)$$

These equations contain parameters that determine the nature of the motion of the exoskeleton, including: L_C - distance passed by the center of mass at one step, x_{C0}, y_{C0}, z_{C0} - the initial location of the center of mass.

We will consider the motion along the supporting plane Oxy of the projections of the points "C" and "Ai". It is obvious that a stable vertical position can be ensured if the condition are fulfilled: the CME must move along a certain trajectory both along the supporting foot and when moving from one foot to the other, and the transferred foot must be adjusted to this movement and synchronously move to the point determined by the movement center of mass.

Now suppose that the exoskeleton moves along straightly along the Ox axis (the plane Oxz is the plane of symmetry of the exoskeleton in the initial position), and the trajectories of the points "Ai" are in the plane parallel to the plane Oxz and, respectively, perpendicular to the support plane, which is horizontal. This means that $y_A = \text{const}$. Then, taking into account the symmetric character of the feet motion of the relatively to the axis Ox, we obtain

$$y_A = \pm y_m \cdot$$

The "+" sign corresponds to the left foot, and "-" to the right, respectively.

Fig. 6 shows the various phases of carrying the weight of a person (CME) while walking, and the trajectory along which the center of mass moves through the foot in a single-support phase is clearly visible. There are four characteristic points K_1, K_2, K_3, K_4 (for the right and N_1, N_2, N_3, N_4 for the left), which determine the position of the projection of the point C at different instants of time.

The projection of the center of mass on the supporting surface coincides with the point of application of the vector of the reduced reaction of the support. The graphs shown in Figure 6 represent the movement of this point from the external part of the heel along the outer edge of the foot in the medial direction to the toes of the foot. The movement trajectory varies according to the pace and type of walking, the support surface relief, the type of footwear, namely the heel height and the rigidity of the exoskeleton foot. The pattern of support reaction is largely determined by the functional state of the muscles of the lower limb and the innervation structure of the walk [1, 2, 21].

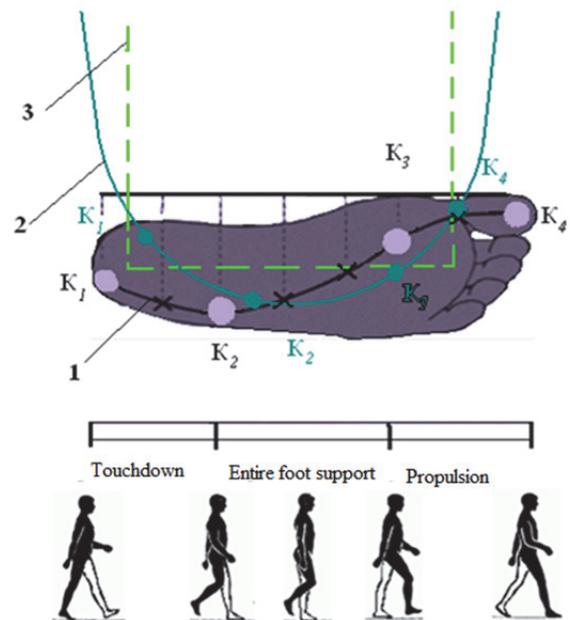


Fig. 6. The movement trajectory of the point "C" through the foot during walking: 1-fast walking, 2-slow walking, 3-mathematical model of the trajectory.

So the diagram 1 corresponds to the fast (dynamic) walking, the diagram 2 describes the displacement of the

center of mass during the slow (quasistatic) walking. The diagram 3 shows some mathematical interpretation of the experimental dependences.

The movement of the point C throughout the foot is connected with a single-support walking phase, when the weight is transferred to this foot, and the second foot performs a predetermined displacement with a detachment from the surface. It is obvious that the exoskeleton in the single-support phase has a much smaller stability margin, because in this case the support area is several times smaller than in the two-support phase.

As can be seen from Figure 6, the real trajectory of the point C movement throughout the foot has a complicated shape and depends on many factors. Therefore, further let's consider the conditions of stable walking for a number of simplified models of the trajectory, the motion of the point C both between the stop and throughout the supporting foot.

4 The stable quasistatic walking condition

To ensure a stable gait, it is necessary to synchronize the motion of points A and C along the axis Ox, that is, the position of the feet Ai must be determined by a certain equation:

$$x_{Ai} = x_{Ai}(x_C)$$

The form of this equation depends on a number of factors. In a simplified version, for the sagittal plane, we can limit ourselves to a linear model, then it is necessary to fulfill the condition at each instant of time:

$$x_{Ai} = \lambda x_C + x_{C0}, \quad v_{Ai} = \lambda v_{Cx} \quad \text{or} \quad \dot{x}_{Ai} = \lambda \dot{x}_C$$

where v_{Ai}, v_{Cx} - the projections of the velocities of the points "Ai" and "C" on the Ox axis, is the coefficient that determines the movement synchronism of the points "Ai" and "C". This parameter depends on the height of the center of mass relative to the support surface. For the frontal plane, the synchronization condition looks similar.

Figure 7 shows the motion scheme of the center of mass and foot along the support plane in synchronous mode. The projection of the center of mass on the support plane Oxy moves with velocity V_C along the trajectory $O-N_1N_2N_3N_4K_1K_2K_3-K_4$, ensuring the transfer of the exoskeleton weight from one foot to the other. On the segment ON_1 , the so-called two-support phase is realized, at which the feet are on the supporting surface and remain fixed, and the center of mass moves due to the movement of the exoskeleton links. On the segment $N_1N_2N_3N_4$, a single-support phase is realized, the weight of the exoskeleton is moved to the left foot and at this moment the right foot, with the point A, can move with the velocity V_A simultaneously with the displacement of the point C, performing the synchronization condition of the motions.

Further, the exoskeleton passes into a two-support phase, that is, the right foot places at the support surface and the point C moves first along the segment of the trajectory N_4K_1 , then the weight moves to the right foot,

and then the point C moves along the trajectory $K_1K_2K_3K_4$, ensuring weight transfer along the foot - this is already the single-support phase.

When the synchronization condition is fulfilled, the foot essentially follows the position of the exoskeleton center of mass, which provides stability to the quasi-static gait.

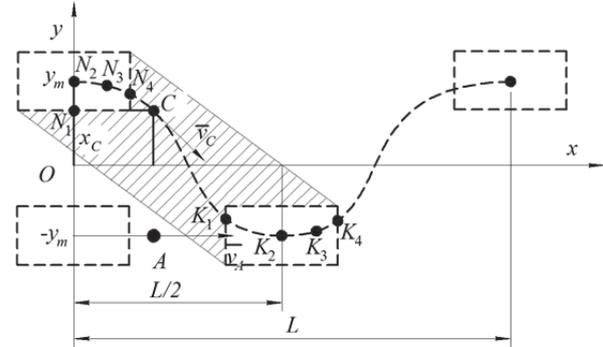


Fig.7 The synchronous motion scheme of the centre of mass and the foot.

Here a_i, b_i and c_i are the coefficients, determined by the limiting conditions. The feet motion can be expressed by the following equations:

$$z_{6,2} = 4 \frac{H}{L} \cdot V \cdot t - 4 \cdot \frac{H}{L^2} \cdot V^2 \cdot t^2 \tag{4}$$

$$y_{6,2} = V \cdot t$$

$$V = \frac{L}{T_y} \tag{5}$$

$$P = \frac{y_6 + y_2}{2} \tag{6}$$

$$y_m = y_{6,2} - \Delta y \tag{7}$$

$$y_C = P + \frac{P - y_m}{T_y} \cdot t$$

$$z_C = z_{c0}$$

$$z_{c0} = \begin{cases} H & l_2 + l_3 < l_2^0 + l_3^0 \\ H - \Delta H & l_2 + l_3 \geq l_2^0 + l_3^0 \end{cases} \tag{8}$$

The formulas that describe the motion of the points A_i and C along to corresponding plane trajectories can be represented in the form:

$$\begin{cases} y_A = \pm y_m \\ x_A = \sum_{i=0}^3 a_i \cdot t^i \\ x_C = \sum_{i=0}^3 c_i \cdot t^i \\ y_C = \sum_{i=0}^3 b_i \cdot t^i \end{cases} \tag{8}$$

The formulas (9) obtained allow us to take into account the beginning of the motion and the approach of the point A_i of the foot and point C to the end point of the trajectory with zero speed. This allows to minimize the acceleration that occurs when the point C moves unevenly along the trajectory.

5 Conclusions

As a result of the analysis of the quasi-static gait of a person in the exoskeleton, three characteristic points determining the walking of the exoskeleton are chosen: this is the center of mass C and the points A_i of the feet. It is shown that to ensure stable walking it is necessary to move point A synchronously with the projection of the center of mass on the longitudinal axis. It is established that for the trajectories under consideration, when the exoskeleton moves along a straight line, the velocity of the foot along the longitudinal axis must be much higher than the velocity of the center of mass. Various mathematical models of the trajectory of the center of mass motion are proposed, and a kinematic analysis of the motion of the center of mass and the points of the feet on the horizontal plane is performed.

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