Simulation of the motion of agricultural worker in a passive exoskeleton with two types spring elements when performing work with higher physical loads

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Abstract. A 2-D model of the protective passive exoskeleton with torsion and tension-compression springs is proposed. The exoskeleton links are of variable lengths. The link consists of a weightless variable-length section with a tension-compression spring in its centre, and the two weighty sections of the constant lengths at the ends of the link. A torsion spring is installed in each hinge that ensures relative rotation of the links. The results of the numerical solution of the Cauchy problem are presented when an agricultural worker moves in a passive exoskeleton with spring elements of two types and when he performs agricultural work associated with increased physical loads.

1. Introduction

The development of safe and comfortable working conditions for agricultural workers using innovative passive exoskeletons that implement a human-machine system will increase the efficiency of agricultural work and reduce the migration of residents from villages to cities. The passive exoskeleton has not only an important production value, allowing the increase in the strength and endurance of the worker to increase productivity, but also socio-medical, allowing to reduce occupational diseases and injuries. Consequently, the use of passive exoskeletons is possible not only in the army, for example, in Russia, the Ministry of Defence developed «Boyets-21» [1], the «Rosteс» state corporation developed «Ratnik» exoskeleton [2]; industry [3-4], rehabilitation and gerontological centers of Russia [5-11], as evidenced by a large number of scientific articles, but also in the work of agricultural workers [12-14].

It should be noted that the existing models of exoskeletons are simplified robotic devices. Therefore, mathematical modelling of the mechanics of motion and interaction of human-machine systems is an important task that has a large number of practical applications in agriculture, which makes the research topic relevant. The importance of the proposed model of a passive exoskeleton lies in the creation of a new class of agricultural robotic technical devices of anthropoid structure, allowing to increase the physical capabilities of the worker: strength and endurance due to the external power
frame. Thus, the creation of passive exoskeletons with spring elements of two types in the form of mechatronic man-machine systems will improve the socio-economic state of the Russian Federation.

The commercialization of these models is hindered by their power consumption and the lack of power sources that can provide sufficient operating time for these exoskeletons. This research is the continuation of the papers [15-18], however the model presented in this paper has been developed for designing exoskeletons. The new models of variable-length exoskeleton link have been also proposed. The proposed models better recuperate energy and thus partially implement the exoskeleton activity.

2. Materials and methods
The passive exoskeleton with spring elements consists of variable-length links (figure 1) joined by cylindrical hinges. The variable-length link consists of a weightless spring and two absolutely rigid parts of lengths $l_{ij} (i = 1,2,\ldots,5; j = 1,2)$. The rigid parts can perform relative motion along the line passing through the beginning and the end of the link. The variability of the link length is implemented through relative motion of the weighty parts along the link on the section $BC_i = \xi_i(t), (i = 1,2,\ldots,5)$. In the double indices of the weighty parts, the first index $i$ corresponds to the link number, while the second one $j$ – corresponds to the number of the weighty part on the link. The torsion springs are installed in the joints-hinges to accumulate the energy of the human musculoskeletal system for further use. The feet are considered weightless, absolutely rigid, connected to the links simulating the shins. The feet ensure the required connection with the surface for motion without slippage. The hinges feature bearings that ensure relative rotation of exoskeleton links with minimal resistance, which is considered in this research equal to zero.

![Figure 1. 2-D model of passive exoskeleton with spring elements.](image)

The state of the mechanism is clearly defined by the angles between the links $\varphi_i(t)$ and the variable lengths of the link sections $\xi_i(t), (i = 1,2,\ldots,5)$. Therefore the exoskeleton model has ten degrees of
freedom. The masses of the weighty absolutely rigid link sections $A_iB_i$ are equal to $m_{1i}$, the moments of inertia relative to the axes passing through its mass centres perpendicular to the motion plane are $I_{1i}$. The masses of the sections $C_iA_{1i}$ are equal to $m_{2i}$, their moments of inertia relative to the axes passing through their ends perpendicular to the motion plan are $I_{2i}$. The moment of inertia of the entire link is not a constant since the weighty parts of the link change their relative position when the length of the weightless link section is changed. The proposed model features links of variable inertia properties. The density of material from which the $j$-th section of the $i$-th link is made is equal to $\rho_{ij}(T_{ij}=\rho_{i})$. The kinetic energy of the links is the sum of the kinetic energies of the weighty link sections $A_iB_i$ and $C_iA_{1i}$, which perform complex movement: rotational movement around the fixed pole situated at the attachment point to the neighboring link, and translational movement along the link. Unlike to the papers [15-18], the angles between the links are calculated counterclockwise from the link with the smaller number to the link with the greater number. This way of angle calculation is related to the fact that the twisting angles of the torsion springs are defined by the relative angular rotation of the links.

Below are the theoretically calculated characteristics of the protective passive exoskeleton in statics for an adult with body mass 70 kg. The rigidness of the coil springs installed in the cylindrical hinges starts from 2000 N/m. The rigidness of the tension-compression springs installed in the links starts from 1000 N/m. The rigidness of the coil springs and torsion-compression springs decreases from maximal in the hinge simulating the ankle joint and the shin of the supporting leg, to minimal in the hip joint and in the link simulating the body. Owing to the energy recuperation and load balancing, the passive exoskeleton makes it possible not only protecting the person from external dangerous effects.

3. The Problem Formulation
To solve the simulation problem of human motion in a protective passive exoskeleton with spring elements of two types, the following should be done:

- Build the system of differential equations of motion for the model presented on the figure 1;
- Transform the torques which are given for a human model in the papers [15-18] with the angles calculated from the horizontal into the torques for the proposed model with the angles calculated between the links;
- Solve the Cauchy problem numerically for the derived system of differential equations of motion taking into account the exoskeleton mass and the given control based on the empirical information;
- Conduct the comparative analysis of the link kinematics obtained by the solution of the system of differential equations of motion with original empirical data about the human links motions [15-18];
- For a visual estimation of the obtained motion of the human-machine robotic system as a person in exoskeleton, synthesize the animated visualization of the motion for the developed model based on the numerical solution of the Cauchy problem.

4. Results
Using the Local Systems of Coordinates for Building the System of Differential Equations of Motion for a Protective Passive Exoskeleton Model with Spring Elements.

The local systems of coordinates are more appropriate for building differential equations of motion when angles are calculated between the exoskeleton links. In the case-study [13], an algorithm of composing the system of differential equations of motion for multi-link mechanisms applicable to robots has been developed. The algorithm uses the major local coordinate systems. Let’s apply it to the considered 2-D exoskeleton model with variable-length links of complex design (figure 1). The differential equations in vector-matrix form (1) that describe the mechanism motion are the results of
the applied algorithm. The matrix subscripts designate the corresponding generalized coordinate: \( \kappa = 1,2 \), here 1 corresponds to the generalized coordinate \( \varphi \), 2 – corresponds to the generalized coordinate \( \xi \).

\[
A_\kappa (\varphi, \xi) \ddot{\varphi} + A_\xi (\varphi, \xi) \ddot{\xi} + D_\varphi (\varphi, \xi) \dot{\varphi} + 2H_\kappa (\varphi, \xi) \dot{\xi} + gP_\kappa (\varphi) = M_\kappa (\varphi, \xi),
\]

(1)

Here: \( \varphi = (\varphi_1, \ldots, \varphi_n)^T \) – the vector of angular generalized coordinates; \( \xi = (\xi_1, \ldots, \xi_n)^T \) – the vector of generalized coordinates describing the lengths change of the links; \( \dot{\varphi} \) – the vector of angular velocities; \( \ddot{\varphi} \) – the vector of angular accelerations; \( \Phi = \text{diag}(\varphi_1, \ldots, \varphi_n) \) – the diagonal matrix; \( A_\kappa, D_\kappa \) – the matrices taking into account the inertia properties; \( P_\kappa \) – the matrices defined by the moments of the gravity forces; \( H_\kappa, A_\kappa \) – the matrices taking into account the variation of the link lengths; \( M_\kappa \) – the vectors of generalized forces. The matrices for the model with five mobile variable-length links are very cumbersome. Therefore they are not listed here.

5. Discussion

Numerical Simulation of Dynamics of the Protective Passive Exoskeleton with Spring Elements.

To simulate the controlled movement of the passive exoskeleton on a person, we will use the controlling torques which were empirically determined for a human [15-18]. These torques were previously utilized to control the motion of exoskeleton models with various designs of variable-length links [15-18]. In contrast to other researches, the variable-length link design in the considered model has been changed. Additional springs, which are energy recuperators, have been added to the hinges and links (figure 1). Below are the values of the parameters used in the calculations. The initial lengths of the non-deformed links are as follows: \( l_i^0 = l_i^1 = 0.385 \, \text{m}, \quad l_2^0 = l_2^1 = 0.477 \, \text{m}, \quad l_3^0 = 0.771 \, \text{m} \). These lengths are distributed on the link as follows: \( l_{11} = l_{14} = 0.15 \, \text{m}, \quad \xi_3^0 = \xi_4^0 = 0.085 \, \text{m}, \quad l_{21} = l_{31} = 0.2 \, \text{m}, \quad \xi_2^0 = \xi_3^0 = 0.077 \, \text{m}, \quad l_{51} = 0.3 \, \text{m}, \quad \xi_5^0 = 0.171 \, \text{m}, \quad l_{11} = l_{12}, (i = 1, 2, \ldots, 5) \). It is assumed, that the exoskeleton link mass accounts for 50% of the corresponding link of the human musculoskeletal system. Therefore the human link masses \( m_1 = m_4 = 2.91 \, \text{kg}, \quad m_2 = m_3 = 8.93 \, \text{kg}, \quad m_5 = 28.93 \, \text{kg} \) are multiplied by 1.5 and distributed equally between the two weighty absolutely rigid link sections, i.e. \( m_{11} = m_{12} = m_i / 2 \) (i = 1, 2, ..., 5). The moments of inertia of the weighty link sections for the rods relative to the axis passing through the bottom point of the weighty link part are as follows: \( I_{11} = I_{14} = 0.011 \, \text{kg} \cdot \text{m}^2, \quad I_{21} = I_{31} = 0.060 \, \text{kg} \cdot \text{m}^2, \quad I_{51} = 0.434 \, \text{kg} \cdot \text{m}^2, \quad I_{11} = I_{12}, (i = 1, 2, \ldots, 5) \). They were multiplied by 1.5. In such a way, the inertial properties of the human-machine system were approximated. The acceleration due to gravity is \( g = 9.81 \, \text{m/s}^2 \). The period of the single-support step phase, i.e. the half of the walking period is \( t_k = 0.36 \, \text{s} \). The curves of controlling torques for the considered model are shown on the figure 2. All the calculations are made and the results are listed in the SI system.

**Figure 2.** The curves representing the experimentally determined controlling torques in the human joints as functions of time.
As a result of the numerical solution of the system of differential equations of motion with the given controlling torques and the initial configuration of the mechanism, the following curves representing the links angular displacements, angular velocities, and angular accelerations as functions of time have been obtained (figure 3). The dotted line curves represent the results of the numerical simulation. The solid line curves represent the link rotation angles which were recorded during an experiment set up to determine the controlling torques, localized in the major human joints, as well as the empirical angular velocities and accelerations. The methodology of assessing these values is described in the paper [15-17]. The figure 3 illustrates that there are minor fluctuations of the rotation angles and more significant variations of angular velocities and accelerations during human link motion in exoskeleton. However, basically the link kinematics of the human musculoskeletal system is replicated. Consequently, the simulation results are satisfactory and demonstrate the effectiveness of using the spring elements as energy recuperators.

![Figure 3. The curves representing the angular displacements, velocities and accelerations as functions of time for the exoskeleton motion with only human controlling torques and spring elements taken into account.](image)

The animated visualization frames of the developed model motion based on the numerical solution of the Cauchy problem are shown on the (figure 4). On the animated frames of the mechanism motion, the weightless parts of the variable-lengths links are shown with thin segments. The thick segments denote the weighty absolutely rigid parts of the links.

![Figure 4. The animated visualization frames of the protective passive exoskeleton motion.](image)

Thus, there is an option to visually evaluate the motion of the proposed model. Figure 3 illustrates the power of this approach and demonstrates the movements’ adequacy of the robotic human-machine system as a person in the protective exoskeleton.
6. Conclusion
The study of the developed model of the protective passive exoskeleton with variable-length links and spring elements, based on the conducted numerical solution of the Cauchy problem, has shown that it can be used by human virtually without adjustments of controlling muscle efforts due to energy recuperation. This is a prospective model for developing protective exosuits for military personnel, rescuers, hazardous occupation workers, space suits, as well as in other domains where the passive human body protection from dangerous effects is required.

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