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Modeling an Exoskeleton with Hydraulic Sections of Links with Adjustable Rigidity for Carrying Heavy Loads on Construction Sites

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Abstract. The study discusses the reasons for the need to use exoskeletons on construction sites. However, modern models of exoskeletons are not very comfortable for human use. One reason is the application of absolutely rigid links. The authors address this setback by applying in exoskeletons the links with variable length and controlled stiffness via alterable strength of magnetic field. A 3-dimensional model of exoskeleton, including five variable-length links with adjustable stiffness, for human musculoskeletal system has been developed. The model uses magneto-rheological fluid to control link stiffness on the variable-length sections. The links connections are simulated with hinges, spherical or cylindrical, implementing required rotational motion. The developed model is closer to the human locomotion system. It can be applied for designing more comfortable exoskeletons compared to the currently existing ones. The use of comfortable exoskeletons will make the work of construction workers easier and will reduce the number of injuries and occupational diseases.

Keywords. Builder, exoskeleton, variable-length link, longitudinal control force, magnetic-rheological fluid, controlled rigidity, external magnetic field, comfort

1. Introduction

On construction sites, workers are often faced with the need to lift and carry heavy objects, as well as routinely perform standard operations for long periods of time. This leads to occupational diseases of the musculoskeletal system. An exoskeleton can reduce the risk of developing these diseases and make the work of construction workers easier. Exoskeletons are already beginning to be used in construction and other industries [1-3].

The exoskeletons that make the everyday life easier for people with musculoskeletal system disorders have a number of issues [4,5]. Works [6-10] are devoted to the use of hydraulic actuators. The control model of variable-length section using magneto-rheological fluid by changing its viscosity under the applied outer magnetic field is considered in the paper [11].

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2. Materials and Methods

Let's consider a comfortable exoskeleton model that can be used by workers on construction sites. Consider a 3-dimenstional model of exoskeleton which includes five variable-length elements with adjustable stiffness in a motion phase when just one element is on the surface. The origin of stationary, fixed to the Earth, Cartesian system of coordinates $A_0x_0y_0z_0$, (figure 1), is placed at the fixed spherical hinge A_0.

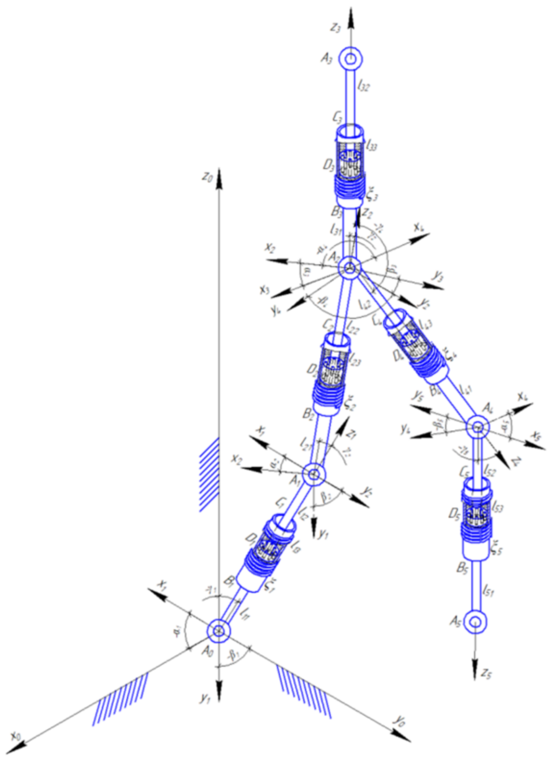

Figure 1. 3-dimensional model of exoskeleton with the links of alterable length and adjustable stiffness.

The model uses spherical hinges that allow achieving various degrees of mobility in the human musculoskeletal system. To compose the set of equations of differential type for the model movement, the mobile local coordinate systems $A_{i-1}x_iy_iz_i$ ($i = 1,2,\ldots,5$) are used, which are firmly fixed with spherical hinges $A_{i,}$ implementing the rotational links movement of the model. The axis z_i are directed along the mobile links $A_{i-1}A_i$ (figure 1).

The links $A_{i-1}A_i$ are of the same design and feature stems A_iD_i with pistons D_i, which are located inside the housings B_iC_i. The housings are the thin-walled cylinders with magnetic coils wound on them. The cylinders are filled with magneto-rheological fluid. The absolutely rigid rods $A_{i-1}B_i$ and A_iB_{i+1} are fixed to the cylinders. The opposite ends of the rods have spherical hinges. The control torques are expected to be applied to these spherical hinges. A schematic representation of the design of one link of a comfortable exoskeleton is shown in figure 2, a drawing of the piston and bushings are presented in figure 3.

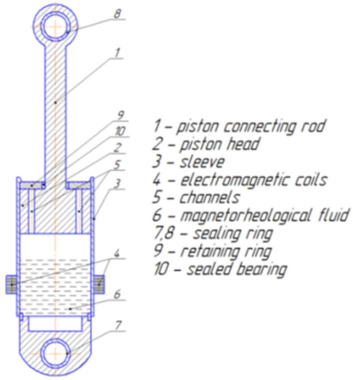

Figure 2. Design of one link of a comfortable exoskeleton.

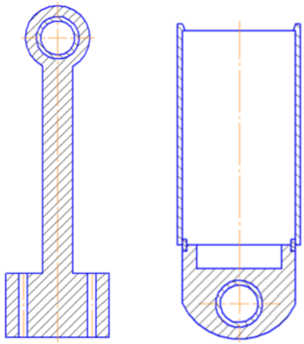

Figure 3. Piston drawing (on the left) and drawing of an exoskeleton link bushing containing magnetic rheological fluid (on the right).

The concentrated mass m_p is placed at the point A_5 at the top part of the mechanism model. This mass approximately simulates the head and the upper limbs of the person's locomotion system. The rod section lengths are denoted as $A_{i\text{-}1}B_i = l_{i1}$, $D_iA_i = l_{i2}$, wherein the first index designates the number of the link, and the second index designates the link section number. The lengths of the cylinders are denoted as $B_iC_i = l_{i3}$. Let's assume that the cylinder with magneto-rheological fluid is simulated with a rod, i.e. it is assumed that diameters of the cylinders are negligibly small compared to their lengths. The masses of individual link elements are denoted as m_{i1}, m_{i2}, m_{i3} respectively. Their moments of inertia for the axis normal to the plane in which the motion of the rods takes place and passing through their ends are I_{i1}, I_{i2}, I_{i3}. In the first approximation, it is assumed that the pistons D_i have negligibly small masses and moments of inertia compared to those of the rods D_iA_i. The length of the link is changed because of respective movement of pistons with stems D_iA_i inside the cylinders with magneto-rheological fluid B_iC_i ($i = 1,2,\ldots,5$) along the links $A_{i\text{-}1}A_i$ and A_iA_{i+1}.

The drag forces F_i ($i = 1,2,\ldots,5$) applied along the stems with pistons are implemented in this model by magneto-rheological fluid. Under the influence of the outer magnetic field, magnetic grains of this fluid are partially arranged along the magnetic field lines (figure 4). Meanwhile, the portion of the arranged particles grows with the intensity of the magnetic field applied to it. Consequently, drag force to the piston motion also increases. This ensures the controlled link change in accordance with the walk phase and loads applied from the neighboring links.

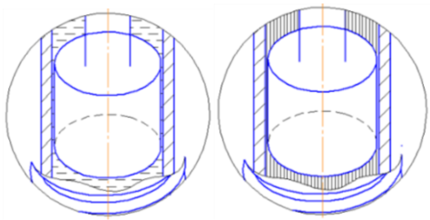

Figure 4. Chaotic arrangement of particles of magnetic rheological fluid when there is no outer magnetic field (left) and oriented magnetic particles under the effect of the outer magnetic field (right).

The left part (figure 4) shows the chaotic behavior of particles of a magnetic rheological fluid when there is no outer magnetic field. The right side (figure 4) shows how magnetic particles are consistently oriented when the outer magnetic field is switched on. The viscosity change of the magnetic-rheological fluid is regulated by outer magnetic field, realized using the coils placed on the cylinder outside. Since without magnetic field the particles have a chaotic arrangement, the magnetic-rheological fluid does not provide significant resistance to the movement of the piston. Under the effect of the outer magnetic field, the liquid exhibits resistance to the movement of the piston, which is greater the more oriented particles it contains. It becomes possible to adjust the stiffness of the links when changing their length. This has a positive effect on the comfort of the exoskeleton.

The position of the links in the mechanical model is determined by twenty variables and is clearly specified by angles $\alpha_i(t)$, $\beta_i(t)$, $\gamma_i(t)$, and by the link sections with alterable length between pistons and bottoms of the cylinders $B_iD_i = \xi_i(t)$. The control torques $M_{i\alpha}$, $M_{i\beta}$, $M_{i\gamma}$ applied to spherical hinges A_{i-1} with ideal constraints are assumed to instantly developing the required force. Let's consider the behavior of magneto-rheological fluid separately. The relative motion of pistons D_i ($i = 1,2,\ldots,5$) in the cylinders B_iC_i, filled with magneto-rheological fluid, results in the fluid viscosity change. This causes resistance change to the piston motion. The particles of magneto-rheological fluid behave chaotically and the fluid does not exert significant resistance to the piston motion if the outer magnetic field is not exerted to it. Under the effect of external magnetic field, the fluid particles are arranged along the magnetic field lines. The magneto-rheological fluid viscosity is controllable by applying outer magnetic field which is implemented by conductors wound on the cylinder. The greater the number of arranged particles in the fluid, the greater resistance exerts the fluid to the piston motion. Hence, it is possible to adjust the stiffness of the links $A_{i-1}A_i$ and A_iA_{i+1} in the process of their length change. The drag force, exerted by magneto-rheological fluid, is the function of the outer magnetic field strength, as follows:

$$F = \left[1 + \varphi_L\left(\alpha_n + \frac{(\zeta_n + \beta_n\lambda_n + \beta_n\cos(2\theta))}{2} + \right.\right.$$
$$\left.\left. + (\chi_n - 2\beta_n\lambda_n)\frac{\sin^2(2\theta)}{4}\right)\right]\eta_f\dot{\gamma}\pi r^2 + \frac{9\pi r^2\varphi_L\mu_0 H^2(n-1)(\chi_f + 1)\sin(2\theta)}{16n_c} \tag{1}$$

In this formula: φ_L – volume fraction of micron particles, n – the amount of grains in the series, n_c – the maximal amount of grains in the series, α_n, …, λ_n – kinetic factors, $\dot{\gamma}$ – the rate of the shear, η_f – the magneto-rheological fluid viscosity, θ – the angle between two vectors: one them is directed alongside the line passing through two micron particles centres, and the other one is the strength vector of the outer magnetic field.

The positions of the links of the mechanism model depend on fifteen parameters. These are the angles $\alpha_1(t)$, $\alpha_2(t)$, $\alpha_3(t)$, $\alpha_4(t)$, $\alpha_5(t)$, $\beta_1(t)$, $\beta_3(t)$, $\beta_4(t)$, $\gamma_3(t)$, $\gamma_4(t)$, providing the required movability of the links, similar to the person's locomotion system. And the variable lengths of the sections of the links between the pistons and the bottom of the cylinders $B_iD_i = \xi_i(t)$ ($i = 1,2,\ldots,5$). Thus, the model of the exoskeleton has 15 freedom degrees. The kinetic energy of the exoskeleton is calculated by integrating over all significant areas $A_{i-1}B_i$, B_iC_i, D_iA_i (i = 1,2,…,5).

$$T = \frac{1}{2} m_p V_{A_3}^2 + \frac{1}{2} \sum_{i=1}^{5} \sum_{j=1}^{3} \int_0^{l_{ij}} \rho_{ij} V_{ij}^2 d\zeta_{ij} \tag{2}$$

Where: i – link number (i = 1,2); j – is the number of link parts, where j = 1 corresponds to the lower sections A_0B_1 and A_1B_2, j = 2 corresponds to the rods with pistons D_1A_1 and D_2A_2, j = 3 corresponds to the cylinders B_1C_1 and B_2C_2; ζ_{ij} – the coordinate of an infinitely miniscule grain of the j-th inertial part of the i-th piece, ρ_{ij} – the denseness of the j-th part of the i-th piece, $m_{ij} = \rho_{ij} l_{ij}$, $I_{ij} = \rho_{ij} l_{ij}^3/3$, m_{ij}, I_{ij}, l_{ij},–the mass, moment of inertia, and the length of the j-th part of the i-th piece, m_p –the payload mass at point A_3, $V_{A_3}^2$ –the squared speed of point A_2, V_{ij}^2 –the squared speed of an infinitely miniscule grain of the j-th part of the i-th link.

The set of equations in differential form for the considered mechanism (figure 1) has been composed applying the second type of Lagrange equations. This system is not listed in this paper due to its cumbersomeness. Next, the laws describing the change of control torques, lengthwise forces, and external magnetic fields as functions of time can be obtained. These laws control the motion of the considered five-link exoskeleton model with links of alterable length stiffness.

3. Results

Solving the inverse dynamics problem, we obtain laws describing the change in longitudinal forces (figure 5) depending on time. These laws govern the movement of the proposed five-link exoskeleton model of variable length and adjustable rigidity.

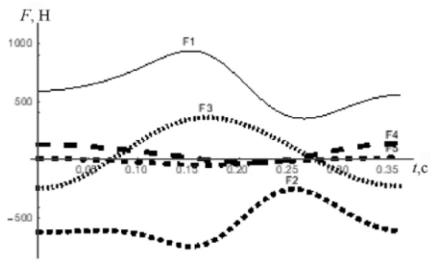

Figure 5. Time Dependences of Controlling Longitudinal Forces in Links of Variable Length.

Knowing the values of the found longitudinal force during the movement of the exoskeleton, presented in figure 5, using formula (1) we find the strength of the outer magnetic field that controls the magnetic-rheological fluid rigidity. The obtained strength values of the applied outer magnetic field are created using coils wound on a cylinder with magnetic rheological fluid. Thus, it is possible to develop the required force and regulate the length alteration of the exoskeleton link for comfortable movement of a construction worker in it when carrying heavy loads and performing standard movements.

4. Discussion

The numerical modeling of an exoskeleton for construction workers with five movable links of alterable length and rigidity confirmed the possibility of controlling the rigidity of the links by exerting an outer magnetic field. The magneto-rheological fluid viscosity becomes sufficient to create the force necessary for adequate functioning of the variable-length sections of the exoskeleton links. As a result of the study, it was established that the rigidity of links of variable length exoskeleton can be regulated using an outer magnetic field. The spatial model after refinement and prototyping, can be used for creating comfortable exoskeletons for people working on construction sites.

5. Conclusion

The work presents a three-dimensional exoskeleton with five variable-length links for workers on construction sites who carry heavy loads and perform typical labor actions for a long time. To increase the comfort of using the exoskeleton, a mechanism for changing the length of the exoskeleton link using magnetic rheological fluid is proposed. This allows you to control the rigidity of the exoskeleton link using an outer magnetic field. The scientific result obtained will lead to the creation of more comfortable exoskeletons for workers in comparison with currently existing models. These exoskeletons will be better synchronized with the worker's musculoskeletal system. The factual originality of the study is that for the first time, an exoskeleton model with links of alterable length and rigidity, regulated by magneto-rheological fluid, has been proposed for construction workers.

Acknowledgments

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References

[1] Nnaji C, Okpala I, Gambatese J, Jin ZY, Controlling safety and health challenges intrinsic in exoskeleton use in construction. Safety Science. 2023; 157: 105943.
[2] Antwi-Afari MF, Li H, Anwer S, Li DW, Yu Y, Mi HY, Wuni IY. Assessment of a passive exoskeleton system on spinal biomechanics and subjective responses during manual repetitive handling tasks among construction workers. Safety Science. 2021; 142: 105382.
[3] Borisov AV, Borisova VL, Konchina LV, Kulikova MG, Maslova KS. Simulation of the motion of agricultural worker in a passive exoskeleton with two types spring elements when performing work with higher physical loads. IOP Conf. Series: Earth and Environmental Science. 2021; 723: 032063.
[4] Borisov AV, Chigarev AV. Mathematical Models of Exoskeleton. Dynamics, Strength, Control, Monograph. Springer, 2022; pp. 232.
[5] Piña-Martínez E, Rodriguez-Leal E. Inverse modeling of human knee joint based on geometry and vision systems for exoskeleton applications. Mathematical Problems in Engineering. 2015; Article ID 145734.
[6] Glowinski S, Obst M, Majdanik S, Potocka-Banaś B. Dynamic model of a humanoid exoskeleton of a lower limb with hydraulic actuators. Sensors. 2021; 21(10):3432.

[7] Andrade RM, Fabriz Ulhoa PH, Fragoso Dias EA. Design and testing a highly backdrivable and kinematic compatible magneto-rheological knee exoskeleton. Journal of Intelligent Material Systems and Structures. 2022; 5.

[8] Rodríguez-León JF, Castillo-Castañeda E, Carbone G. A feasibility study of exopass, a passive magnetic-spring support exoskeleton to reduce worker's physical strain. In: IFToMM Italy 2022. Mechanisms and Machine Science, 2022; vol. 122. Springer, Cham.

[9] Bira N, Dhagat P, Davidson JR. A review of magnetic elastomers and their role in soft robotics. Front Robot AI. 2020 Oct 23; 7:588391. doi: 10.3389/frobt.2020.588391. PMID: 33501346.

[10] Lebedev AV. Viscosity of magnetic fluids must be modified in calculations of dynamic susceptibility. Journal of Magnetism and Magnetic Materials. 2017; 431: 30–32.

[11] Blinov A, Borisov A, Konchina L, Novikova M. Applying the models of magneto- rheological substances in the study of exoskeleton variable-length link with adjustable stiffness. Journal of Applied Informatics, 2022; 98(2): 133-142.