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3D Model of Exoskeleton Lower Limbs with Four Variable-Length Links of Adjustable Stiffness for Builder and Rescue Works

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Abstract. A new lower limbs exoskeleton model for builder and rescue workers, firefighters, and personnel of other emergency services is proposed in the paper. The proposed exoskeleton model is more comfortable than the existing ones because it uses links of alterable length and artificial resilience resulting from the magneto-rheological fluid utilization in the link design. The utilization of this fluid makes it possible to control link stiffness by applying external magnetic field. The exoskeleton has four links of controlled length and the same design. Each link includes the absolutely rigid bottom part with a cylinder attached to it and filled with magneto-rheological fluid. A coil of wire is wound on the cylinder surface. The coil is energized by the electric current when required. The top part of the link includes a piston inside the cylinder with a stem passing outside it. The piston moves inside the cylinder filled with magneto-rheological fluid. The piston features microscopic channels through which the magneto-rheological fluid can flow relatively easy in the absence of magnetic field. If magnetic field is applied, the particles of magneto-rheological fluid are arranged in a way to prevent free flow of the fluid through the piston. Thereby the link stiffness, and consequently the link length control are implemented. The paper lists results of numerically found lengthwise forces applied to the piston in the cylinder filled with magneto-rheological fluid. The proposed exoskeleton model can be widely used by builder and rescue workers because of its comfort, high-speed performance, noiselessness, and great developed force.

Keywords. Lower limbs exoskeleton for builder and rescue workers, link with alterable length, adjustable stiffness, magneto-rheological fluid, external magnetic field, piston with microscopic channels, lengthwise force, hinge.

1. Introduction

The problem of developing equipment for rescue workers, firefighters and other emergency services personnel is actual and in-demand because of limited human

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capabilities such as developed force, stamina, mobility, possible injuries, and occupational diseases. Application of exoskeletons can partially resolve these problems. For example, the exoskeleton frame can bear the weight of protective equipment and useful cargo of rescue worker. The exoskeleton can facilitate the transportation of injured people; enhance the physical capabilities of rescue worker when removing the ruins etc. However, despite all the benefits of the exoskeletons to rescue workers, the existing theoretical [1-5] and practical [6-10] exoskeleton models are still not comfortable and functional enough for widespread use by emergency services.

The idea of applying variable-length links in exoskeleton design in order to enhance rescue worker's comfort is proposed in this article. To make exoskeleton model not too heavy and power-consuming, unlike to the studies [11-13] using electric motor with rack and pinion or screw-drive gears to change the link length, it is suggested to use a cylinder with magneto-rheological fluid, a piston with microscopic channels, and a winding on the cylinder surface for creating magnetic field as a mechanism controlling the link length change. Being exposed to the external magnetic field, the fluid properties are changed. The fluid particles are arranged as required [14-20] under the effect of external magnetic field which changes the drag force applied to the piston in the process of its motion inside the cylinder. The model of controlled stiffness of the variable-length link is implemented in this way. The fast change of the link stiffness, almost simultaneous with the human musculoskeletal system [21], is another advantage of this model. The lag in the exoskeleton link length change is minimal. The mechanism response without lag is an important factor enhancing the comfort of exoskeleton application, which results in synchronous motion of human musculoskeletal and the corresponding exoskeleton links. It follows from the above, that development of mathematical model for 3D lower limbs exoskeleton with four mobile variable-length links with adjustable stiffness for rescue workers is an actual scientific and practically important task.

2. Description of 3D Lower Limbs Exoskeleton Model with Four Variable-length Links with Adjustable Stiffness

Consider a 3D exoskeleton model, including four variable-length links with adjustable stiffness, in a single-support motion phase. The first bottom link A_0A_1 simulates the shin of the supporting leg. The second link A_1A_2 simulates the hip of the supporting leg. The third link A_2A_3 simulates the hip of transferred leg. The fourth link A_3A_4 simulates the shin of the transferred leg. There is a concentrated mass m_N at the point B of the mechanism. This mass simulates useful load on the exoskeleton from protective suit and equipment carried by rescue worker. The method of composing motion equations, which is based on the application of local systems of coordinates, proposed in the paper [21], is used in this study. Let's introduce the fixed Cartesian system of coordinates $A_0x_0y_0z_0$ (figure 1) with the origin at the point A_0, where the hinge is fixed.

Various hinges and their combinations are used in the model. For example, there is a combination of two cylindrical hinges with mutually orthogonal axes at the hinge A_0. This design corresponds to the motion of human ankle joint in which practically no shin rotation around its longitudinal axis is observed in walking. Therefore, the spherical hinge is not applied in the model of human ankle joint. There is a cylindrical hinge simulating human knee joint at the point A_1. The human hip joint is a spherical hinge, therefore there is a spherical hinge at the point A_2 simulating all existing degrees of freedom. The mobile local systems of coordinates $A_0x_1y_1z_1$, $A_1x_2y_2z_2$, $A_2x_3y_3z_3$, and $A_3x_4y_4z_4$, fixed to the hinges A_0, A_1, A_2, and A_3, implementing the link rotations, are used for composing the system of differential equations. This method of mechanism description uses the angles between the links. These angles correspond to the working mode of real exoskeleton drives that actually change these angles. The axes z_1, z_2, z_3, and z_4 are directed along the mobile links A_0A_1, A_1A_2, A_2A_3, and A_3A_4. The figure 1 shows the rotation angles used in the model.

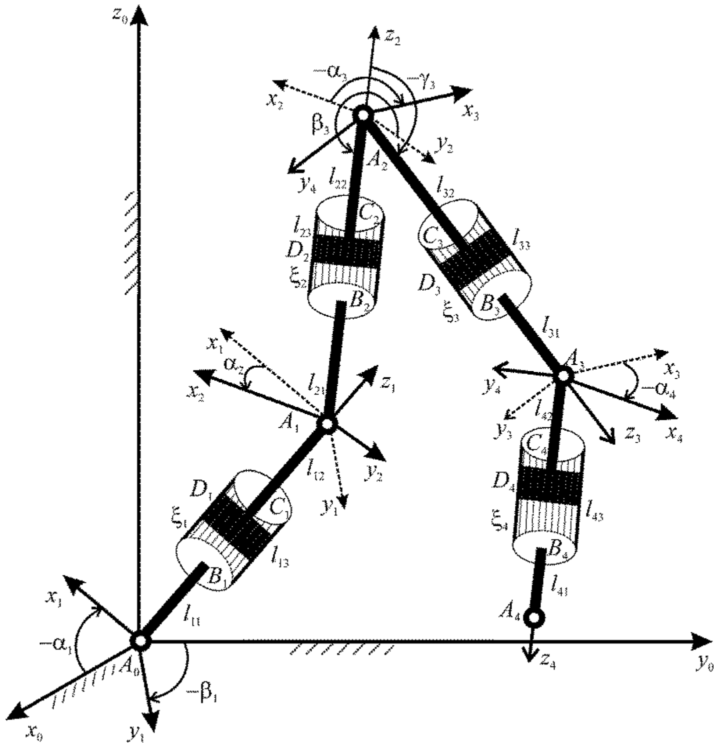


Figure 1. 3D exoskeleton model of four links with variable length and adjustable stiffness (the state when the external magnetic field is applied, and the magnetic particles are arranged along the magnetic field lines, is shown in the Figure).

The links of identical design A_0A_1, A_1A_2, A_2A_3, and A_3A_4 include absolutely rigid stems A_1D_1, A_2D_2, A_2D_3, and A_3D_4 fixed to the pistons with microscopic channels D_1, D_2, D_3, and D_4, inside the housings B_1C_1, B_2C_2, B_3C_3, and B_4C_4. The housings are the thin-walled cylinders with the electromagnetic coils wound on them. The cylinders are filled with magneto-rheological fluid. The absolutely rigid rods A_0B_1, A_1B_2, A_3B_3, and A_4B_4 are fixed to the bottoms of the corresponding cylinders. There are hinges at the end of the rods. It is assumed that the required control torques could be applied to the hinges. The cylinders with magneto-rheological fluid are shown in the section in the figure 1. The link lengths are changed due to the relative motion of pistons with the stems A_1D_1, A_2D_2, A_2D_3, and A_3D_4 inside the cylinders B_1C_1, B_2C_2, B_3C_3, and B_4C_4 filled with magneto-rheological fluid along the directions of the links A_0A_1, A_1A_2, A_2A_3, and A_3A_4. The drag forces F_1, F_2, F_3, and F_4 are applied by the magneto-rheological fluid along the stems with the pistons. Under the effect of external magnetic field, the magnetic particles of the fluid are partially arranged along the magnetic field lines. The proportion of arranged particles grows with the growth of magnetic field strength, which makes the drag force, applied by the magneto-rheological fluid to the moving piston, more strong. This ensures the controlled link length change in accordance with the phase of the walk and the loads applied from the neighbouring links. The position of the exoskeleton links is clearly defined by the angles $\alpha_1(t)$, $\beta_1(t)$, $\alpha_2(t)$, $\alpha_3(t)$, $\beta_3(t)$, $\gamma_3(t)$, $\alpha_4(t)$ and by the lengths of the variable-length link sections between the pistons and the cylinder bottoms $B_1D_1 = \xi_1(t)$, $B_2D_2 = \xi_2(t)$, $B_3D_3 = \xi_3(t)$, and $B_4D_4 = \xi_4(t)$ (figure 1). Therefore, the model has eleven degrees of freedom. Let's designate the control torques applied to the hinges A_0, A_1, A_2, and A_3 with ideal constraints as $M_{1\alpha}$, $M_{1\beta}$, $M_{2\alpha}$, $M_{3\alpha}$, $M_{3\beta}$, $M_{3\gamma}$, $M_{4\alpha}$. It is assumed that control torques can instantly develop the required values.

For the proposed in the figure 1 model of the exoskeleton supporting legs including four variable-length links with adjustable stiffness, the system of differential equations of motion using the Lagrange equations of the second kind has been composed. The system of differential equations is too large and therefore it is not listed in the article.

3. Program-based Method to Control 3D Exoskeleton Model with four Regulated Variable-length Links with Adjustable Stiffness

The idea of program-based method to control motion, as applied to exoskeletons, includes the following steps: the exoskeleton, using its sensitive system, measures the angles between the wearer's links; the required control torques and forces are calculated based on these measurements; the calculated torques and forces are applied to the exoskeleton drives, thus helping rescue worker to carry out his job. For the purpose of mathematical simulation, let's specify the motion control of exoskeleton links in the form of continuously differentiable periodic functions synthesizing anthropomorphic walk. The phase trajectories, plotted using these functions, are presented in figure 2 – for angular coordinates, and in figure 3 – for generalized linear coordinates specifying the change of the link lengths. The measurement units of all values are given in SI system.

The phase trajectories presented in the figure 2 have been plotted for the doubled motion time. The point is that there is no periodic motion and the phase trajectories are not closed, if we consider incomplete step cycle for just one single-support step phase of the walk. The link rotation angles become periodic only for the full period of walking.

The closed phase trajectories indicate that the link length changes are periodic within the single-support motion phase, which is half of the walking period and does not include switch of the legs.

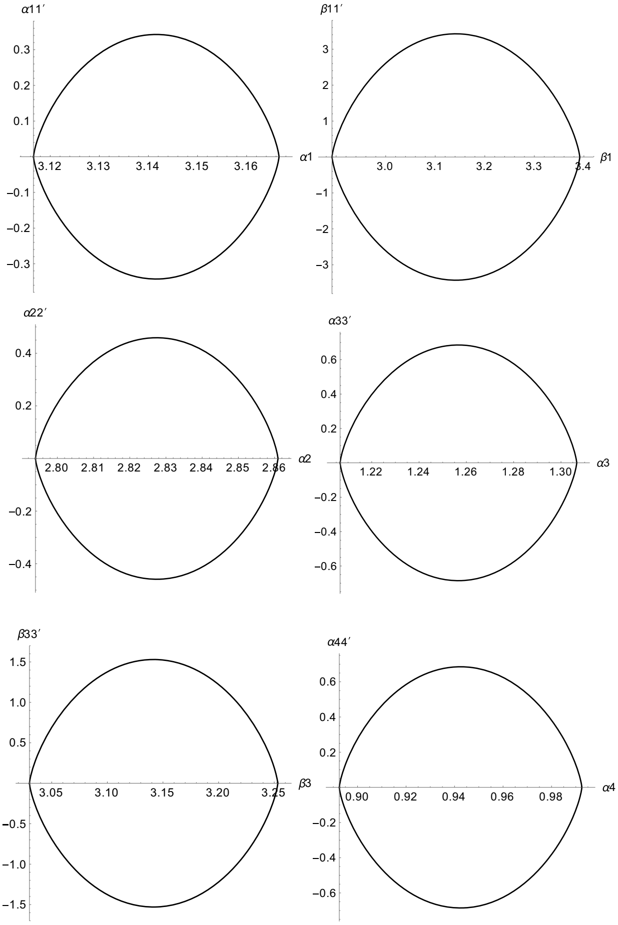
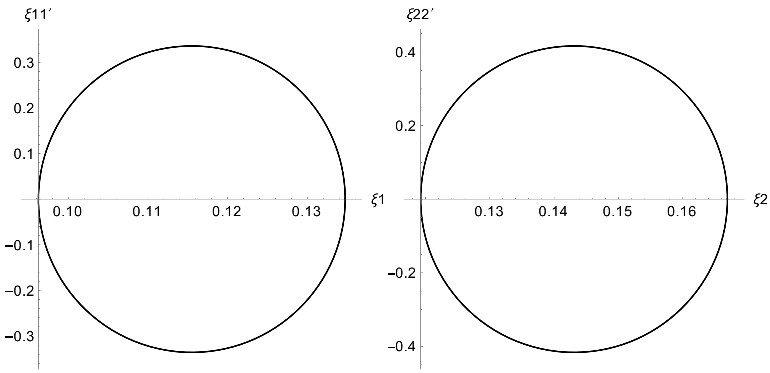


Figure 2. Phase trajectories of generalized angular coordinates as functions of generalized angular velocities for the four variable-length links with adjustable stiffness of 3D exoskeleton model.



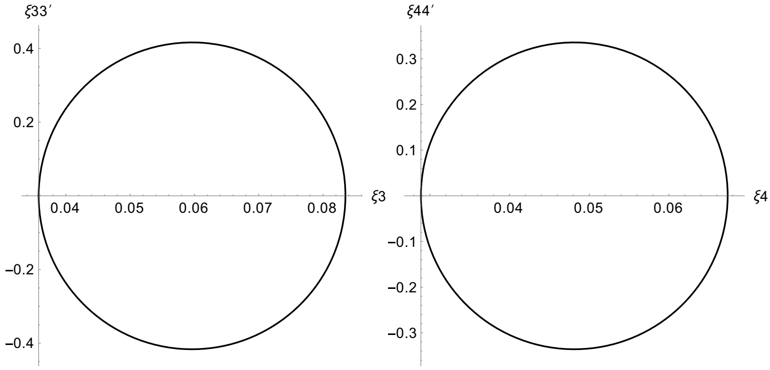


Figure 3. Phase trajectories of generalized linear coordinates as functions of generalized linear velocities for the four variable-length links with adjustable stiffness of 3D exoskeleton model.

4. Calculating Control Torques and Lengthwise Forces Required for Exoskeleton Motion

Solving the inverse dynamics problem, i.e. solving the system of motion equations algebraically for the torques and lengthwise forces, we can find $M_i(t)$, $F_i(t)$ ($i = 0,1,2,3$) for the drives in the hinges A_0, A_1, A_2, A_3 (figures 4 and 5).

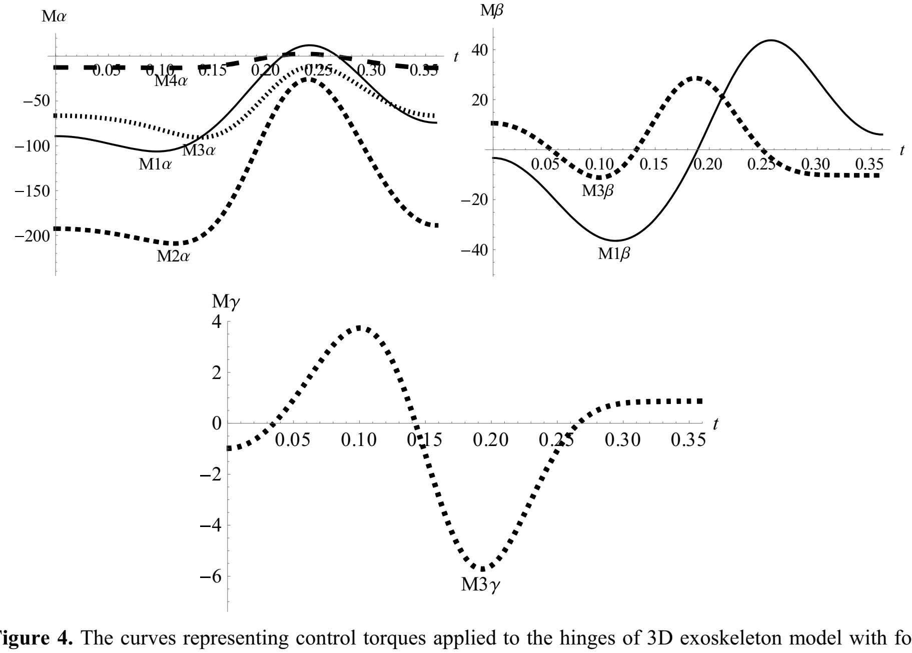


Figure 4. The curves representing control torques applied to the hinges of 3D exoskeleton model with four variable-length links with adjustable stiffness as functions of time.

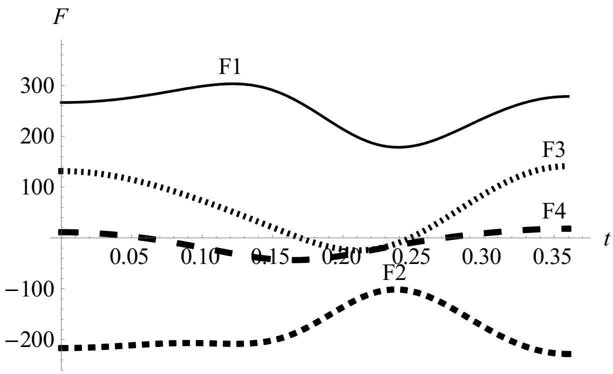


Figure 5. The curves representing lengthwise forces applied to each of the four variable-length links with adjustable stiffness of 3D exoskeleton model as functions of time.

Thus, the inverse dynamics problem has been solved applying the program-based control method of exoskeleton model motion. The values of required control torques have been found (figure 4). Based on these values, the electric drives can be selected for implementing the controlled exoskeleton motion. The lengthwise forces have been calculated (figure 5). These results are further used for selecting the final composition and properties of magneto-rheological fluid, and thereafter for calculating the strength of external magnetic field that is required for implementing the corresponding force.

5. Conclusions

As a result of this study, the 3D lower-limbs exoskeleton model that includes four variable-length links with adjustable stiffness, and can be used by rescue worker has been created for the first time. The mathematical model of exoskeleton in the form of Lagrange equations of the second kind has been composed. It has been proposed to enhance the variable-length section of the link design by applying magneto-rheological fluid to control the link stiffness. An experiment on developing magneto-rheological fluid and studying its properties has been set up. It has been found that developed magneto-rheological fluid has stable and reproducible properties, which makes its potentially useful for various industrial and scientific applications, including the model of lower limbs exoskeleton with variable-length links with adjustable stiffness for rescue workers. Using the composed system of differential equations, describing the exoskeleton motion, and the program-based method of motion control, the numerical experiment has been conducted to determine the required control torques and lengthwise forces that should be applied to exoskeleton hinges and developed in the cylinders with magneto-rheological fluid respectively. The developed lower limbs exoskeleton model is more comfortable, fast-responding, and can be used by rescue workers for carrying out their working routines.

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