Kinematic and Dynamic Analysis of a Mechanism for Assisting Human Locomotion

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Abstract. In this paper we will present a new robotic system designed to assist human locomotion. The purpose of using this exoskeleton is to rehabilitate people with locomotor disabilities. We will present the kinematic diagram of a new mechanism used as the leg of an exoskeleton for rehabilitation. We performed a kinematic analysis of the robotic system. The kinematic study is completed with a 3D design of the exoskeleton, based on which we will perform a dynamic simulation with the multibody analysis program MSC.ADAMS. The data obtained by dynamic analysis are also presented and commented, in order to highlight the performances of this new robotic system proposed.

Keywords: robotic system · exoskeleton · rehabilitation · kinematics · dynamic simulation

1 Introduction

In the field of robotics, for mobile robots there are several directions of development: robots that use rolling systems (wheels, omni-wheels, tracks) and a second important category is that of stepping robots. The stepping robots have developed in several important directions, namely: bipedal, quadrupedal, hexapods robots. In the carriage of hexapods robots (with six legs) the balance is ensured more easily, because during the step three or more legs remain on the ground simultaneously. In four-legged robots, the problem of maintaining balance is solvable, and balance can be maintained during stepping. This balance problem is much more delicate in bipedal robots, because during the step the weight of the robot is supported by only one leg. This problem is solved by creating a contact surface between the foot and the ground, much larger than in other situations, by using support brackets. However, within the active gait rehabilitation systems we find two main categories of solutions: stationary systems and mobile systems. Within the stationary rehabilitation systems, we can notice the solutions such as the plate under the foot, which performs movements similar to the human foot, through which the human leg is subjected to movements specified by physiotherapists, or stationary robotic systems, where the patient immobilized in bed has his leg tied to a system robot that helps

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him make movements. The most commonly used mobile solutions are active orthoses, designed to assist a single joint of the foot, usually the ankle or knee and the exoskeletons. The exoskeleton is a robotic system, which is attached to a human subject and gives it the extra strength needed for gait. Most achievements in the field of exoskeletal robotic systems are made with motors placed in the joints of the leg. Another category of exoskeletons is based on kinematic chains, usually driven by a single motor, which are designed to provide similar movements as in human gait [1–6]. Kinematic chains are also used to drive a single leg joint separately.

In this paper we will present an original robotic system solution to assist human walking. The developed robotic system is a solution that uses a kinematic chain driven by a single motor, being based on kinematic chains of the quadrilateral type. This solution provides support for the hip and knee joints. We will present the structural solution, and we will perform a kinematic analysis of the proposed kinematic chain as a solution for the exoskeleton leg. In the third part of the paper, we will present a CAD model of the proposed solution based on which we will develop a dynamic analysis using the MSC.ADAMS program.

2 Kinematic Analysis of the Mechanism of the Exoskeleton Leg

The original kinematic solution that is proposed for the construction of an exoskeleton type robotic system for rehabilitation has the kinematic scheme presented in Fig. 1.

According to the kinematic scheme, the structure of the mechanism has a motor element, which is denoted by (1), and 4 dyad-type structural groups, namely: ECB, DCF, FIH and JKL.

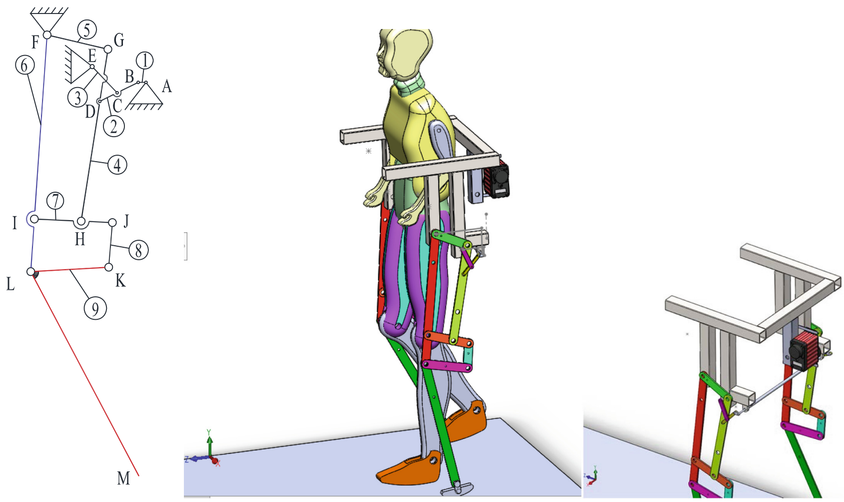

Fig. 1. Kinematic diagram of the mechanism of the exoskeleton leg.

The following system of equations can be written for the ECB dyad:

$$\begin{cases} l_{BC}cos\varphi_2 = (x_E - x_B) + l_{CE}cos\varphi_3 \\ l_{BC}sin\varphi_2 = (y_E - y_B) + l_{CE}sin\varphi_3 \end{cases} \tag{1}$$

The following system of equations is written for the DCF dyad.

$$\begin{cases} l_{FG}cos\varphi_5 = (x_D - x_F) + l_{DG}cos\varphi_4 \\ l_{FG}sin\varphi_5 = (y_D - y_F) + l_{DG}sin\varphi_4 \end{cases} \tag{2}$$

The following system of equations can be written for the FIH dyad:

$$\begin{cases} l_{FI}cos\varphi_6 = (x_H - x_F) + l_{HI}cos\varphi_7 \\ l_{FI}sin\varphi_6 = (y_H - y_F) + l_{HI}sin\varphi_7 \end{cases} \tag{3}$$

The following system of equations can be written for the JKL dyad:

$$\begin{cases} l_{JK}cos\varphi_8 = (x_L - x_J) + l_{LK}cos\varphi_9 \\ l_{JK}sin\varphi_8 = (y_L - y_J) + l_{LK}sin\varphi_9 \end{cases} \tag{4}$$

In the systems of equations (1)–(4) the following mathematical operations are performed. For each system, square up and add the two equations in the system. We obtain the following equations of degree two with trigonometric function as coefficients.

To determine the law of variation of the angle phi 3, the equation (5) is solved.

$$l_{BC}^2 - a_1^2 - a_2^2 - l_{CE}^2 - 2a_1 l_{CE}cos\varphi_3 - 2a_2 l_{CE}sin\varphi_3 = 0 \tag{5}$$

To determine the law of variation of the angle phi 2, equation (6) is solved.

$$l_{CE}^2 - l_{BC}^2 - a_1^2 - a_2^2 + 2a_1 l_{BC}cos\varphi_2 + 2a_2 l_{BC}sin\varphi_2 = 0 \tag{6}$$

The variation laws for the angles phi 4 and phi 5 are determined by equations (7) and (8).

$$l_{FG}^2 - b_1^2 - b_2^2 - l_{DG}^2 - 2b_1 l_{DG}cos\varphi_4 - 2b_2 l_{DG}sin\varphi_4 = 0 \tag{7}$$

$$l_{DG}^2 - b_1^2 - b_2^2 - l_{FG}^2 + 2b_1 l_{FG}cos\varphi_5 + 2b_2 l_{FG}sin\varphi_5 = 0 \tag{8}$$

The laws of variation of the angles phi 6 and phi 7 are determined from equations (9) and (10).

$$l_{FI}^2 - c_1^2 - c_2^2 - l_{HI}^2 - 2c_1 l_{HI}cos\varphi_7 - 2c_2 l_{HI}sin\varphi_7 = 0 \tag{9}$$

$$l_{HI}^2 - c_1^2 - c_2^2 - l_{FI}^2 + 2c_1 l_{FI}cos\varphi_6 + 2c_2 l_{FI}sin\varphi_6 = 0 \tag{10}$$

The angles phi 8 and phi 9 in equations (11) and (12) are similarly determined.

$$l_{LK}^2 - d_1^2 - d_2^2 - l_{JK}^2 + 2d_1 l_{JK}cos\varphi_8 + 2d_2 l_{JK}sin\varphi_8 = 0 \tag{11}$$

$$l_{JK}^2 - d_1^2 - d_2^2 + l_{LK}^2 - 2d_1 l_{LK} cos\varphi_9 - 2d_2 l_{LK} sin\varphi_9 = 0 \quad (12)$$

In equations (5) to (12) we used the following notations:
$(x_E - x_B) = a_1$, $(y_E - y_B) = a_2$, $(x_D - x_F) = b_1$, $(y_D - y_F) = b_2$
$(x_H - x_F) = c_1$, $(y_H - y_F) = c_2$, $(x_L - x_J) = d_1$, $(y_L - y_J) = d_2$
The solutions of equations (5) - (12) are obtained by solving equations of type (13).
To determine the law of variation of the angle phi i, solve equation (13).

$$\varphi_i = 2arctg \frac{A_i^2 \pm \sqrt{A_i^2 + B_i^2 - C_i^2}}{B_i^2 - C_i^2} \quad (13)$$

where we have, $i = 2..9$. The A_i coefficients have the following relations:

$$A_2 = 2a_2 l_{BC};\, B_2 = 2a_1 l_{BC};\, C_2 = l_{CE}^2 - a_1^2 - a_2^2 - l_{BC}^2 \quad (14)$$

$$A_3 = -2a_2 l_{CE};\, B_3 = -2a_1 l_{CE};\, C_3 = l_{BC}^2 - a_1^2 - a_2^2 - l_{CE}^2 \quad (15)$$

$$A_4 = -2b_2 l_{DG};\, B_4 = -2b_1 l_{DG};\, C_4 = l_{FG}^2 - b_1^2 - b_2^2 - l_{DG}^2 \quad (16)$$

$$A_5 = -2b_2 l_{FG};\, B_5 = -2b_1 l_{FG};\, C_5 = l_{DG}^2 - b_1^2 - b_2^2 - l_{FG}^2 \quad (17)$$

$$A_6 = 2c_2 l_{FI};\, B_6 = 2c_1 l_{FI};\, C_6 = l_{HI}^2 - c_1^2 - c_2^2 - l_{FI}^2 \quad (18)$$

$$A_7 = -2c_2 l_{HI};\, B_7 = -2c_1 l_{HI};\, C_7 = l_{FI}^2 - c_1^2 - c_2^2 - l_{HI}^2 \quad (19)$$

$$A_8 = 2d_2 l_{JK};\, B_8 = 2d_1 l_{JK};\, C_8 = l_{LK}^2 - d_1^2 - d_2^2 - l_{JK}^2 \quad (20)$$

$$A_9 = -2d_2 l_{LK};\, B_9 = -2d_1 l_{LK};\, C_9 = l_{JK}^2 - d_1^2 - d_2^2 - l_{LK}^2. \quad (21)$$

These equations describe the kinematic model of the exoskeleton robotic system. Their numerical solution will be done by calculation in the MATLAB environment and then they will be validated by simulating the motion in the kinematic case, by simulation in the analysis environment of the multibody-ADAMS View system.

3 Kinematic Simulation of the Exoskeleton Robot

We must specify that the kinematic model presented in the previous paragraph corresponds to the situation related to the kinematic scheme in Fig. 1, namely the kinematic joints of rotation A, F and E are connected to the fixed base. In this situation the mechanism of the exoskeleton leg operates on a supporting frame, and the trajectory described by point M, which corresponds to the foot, must be a closed curve of the ovoid type.

To simulate the movement of the exoskeleton, with the help of MSC.ADAMS software, we made an assembly of the two legs. We opted for the constructive solution

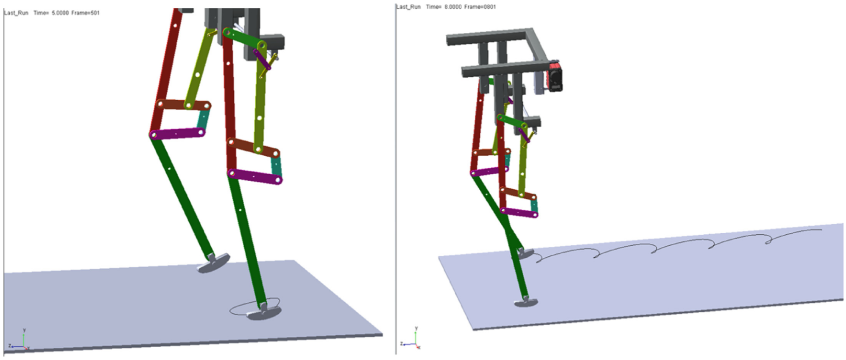

Fig. 2. The path calculated in ADAMS for the exoskeleton leg, corresponding to the two operating hypostases.

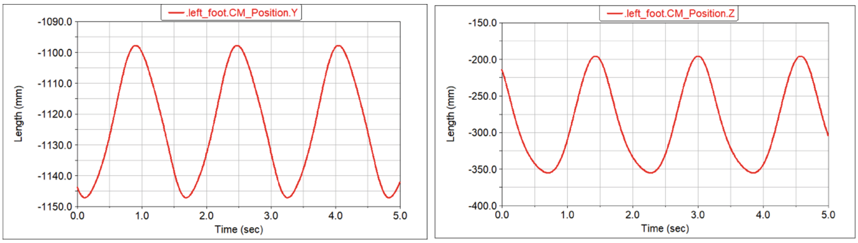

Fig. 3. Graphs of time variation of the position of the center of mass of the sole of the left foot.

presented in Fig. 1, where the developed assembly solution can be distinguished. This solution consists of a square tube top frame, joined by welding. Coupling A, through which the motor element (1) is connected by the upper frame, is constructed by means of a shaft, on which are assembled at the ends the two cranks (1), positioned at an angle of 180°, to ensure the sequence of steps. For kinematic reasons, we considered the angular velocity of the shaft on which the two motor elements are mounted, of 4 rad/s. Thus, the kinematic parameters of the exoskeleton will be close to the situation of normal gait performed by a human subject. In Fig. 2 can be observed the trajectory described by the foot, for the two hypostases of simulation, namely when the exoskeleton has the upper frame fixed to the base and for the situation when the exoskeleton performs the activity of walking on the floor.

In Fig. 2 it is observed that for the stationary operation situation of the exoskeleton, the trajectory described by the ankle is an ovoid one, acceptable for the good functioning of the robot. On the right side of the figure, it is observed that the exoskeleton performs the activity of walking on the floor.

In Figs. 3, 4 and 5 we presented the laws of variation for the position, velocity and acceleration of the center of mass of the sole of the left foot of the exoskeleton. It can be observed from Fig. 2 that the Y axis is vertical and the Z axis horizontal, and the origin of the coordinate system is placed in the coupling A. According to Fig. 3, it can be concluded that the pitch height is 50 mm and the pitch length is 150 mm. These parameters are

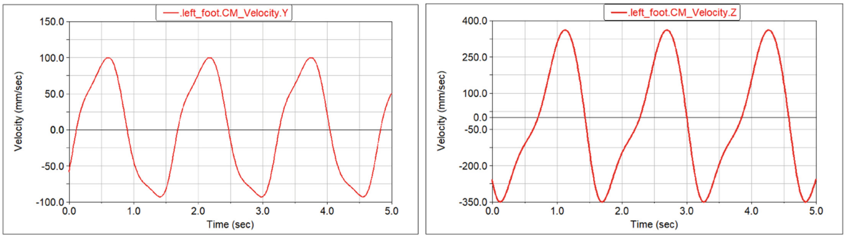

Fig. 4. Graphs of time variation for the speed of the center of mass of the sole of the left foot.

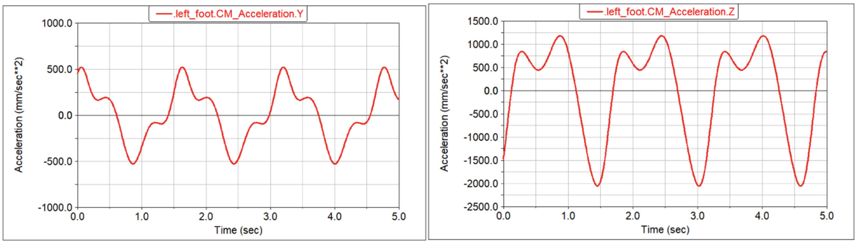

Fig. 5. Graphs of variation over time in the acceleration of the center of mass of the sole of the left foot.

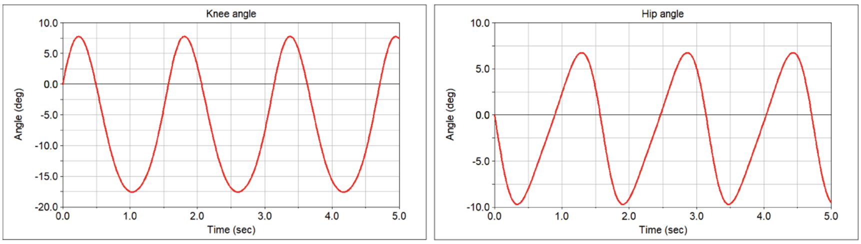

Fig. 6. Graphs of time variation of the angle of the L and F joints (knee and hip).

very good, because the height of 50 mm at which the exoskeleton raises the leg in the swing phase ensures the step without hindrance, and the step length doubles, being 300 mm, because we have two legs. Variation graphs for the components of the speed and acceleration of the sole, show a smooth variation, without sudden jumps, which ensures a correct operation of the robot. Also, the angular amplitudes in the hip and knee joint are smaller than those in normal human gait. This is not an obstacle for the exoskeleton to provide locomotion assistance, as we will present below. The results presented in this paragraph are obtained in the case of the first hypothesis, when the exoskeleton operates with the couplings A, E, F connected to a fixed base. In the next paragraph we will present the results obtained in the situation when the exoskeleton performs the activity of stepping on the ground (Fig. 6).

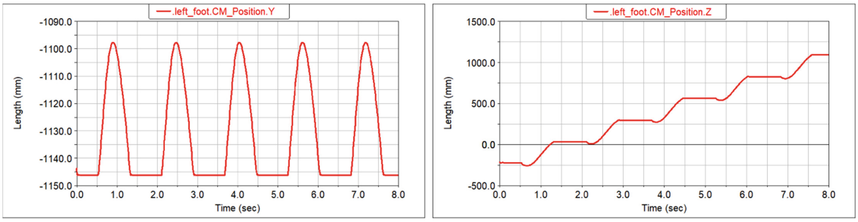

Fig. 7. Graphs of time variation of the position of the center of mass of the sole, in the case of the stepping activity of the exoskeleton.

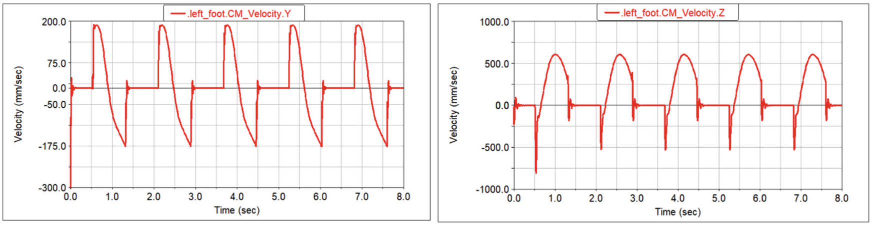

Fig. 8. Graphs of time variation of the speed of the center of mass of the sole, in the case of the activity of stepping the exoskeleton.

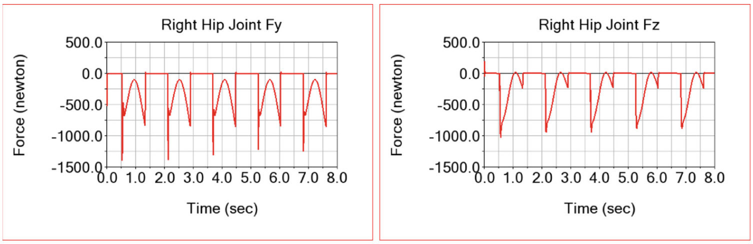

Fig. 9. Graphs of the variation over time of the components of the connecting forces in the hip.

4 Dynamic Modelling of the Exoskeleton While Walking

For dynamic modelling, we will use the simulation environment of multibody systems, ADAMS.View. In this case, we considered the torques previously connected to the fixed base, namely the rotation torques A, E and F to be connected to the upper frame. This frame is allowed to translate vertically and horizontally during the simulation. We defined the contact between the sole and the ground, where we also took into account the friction forces.

Under these simulation conditions, the exoskeleton can step on the floor. The graphs presented below are determined in this case.

Thus, in Fig. 7, it can be seen that while walking the height of the exoskeleton step is 50 mm. Also, from this figure you can see that the exoskeleton performs 5 steps and travels a distance of 1500 mm, so the length of a step is 300 mm. From Fig. 8 it is found that the calculated speeds for the sole show small abrupt variations on contact with the

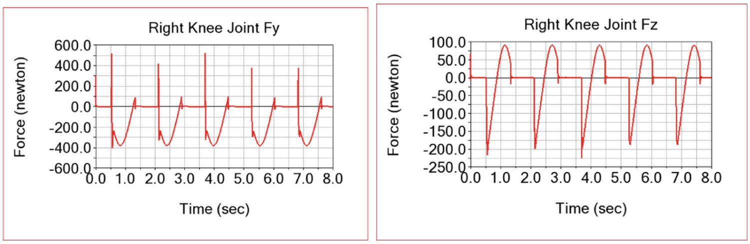

Fig. 10. Graphs of the variation over time of the components of the connecting forces in the knee.

ground. Also in the dynamic simulation, we calculated the components of the connecting forces in the hip and knee joints of the exoskeleton. It is observed that higher values are recorded along the vertical Y axis (Figs. 9 and 10).

5 Conclusion

In this paper, we presented a kinematic and dynamic analysis for an exoskeleton-type robotic system designed to assist human locomotion. The mechanism solution used for the exoskeleton leg is original, being patented. The structure of the mechanism comprises a driving element and four RRR type dyads. The kinematics of the proposed mechanism as a constructive solution for the exoskeleton leg are studied by analytical methods and by simulation in ADAMS. The laws of variation of the angles of flexion/extension in the hip and knee joints are suitable for the use of the mechanism as a solution for the assistant exoskeleton of human gait. The dynamic simulation involved the exoskeleton stepping on the floor. The obtained results allow us to validate the proposed solution and move to the next stage of making a physical prototype and experimental testing.

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