Study on Assisting People with Locomotor Disabilities to Climb Stairs with the Help of an Exoskeleton

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Abstract

In this paper we aim to address the topic of assisting the locomotion of a person with locomotor disabilities when climbing stairs. This assistance will be achieved with the help of a robotic system such as an exoskeleton. The designed exoskeleton must provide the step length corresponding to the distance between two steps, as well as the lifting height of the leg sufficient to step on the next stair step. For this purpose, an exoskeleton robotic system design solution is proposed. Based on this constructive solution, a virtual prototype of the robotic system will be realized, followed by a dynamic simulation, using software for dynamic analysis of multibody systems, namely ADAMS. The simulation results allow us to validate the design solution, on this conclusion we will proceed to the next stage of the research, namely the execution of an experimental prototype.
Keywords: Dynamic analysis, Exoskeleton, Stairs, Motion assistance.

1. Introduction

The subject of assisting people with disabilities is often studied. Evidence of this is the existence of a very large number of research articles addressing this topic. Thus, this research topic is present in the field of electronics, and addresses the problem of cooperative control between the exoskeleton and the human subject [1], or for reducing energy consumption when climbing stairs [2]. Preliminary evaluations are performed for this topic [3], as well as analyses of fall possibilities [4]. The case of stair descent by means of assistance with an exoskeleton [5] or improvement of stair climbing abilities by means of an exoskeleton actuated by myoelectric muscle signals [6] is also addressed. As mentioned, there are a vast number of articles dealing with this subject [7-13]. This kind of activity is necessary to support the mobility of people with disabilities, when there is no lift in a multi-storey building. It should be noted that within our research team there have been concerns about the design of an exoskeleton systems to assist stair climbing [14].

In this paper we have presented two constructive solutions of exoskeleton-type robotic systems for assisting a human subject when climbing or descending stairs. For the kinematic and dynamic study, we will use the first solution, with the second solution to be presented in future research.

2. Kinematic and dynamic analysis of the robotic system

The two kinematic schemes are shown in Figure 1. The first solution has seven kinematic elements and the second solution is designed with a number of 9 kinematic elements. Both solutions are monomobile, being driven by a single motor element. In the first phase we will study the first solution, the one with 7 kinematic elements.

The kinematic scheme of the implemented exoskeleton robot leg mechanism is shown in Figure 1, a. Based on this kinematic scheme, a virtual prototype of an exoskeleton robot leg is made, as shown in Figure 2. This model is made of link-type elements. The two mechanisms that model the two legs of the exoskeleton robot are identical, what differs is the angular positioning of the leading element in the overall model. For the right leg, the driver element is rotated 180 degrees relative to the left leg. In these mounting positions, the left leg will be in contact with the ground and the right leg will be in the swing phase.

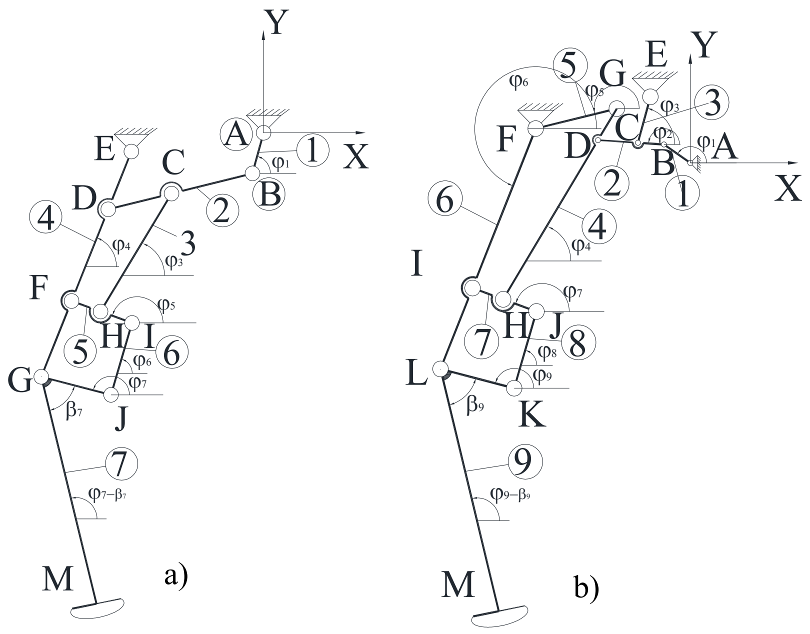

Figure 1. Kinematic scheme of the foot mechanism, with the two possible structural solutions

Based on the preliminary geometrical synthesis, we developed a virtual prototype of an exoskeleton, as shown in Figure 2. Constructively, this exoskeleton is built from an upper frame, on which the two exoskeleton leg mechanisms are attached. The driving elements are mounted on a shaft driven by means of a chain drive and are angularly offset by 180 degrees.

In order to simulate the stair climbing movement, a staircase is constructed that has the size regulated by existing design standards. To be compatible with stair climbing activity, the pitch of the exoskeleton must be equal to the distance between two consecutive steps. The step height must also be high enough to enable the next step of the ladder to be negotiated.

The simulation model was built with the help of the multibody dynamic systems analysis software ADAMS View. The development of the dynamic model involved the definition of the kinematic torques, the definition of the materials of the elements, the corresponding definition of the contact between the exoskeleton sole and the stairs. The results obtained are presented below. In a first step, we obtained the laws of variation of the rotation angles in the knee joints of the exoskeleton, Figure 3, as well as from the exoskeleton hip joint, in Figure 4. These joints correspond to the kinematic torques E and G. From Figure 3 it is observed that the angle in the knee joint reach a total amplitude of 40.11 degrees, and at the hip reach a value of 35 degrees.

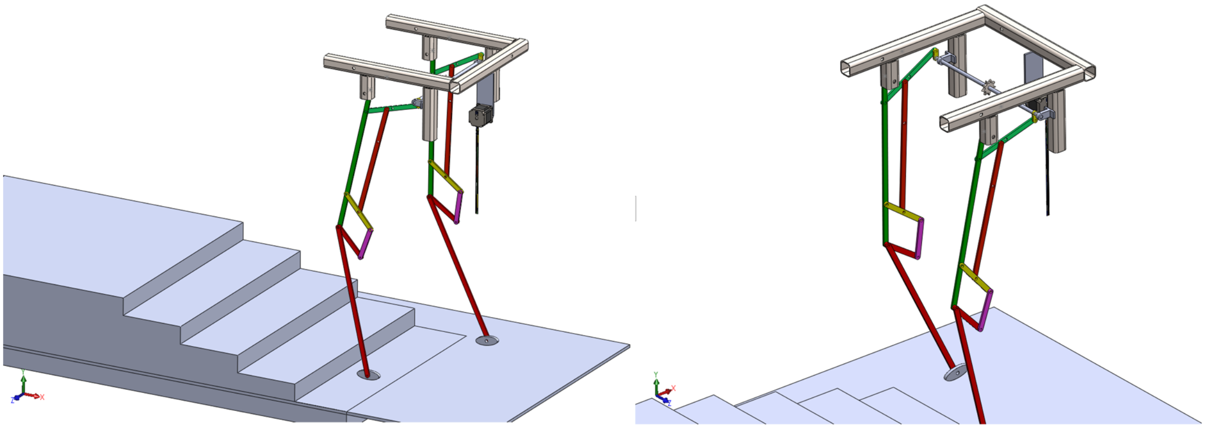

Figure 2. Virtual model of the robotic system, designed in SolidWorks

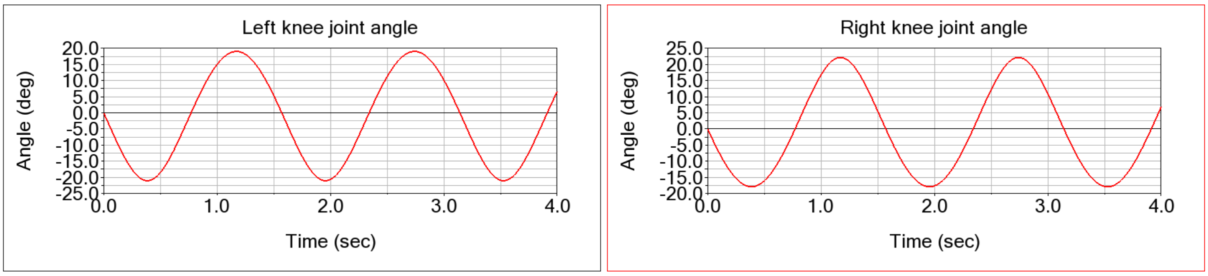

Figure 3. Motion variation laws [degrees] for the exoskeleton knee joints during walking

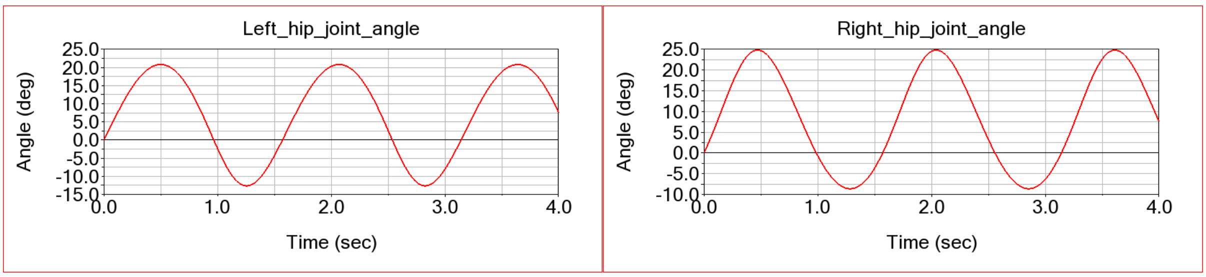

Figure 4. Motion variation laws [degrees] for the exoskeleton hip joints during walking

The positions (Figure 5) and linear velocities (Figure 6) for the centre of mass of the exoskeleton sole are also obtained. According to Figure 2, it is noted that the horizontal axis is denoted by X and the vertical axis by Y. Another set of results of interest are the laws of variation of the components of the connecting forces in the kinematic couplings of the mechanism. These are important for sizing in terms of mechanical strength. Thus, in Figure 7 and 8 these results are shown for the knee and hip joints. Maximum connection force values of 900 N are observed for the knee joint, and much higher values for the hip joint. The large difference between the values obtained for the hip joint comes from the eccentric placement of the drive motor. To optimize the dynamic model, the motor will be placed centrally between the two legs of the exoskeleton. The driving motor moment of the exoskeleton, according to Figure 9, has quite high values, namely 50 Nm.

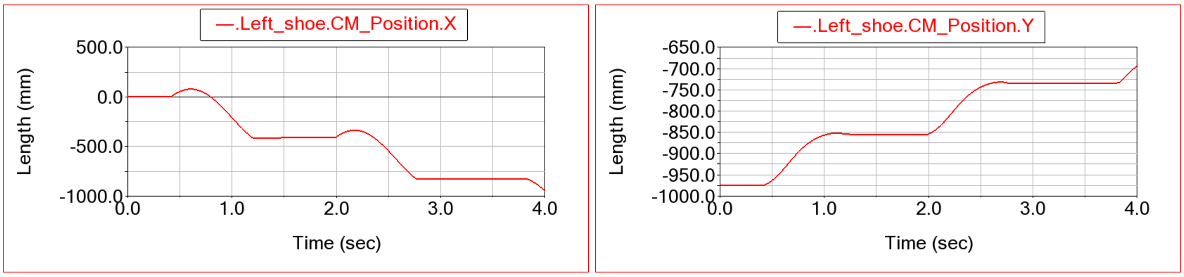

Figure 5. Exoskeleton feet centre of mass position

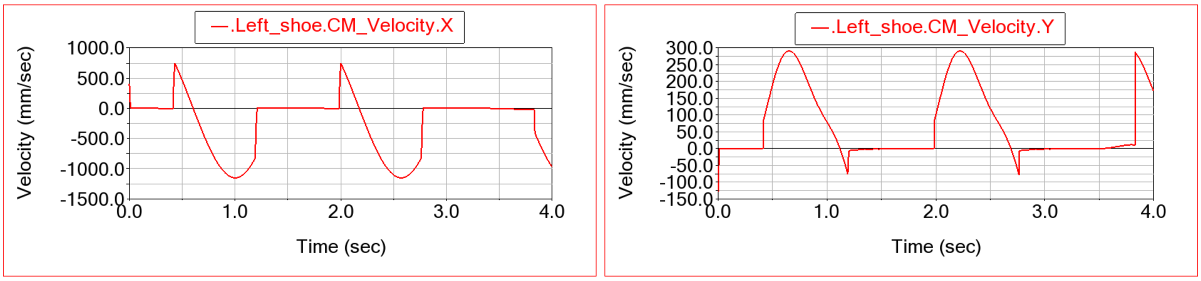

Figure 6. Exoskeleton feet linear velocity components

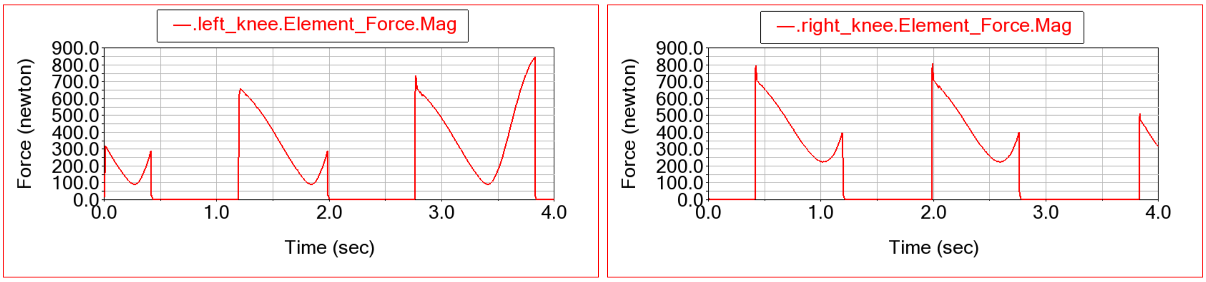

Figure 7. Exoskeleton knee joints force reactions during walking

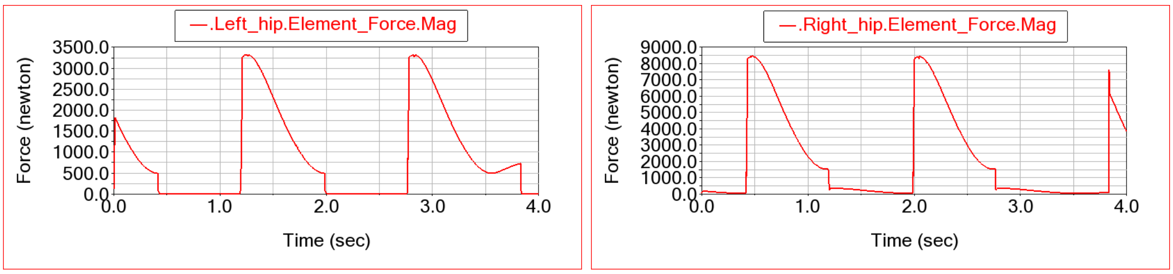

Figure 8. Exoskeleton hip joints force reactions during walking

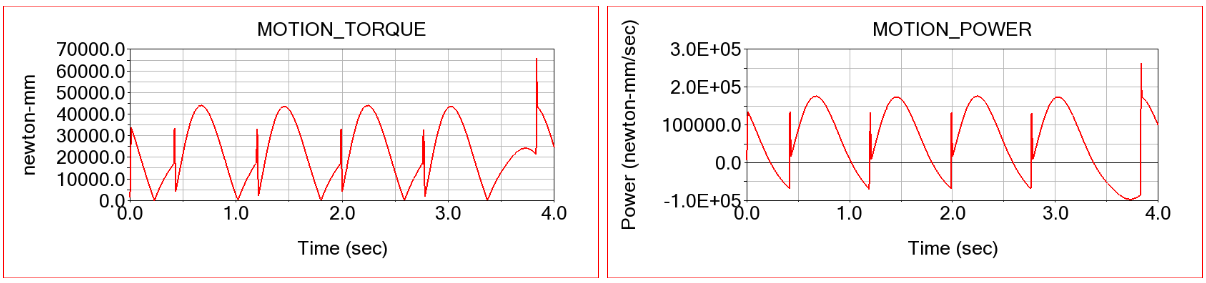

Figure 9. Torque and motion power for the exoskeleton actuation during walking

A sequence during the exoskeleton motion simulation for staircase motion assistance is shown in Figure 10, and in Figure 11 successive frames.

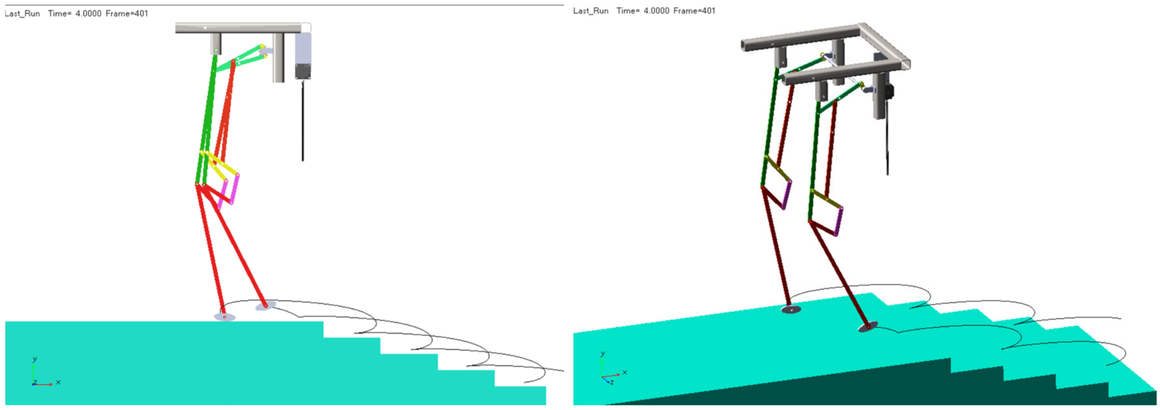

Figure 10. The trajectory described by the sole while climbing the stairs

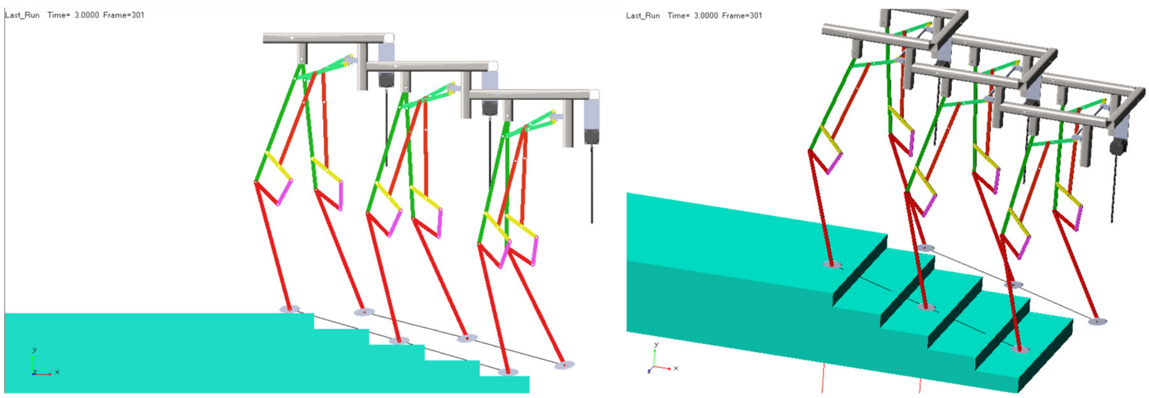

Figure 11. Exoskeleton snapshots from climbing the stairs

In the second part of the paper, we aim to comparatively analyse the behaviour of the exoskeleton robot in the situation when it climbs the stairs and then walking on a horizontal floor. The simulation of the motion in this situation is shown in Figure 12, where the trajectories described by the two legs are observed.

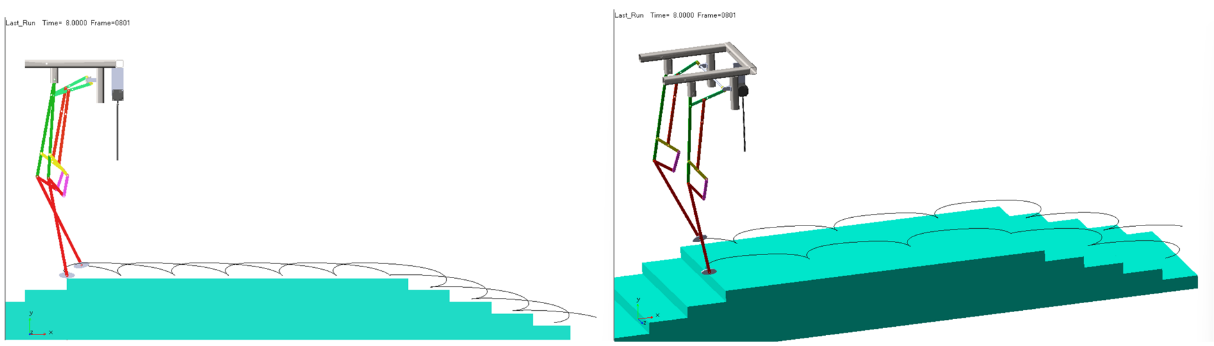

Figure 12. Virtual simulations of the exoskeleton during climbing stairs and walking in a straight path on a horizontal floor

For this simulation case, the results of interest are detailed below. Thus, in Figure 13 and 14 the resulting values of the connection forces in the hip and knee joints are shown. It should be noted that in the case of the hip joint the same large difference in value occurs between the left and right leg due to the positioning of the drive motor.

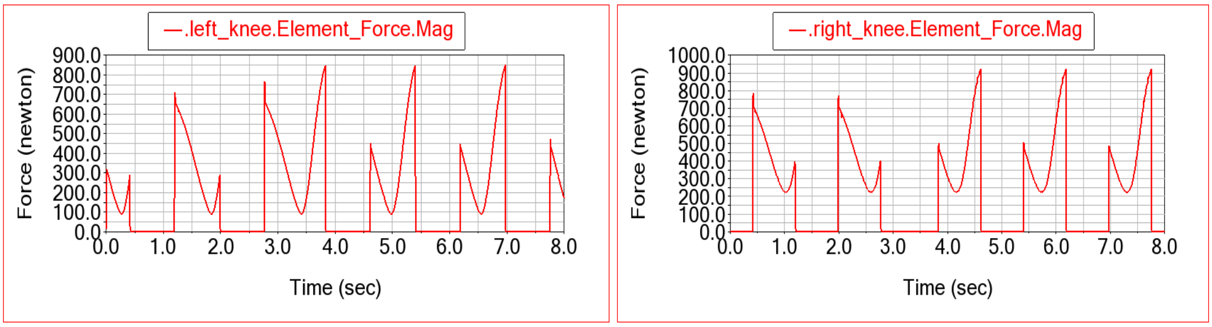

Figure 13. Exoskeleton knee joints connection force during walking and stair climbing

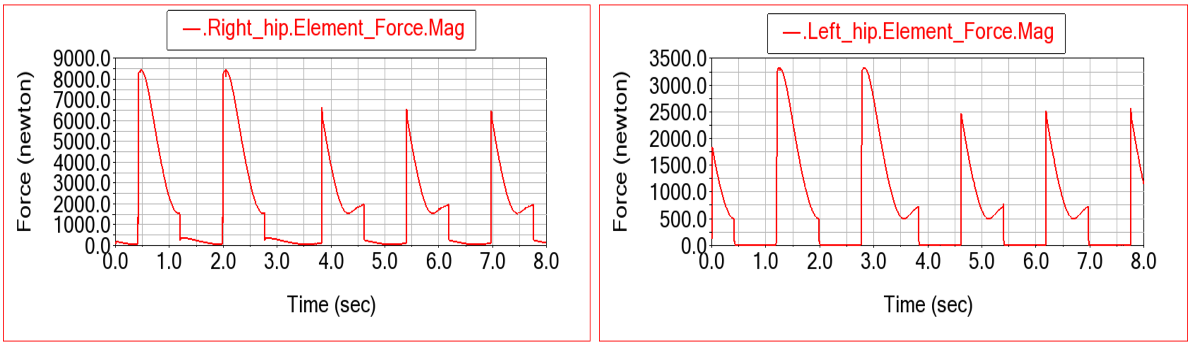

Figure 14. Exoskeleton hip joints connection force during walking and stair climbing

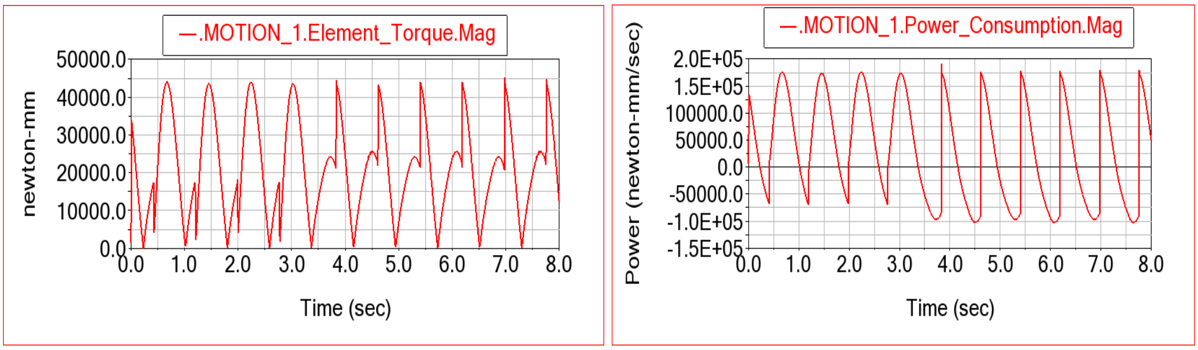

Figure 15. Torque and motion power for the exoskeleton actuation during walking and stair climbing

The next stage of the research development is the realization of the experimental prototype using additive manufacturing technology. The parts of the exoskeleton were made by 3D printing from the material called PLA-F, as shown in Figure 16. Thus, it can be remarked that the rapid prototyping by using 3D printers give us a lot of opportunities and it is much faster to validate a prototype by crossing from a concept solution represented by a virtual model, to a prototype that can be validated through laboratory experimental tests.

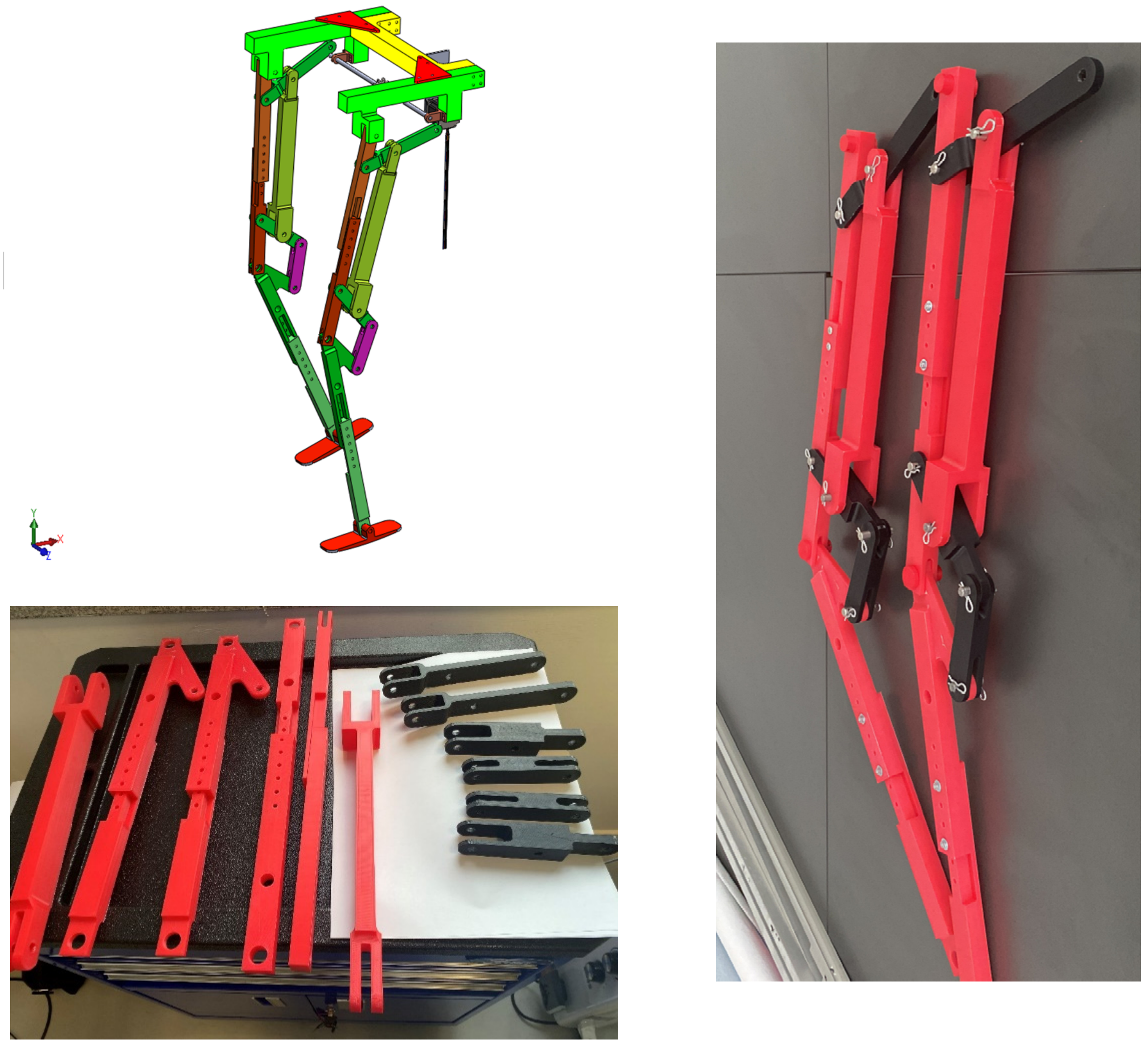

Figure 16. Exoskeleton components made by 3D printing for assembly purpose

3. Conclusions

In this paper we have performed a dynamic simulation of an exoskeleton robotic system designed to assist movement on stairs. The results obtained consisted of the variation laws of the angles in the hip and knee joints, in a first phase. Another category of results presented in the paper consists of the connection forces in the kinematic couplings of the exoskeleton, namely those obtained for the knee and hip joints are presented. The paper also presents the trajectory of the exoskeleton's sole when climbing stairs and walking a horizontal section. Preliminary simulation results demonstrate the feasibility of the virtual model. Consequently, the next step will be to validate the experimental model.

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