KINEMATIC AND DYNAMIC EVALUATION OF EXOSKELETON-ASSISTED GAIT ON AN INCLINED PLANE

IONUT GEONEA , DANIELA TARNITA

Abstract. This paper presents aspects of how an exoskeleton assists disabled people to walk on an inclined plane. This study is carried out with the help of the dynamic modelling software for mobile mechanical systems, ADAMS. Variation laws of kinematic parameters of interest, such as rotation angles in knee and hip kinematic couplings, and connecting forces in kinematic couplings are presented. The next stage in the development of this research is the realization of the experimental prototype using 3D printing technology. For this purpose, in the last part of the work we performed a structural optimization using ANSYS software for a kinematic element of the exoskeleton structure. The results obtained allow us to validate the virtual model and give us the certainty of the functionality of the robotic system for assisting human subjects when walking on an inclined plane.

Key words: exoskeleton, locomotor assistance, dynamic modelling, inclined plane, structural optimization.

1. INTRODUCTION

A medical exoskeleton is a device that assists paraplegics who have suffered a total or partial spinal cord injury or stroke to stand, walk, sit and even climb steps [1].

Medical exoskeletons are intended for paraplegics who have suffered a total or partial spinal cord injury or stroke [2].

Such a device consists of orthoses that are operated by servomotors positioned at the hips or knees. These servomotors are controlled by a central computer which, using data from a number of sensors, generates a sequence of steps that mimics a natural gait. The patient can thus perform various movements by simply pressing specific buttons: forwards, up or down stairs, etc. The device is battery-operated, which ensures mobility for several hours [3–5].

Rehabilitation with this revolutionary device is anatomically, physiologically and psychologically very important. From an anatomical point of view, medical

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exoskeleton therapy helps the patient to relearn the gait pattern, this is achieved by the device taking over the gait function and through repeated cycles of steps the patient regains the gait function.

Patients using medical exoskeletons become much more independent, being able to stand up and sit down, walk on their own and even climb up and down stairs. In short, they regain their self-confidence and can resume their lives and activities as before the accident [6–8].

Physiologically, a medical exoskeleton significantly reduces spasticity, helps to increase muscle mass and tone it, improves the cardiovascular system, contributes to bowel transit, reduces the risk of urinary tract infections, helps to reduce body fat and significantly improves the patient's quality of life. From a psychological point of view, exoskeleton therapy gives the patient the freedom of movement and independence to manage on their own, which has a positive impact on their overall well-being.

This device (exoskeleton) keeps paralyzed or paraplegic people upright, interacts with the patient's motor intentions and supports the body in movements that the muscles can no longer perform. In addition to a wheelchair, that does not activate the locomotor function of the lower limbs at all; the exoskeleton helps muscles become more flexible and toned, gets the blood moving and strengthens the muscular system. Unlike a wheelchair, moving around with a medical exoskeleton gives the patient a great deal of freedom of movement and allows them to remain active, enjoy activities such as walking on their own feet, going up and down stairs, sitting and getting up from a chair [9–11].

The paper is structured in three parts. In the first part, general aspects of the use of exoskeletons in locomotor assistance for people with locomotor disabilities are presented. In the second part, a kinematic and dynamic analysis of the exoskeleton robotic system is carried out with the help of ADAMS software. This simulation is carried out in the situation when the exoskeleton is moving on an inclined plane, in a climbing situation. In the last part of the paper, a structural optimization of a kinematic element of the exoskeleton structure is performed using ANSYS software.

2. KINEMATIC AND DYNAMIC ANALYSIS OF THE EXOSKELETON

The kinematic scheme of the robotic system for locomotor assistance of a human subject on an inclined plane is shown in Fig. 1. According to the kinematic scheme, it can be seen that the leg mechanism is of the closed kinematic chain type which has in its structure 9 kinematic elements and 14 rotating torques. The drive is by means of a single motor. By kinematic simulation performed with ADAMS software [12], when the robotic system operates on a base support, the ovoid trajectory described by the sole is obtained. According to Fig. 2, it can be seen that this trajectory is a closed curve without jumps and discontinuities.

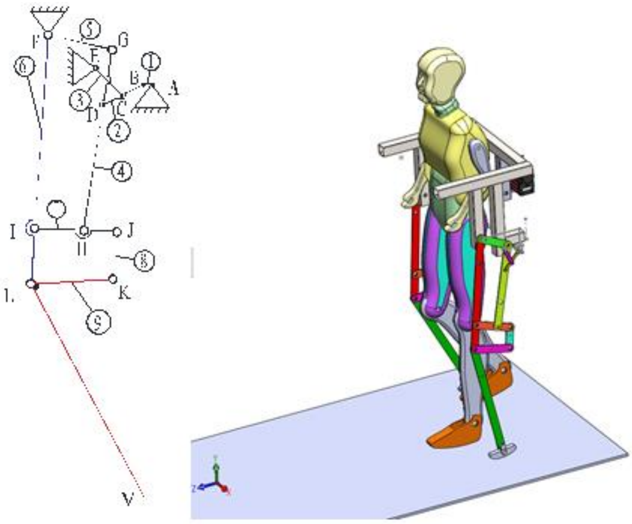

Fig. 1 – Kinematic scheme and virtual model of the exoskeleton robotic system.

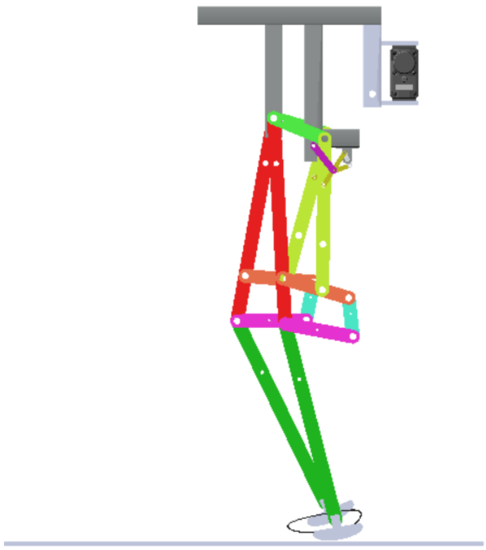

Fig. 2 – The ovoid trajectory written by the center of mass of the exoskeleton sole.

To study the motion of the exoskeleton on an inclined plane, we built a dynamic simulation model in ADAMS. We first considered a 15-degree tilt of the inclined plane, as shown in Fig. 3. The simulation is conclusive, the exoskeleton can climb the inclined plane, as shown in Fig. 4, where the trajectory described by the soles of the exoskeleton during the walk can be seen.

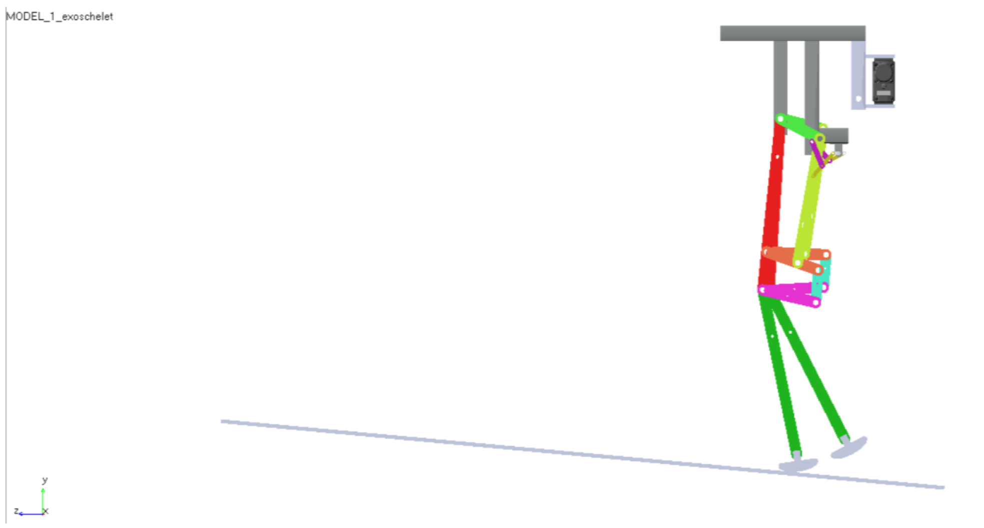

Fig. 3 – The exoskeleton in the beginning phase of the ascent on the inclined plane.

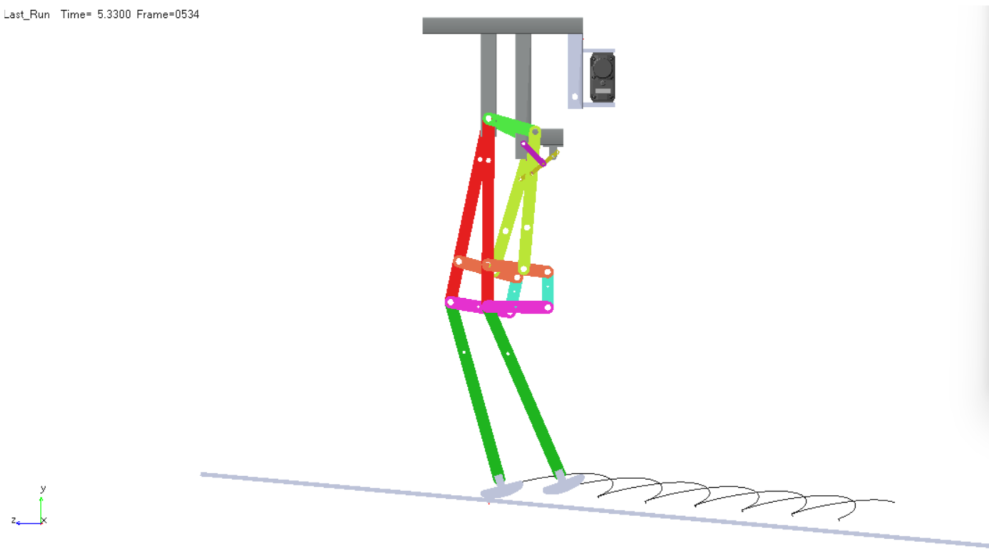

Fig. 4 – The exoskeleton during ascent on the inclined plane and the trajectory described by the two feet.

As graphical results, we have shown in Fig. 5 the laws of variation of the centre of mass coordinates, for both legs, along the vertical axis, and in Fig. 6 along the horizontal Z axis. These results are calculated with respect to the origin of the fixed coordinate system, which is oriented as in Fig. 4, and the origin is in the extreme left side of the upper frame.

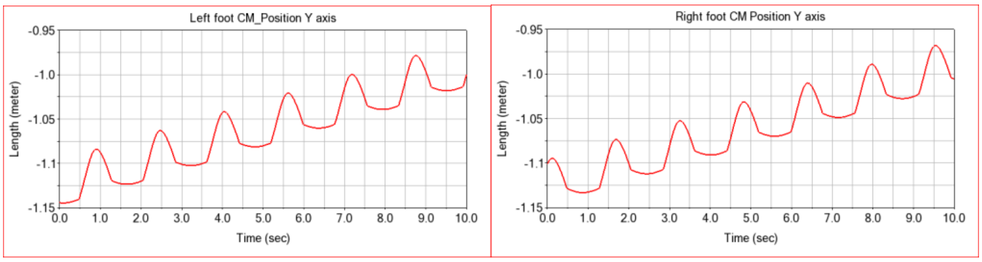

Fig. 5 – Left and right foot center of mass position (upon Y axis -Vertical).

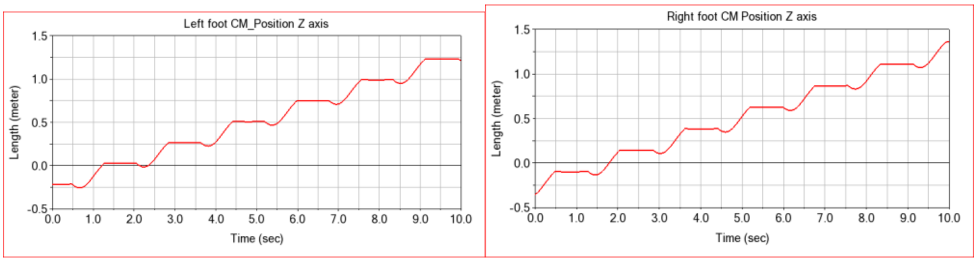

Fig. 6 – Left and right foot center of mass position (upon Z axis -Horizontal).

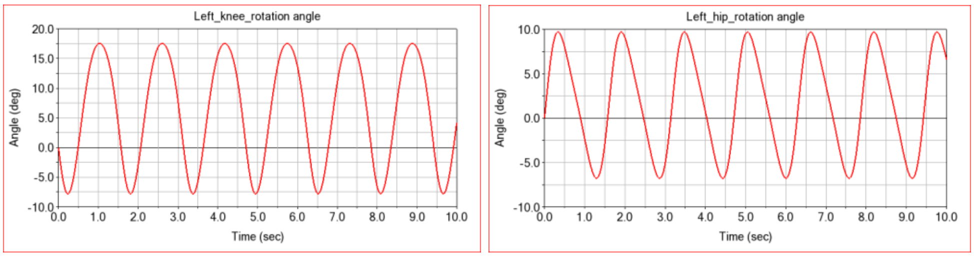

Fig. 7 – Laws of variation of rotation angles in knee joints.

According to Fig. 7 it can be seen that in the knee joint we have an angular amplitude of 25 degrees and in the hip joint the amplitude is 17 degrees.

Regarding the link forces in the exoskeleton joints, we have shown in Fig. 8, the variation of the components along the Z and Y axis, for the exoskeleton knee joint, namely for the left leg. It can be seen that the largest value is the vertical component, that along the Y axis.

In Fig. 9 we have shown the laws of variation of the link force components for the exoskeleton hip joint. It can be seen that the highest value is the vertical component, that is, after the Y-axis, with a maximum of 1 700 N. This maximum occurs due to the shock, originating from the contact between the sole and the ground, which in the simulation are considered rigid. In the real situation, on the exoskeleton's sole we will fix a shock-absorbing material, i.e. a portion of soft rubber fixed by gluing. As for the resulting forces, from the hip and knee joints, these variations are shown in Fig. 10. It can be seen that the maximum resistive force occurs in the hip joint, with a value close to 2 000 N. The components along the horizontal Z-axis have higher values in the situation of climbing on an inclined plane than when walking on a floor without inclination.

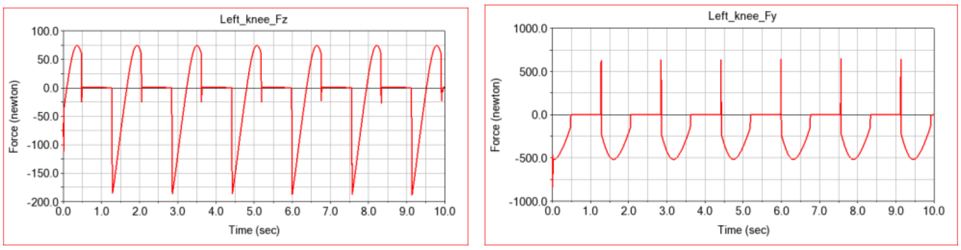

Fig. 8 – Connecting forces in the knee joint, upon horizontal and vertical axis.

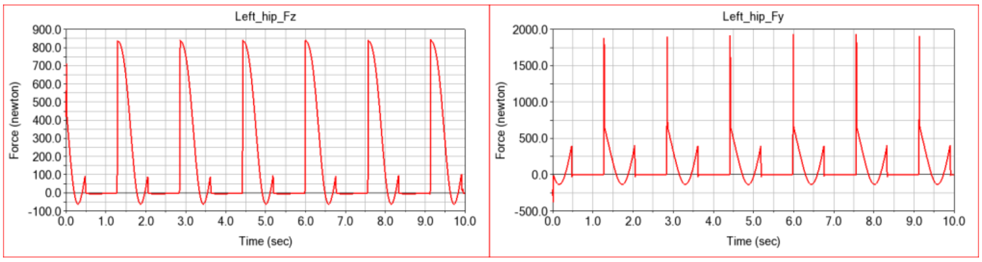

Fig. 9 – Connecting forces in the hip joint, upon horizontal and vertical axis.

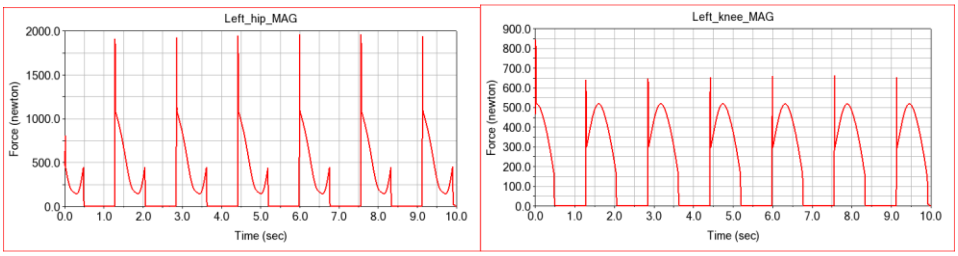

Fig. 10 – Resulting forces in the hip and knee joints.

The idea of assisting a disabled person to walk on an inclined plane is particularly useful for facilitating access for these people in institutions or at home. This assistance is less dangerous for the assisted person than assistance in climbing stairs.

For these safety reasons, the components of the exoskeleton must be designed to ensure adequate mechanical and fatigue resistance. For this reason, we will present the structural optimization of such an element using ANSYS software.

3. STRUCTURAL OPTIMISATION OF AN ELEMENT OF THE ROBOT STRUCTURE

The structural optimization of kinematic elements is carried out with the aim of reducing element mass as well as reducing stress concentrators. The geometrical model of the structural element is shown in Fig. 11, where the input parameters are also indicated.

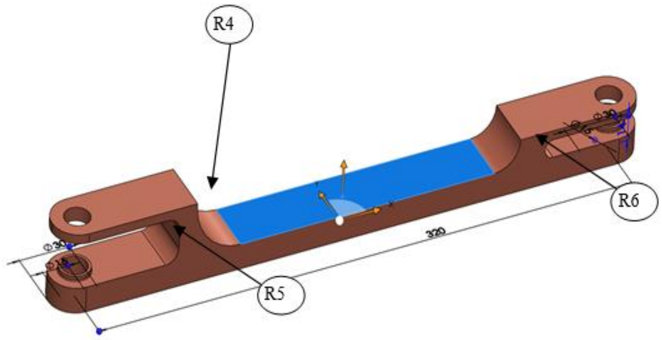

Fig. 11 – The geometric model of an element and its input parameters.

As input parameters we defined, according to Fig. 11:

- The radius of connection R4 (FBlend4), defined as parameter P1, with limits 9–27.5 mm;
- The radius of splice R5 (FBlend5), defined as parameter P2, with limits of variation 5–12 mm;
- The extrusion height of the primary profile, Extrude 1, referred to as parameter P4 with limits of variation 10–14 mm;

The geometric model of the element, is made parametrically, using ANSYS Design Modeler, as shown in Fig. 12.

The output parameters are the von Mises equivalent stress, the specific deformations and the mass of the element. As conditions for the bearing and the loading of the element, we have specified a force on one of the bores, 2 000 N, which stresses in tension. The other bore we considered fixed. These aspects, including the hexahedral finite element discretization of the element, are shown in Fig. 13.

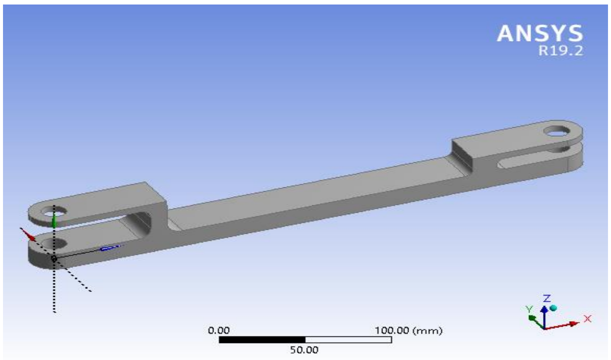

Fig. 12 – Parameterized geometric modeling in ANSYS Design Modeler.

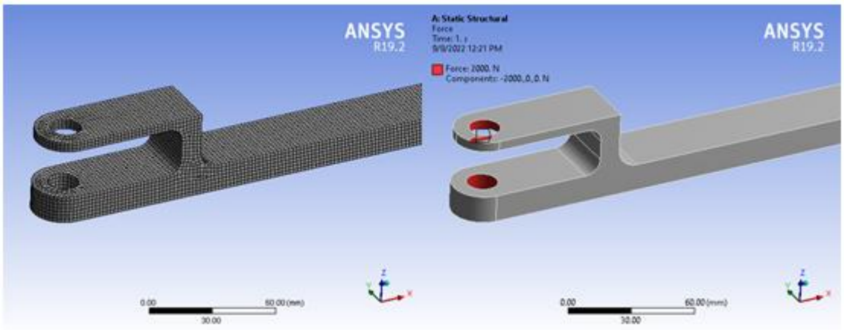

Fig. 13 – Element mesh and load apply.

Thus, we obtained the response surfaces, shown in Figs. 14 and 15. These show us the dependence of an output parameter on two other input parameters. In Fig. 14 we can see the dependence of the element mass on the parameters P2 and P3, or P3 and P5.

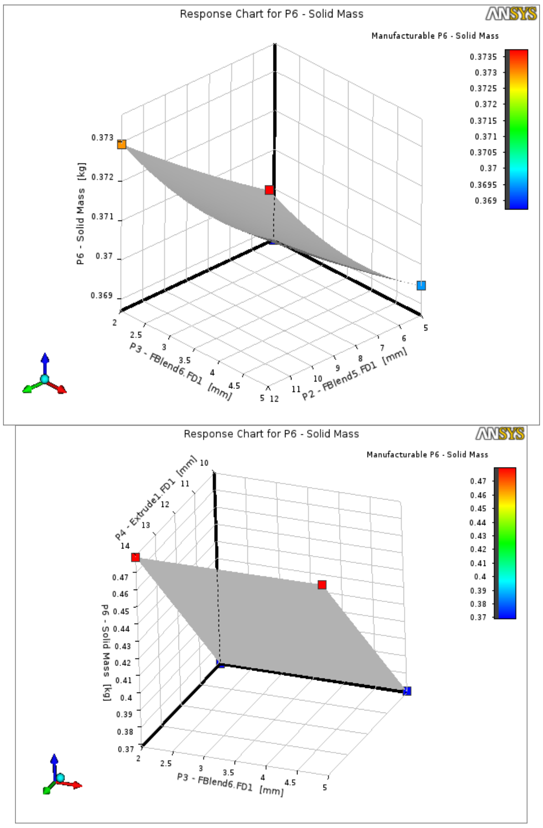

Fig. 14 – Response chart for P6-Solid Mass.

Figure 15 shows the response surface of the parameter P7 – Equivalent Stress Maximum, in relation to the input parameters P2, P3 and P3, P4.

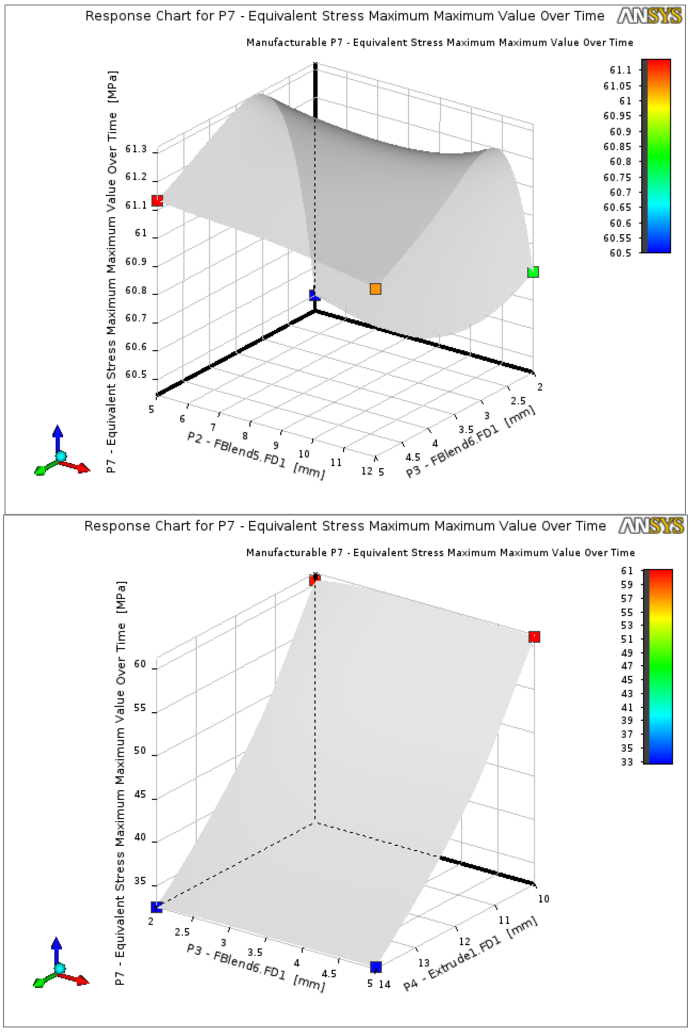

Fig. 15 – Response chart for P7 – Equivalent Stress Maximum.

The objective of the optimization is to reduce the mass of the element as well as to reduce the total displacements.

The optimal solution assumes the following values for the input parameters:

- ➢ The radius of connection R4 (FBlend4), defined as parameter P1, is 11 mm;
- ➢ The radius R5 (FBlend5), defined as parameter P2, is 5 mm;
- ➢ The radius R6 (FBlend6), defined as parameter P3, is 2 mm;
- ➢ The extrusion height of the primary profile, Extrude 1, is 14 mm;

1	Input Parameters		
2	Name	Lower Bound	Upper Bound
3	P1 - FBlend4.FD1 (mm)	9	11
4	P2 - FBlend5.FD1 (mm)	5	12
5	P3 - FBlend6.FD1 (mm)	2	5
6	P4 - Extrude1.FD1 (mm)	10	14

Fig. 16 – Optimal input parameter values.

The optimized output parameters are given below, as shown in Fig. 16:

- von Mises equivalent stress, with the value of 32.606 MPa;
- specific strains, P8 – Equivalent Elastic Strain Maximum 0.0004586;
- element mass, 0.4797 kg.

For the optimal geometrical solution shown in Fig. 17, the distribution maps for the following parameters: equivalent elastic strain, equivalent elastic stress, directional deformation.

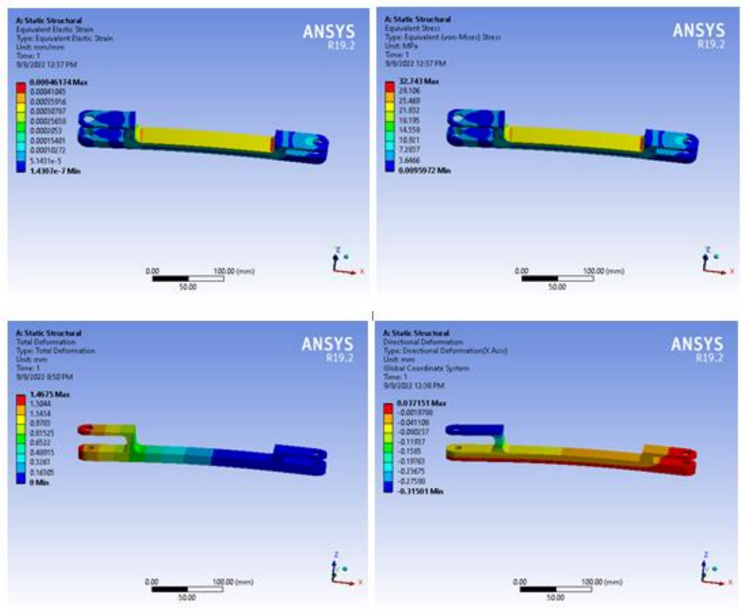

Fig. 17 – Maps for equivalent elastic strain, equivalent elastic stress, directional deformation.

4. CONCLUSIONS

In this paper we proposed an original solution of an exoskeleton that helps to assist the movement of a human subject on an inclined plane. We performed a kinematic and dynamic simulation in ADAMS in order to validate the virtual model. In order to be able to develop the physical prototype, structural optimization of the elements is necessary, with the aim of reducing the mass of the elements, but preserving the structural integrity of the exoskeleton. For this purpose, we have performed a structural optimization of a kinematic element, which will be extended to all elements of the exoskeleton.

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