Design and Numerical Characterization of a Leg Exoskeleton Linkage for Motion Assistance

I. Geonea, S. Dumitru, C. Copilusi, A. Margine and P. Rinderu, *Member, IAENG*

***Abstract*—In this paper is presented the structural and mechanical design completed with kinematic analysis of a leg exoskeleton for human motion assistance and rehabilitation. The exoskeleton proposed design is based on a seven links mechanism, designed to fulfill human locomotion tasks. A kinematic model of the proposed mechanism is studied and solved with a computational algorithm, to obtain numerical results with plots. A 3D model is designed for simulation purposes in ADAMS multi body dynamics software. The obtained simulation results are useful to appreciate the exoskeleton usefulness for human rehabilitation purposes.**

***Index Terms*—Human gait, exoskeleton design, kinematics, design, dynamic simulation.**

I. Introduction

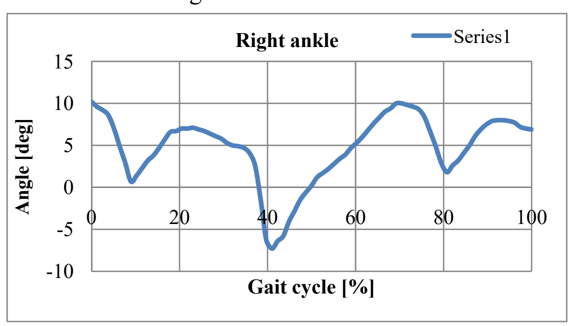
CURRENTLY, the subject of human motion assistance and rehabilitation is present in a large number of research papers. In the field of medical recovery therapies, the recovery of locomotion capabilities is needed for patients who have disease like stroke or spinal cord injuries. To regain motion capabilities, the human subject practice a repetitive assisted gait motion. The first research in this area, of exoskeleton robotic systems development, started in 1960, and the initiative belongs to two separate groups of researchers. The first one is from the US and the second one from the former Yugoslavia. The first group intended to develop a robotic technology in order to improve the abilities of the human carrier body, mainly for military purposes, mean while the second group of researchers intended to develop this new technology for assisting the motion of people with disabilities.

Currently the development of robotic devices for human motion assistance and rehabilitation is presented in a large number of studies, research articles and books. For disabled people's motion assistance are designed and manufactured exoskeleton systems in different research laboratories. The main purpose of these robotic systems is to assist the human gait (practiced on the rehabilitation therapy). Most relevant existing robotic exoskeleton systems are presented in review papers published by: Chen, (2016) [1]; Anama (2012) [2]; Diaz (2011) [3]; Yan (2015) [4]; Huo (2016) [5]. These studies present the stage to day of existing design solutions. Easy operation and low cost exoskeleton robotic systems are developed and studied by: Copilusi (2015) [6, 7]; Margine (2017) [12]; Geonea (2018) [8-11, 13-15]. An important feature of robotic exoskeleton systems is represented by the reduced cost and easy operation characteristics and also easy implementation in the field of rehabilitation.

In this study a new exoskeleton leg solution is proposed. The novel exoskeleton is designed based on low cost and easy operation implementation in practical activities. The design solution is studied based on the results of numerical simulation from ADAMS.

II. Human gait experimental study

Today are available on the market, a large number of equipment's and software for the experimental human gait analysis. The human ankle, knee and hip joints angular variations were analyzed for a healthy male of 1.67 m height, 68 kg, age 36 by attaching goniometers sensors on each joint. The goniometer sensor is used to measure flexion-extension angle.



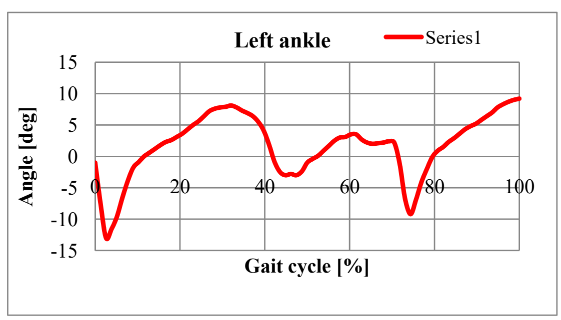


Fig. 1. Ankle joints angle variation for a complete step.

In Fig. 1 is plotted the ankle joints angle variation (for right and left leg) for a complete gait cycle corresponding to

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a complete step of the human gait. The time duration of a step is 1.56 seconds. In Figs. 2 and 3 is plotted the knee and hip joints angle variation, corresponding to a walking step.

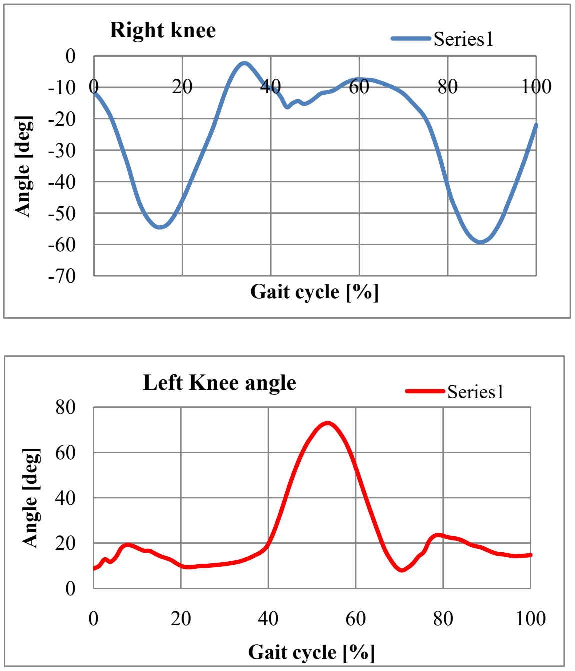

Fig. 2. Knee joints angle variation for a complete step.

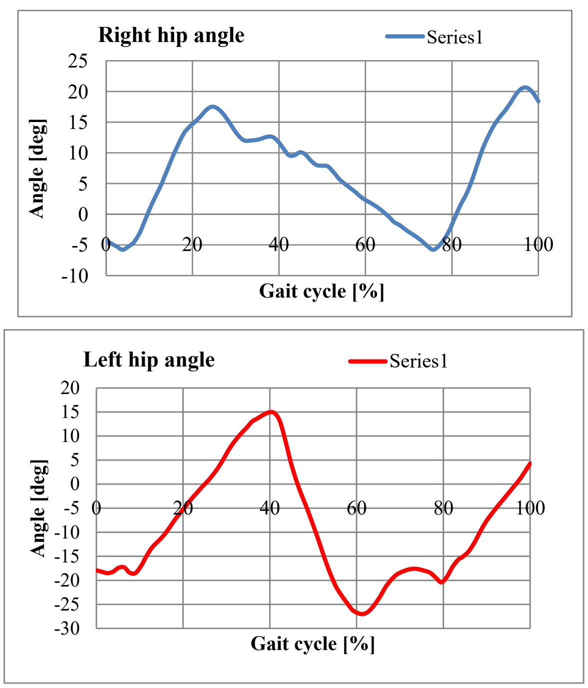

Fig. 3. Hip joints angle variations for a gait cycle.

With the aid of electro-goniometers sensors and Biometrics software, the angular variations of each human leg joint is acquired and plotted, in Figs. 1-3. The obtained results for the human gait are comparable with others obtained by other researchers, presented in published articles [6, 7]. Our obtained results are comparable with results obtained for normal gait. The ankle joint flexion extension angle reaches 20°, as is plotted in Fig. 1. The knee joint angular amplitude reaches 68°, as is plotted in Fig. 2, and the hip joint angle amplitude reaches 35°, as is presented with plots in Fig. 3.

III. Leg Exoskeleton Mechanism Design

The kinematic scheme of the mechanism for the assistant's exoskeleton legs is shown in Fig. 4. The proposed leg mechanism is composed by a parallelogram mechanism completed with a chain comprising a three links mechanism.

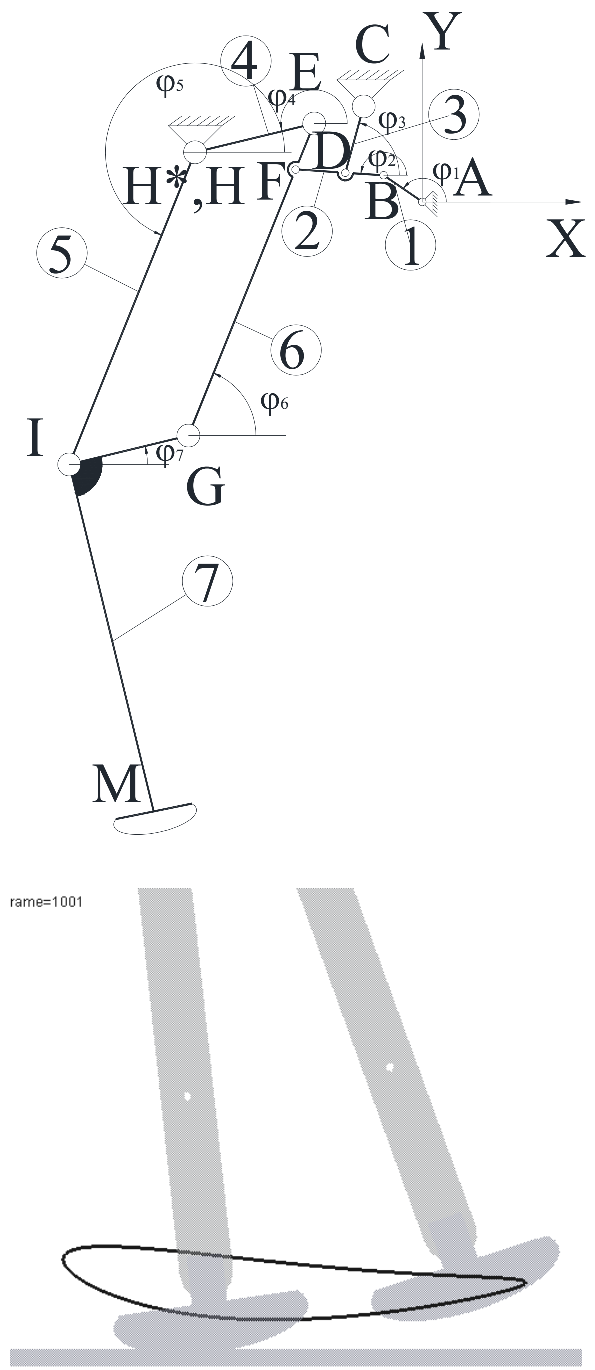

Fig. 4. A kinematic scheme of the proposed leg mechanism and foot computed trajectory in ADAMS.

The links are noted with digits from (1) to (7) and the joints with letters. The motor link of the mechanism is denoted with (1). The link (5) represents the femur, the tibia link is (7), the joint H represents the hip joint, and the knee

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joint is denoted with I. The size of the links (5) and (7) can be adjusted so that the shape of the point M trajectory to be an ovoid one, as to human gait (as plotted in Fig. 4).

This leg mechanism can assure the mobility of knee and hip joints. The ankle joint is not considered because its angular amplitude during walking is small.

IV. A Kinematic Analysis

A theoretical analysis of the leg exoskeleton kinematics was carried out in order to evaluate characteristics and simulate performances and operation features. The point M position, reported to the XY reference system, Fig. 4, can be evaluated as a function of input angle φ_1 and dimensional parameters of the linkage. Point D position, according to the fixed reference system is computed with Eq. (1):

$$\begin{aligned} x_D &= x_B + l_{BD}\cdot\cos\varphi_2 = x_c + l_{CD}\cdot\cos\varphi_3 \\ y_D &= y_B + l_{BD}\cdot\sin\varphi_2 = y_c + l_{CD}\cdot\sin\varphi_3 \end{aligned} \quad (1)$$

Point E position is computed with Eq. (2) and point I position with Eq. (3).

$$\begin{aligned} x_E &= x_F + l_{FE}\cdot\cos\varphi_6 = x_H + l_{HE}\cdot\cos\varphi_4 \\ y_E &= y_F + l_{FE}\cdot\sin\varphi_6 = y_H + l_{HE}\cdot\sin\varphi_4 \end{aligned} \quad (2)$$

$$\begin{aligned} x_I &= x_H + l_{HI}\cdot\cos\varphi_5 = x_G + l_{GI}\cdot\cos\varphi_7 \\ y_I &= y_H + l_{HI}\cdot\sin\varphi_5 = y_G + l_{GI}\cdot\sin\varphi_7 \end{aligned} \quad (3)$$

The D, E and I velocity can be evaluated by using time derivatives from Eqs. (1) to (3) and angles φ_i (i = 2-7) can be solved from closure loops equations as function of φ_1.

$$\varphi_i = 2\tan^{-1}\frac{A_i \pm \sqrt{A_i^2 + B_i^2 - C_i^2}}{B_i - C_i};\ i = \overline{2,7} \quad (4)$$

With:

$$\begin{aligned} &A_3 = -2(y_C - y_B)l_{CD};\ B_3 = -2(x_C - x_B)l_{CD}; \\ &C_3 = l_{BD}^2 - (x_C - x_B)^2 - (y_C - y_B)^2 - l_{CD}^2. \\ &A_4 = -2(y_H - y_F)l_{HE};\ B_4 = -2(x_H - x_F)l_{HE}; \\ &C_4 = l_{FE}^2 - (x_H - x_F)^2 - (y_H - y_F)^2 - l_{HE}^2. \\ &A_7 = -2(y_G - y_H)l_{GI};\ B_7 = -2(x_G - x_H)l_{GI}; \\ &C_7 = l_{HI}^2 + (x_G - x_H)^2 + (y_G - y_H)^2 - l_{GI}^2. \end{aligned} \quad (5)$$

A kinematic analysis is performed with the above equations. An algorithm was created in Maple Software, with the input data as: l_{AB}=10 mm; l_{CD}=90 mm; l_{BF}=115 mm; l_{DF}=65 mm; l_{EH}=160 mm; l_{HI}=440 mm; l_{IM}=450.

Numerical results have been obtained without considering the leg's interaction with the ground. In Figs. 5-8 are presented the angular variation computed for the exoskeleton hip and knee joints. In Fig. 9 is presented the computed motor torque.

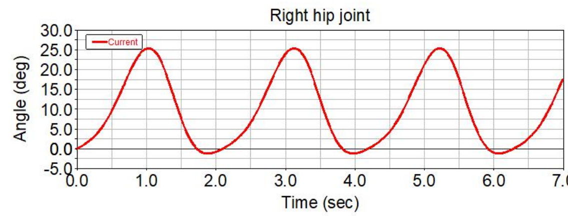

Fig. 5. Computed angular variation of hip joints.

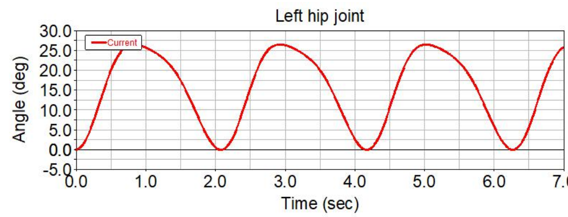

Fig. 6. Computed angular variation of hip joints.

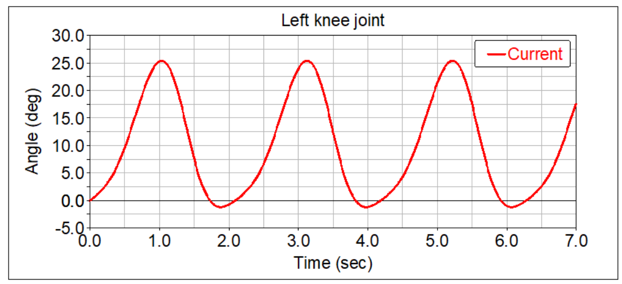

Fig. 7. Computed angular variation of left knee joint.

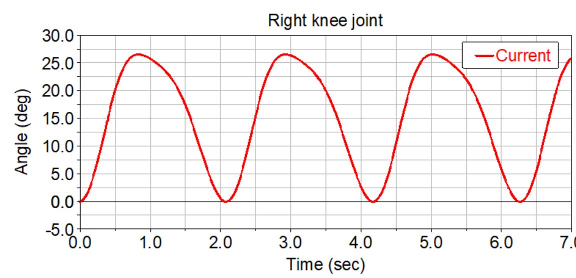

Fig. 8. Computed angular variation of right knee joint.

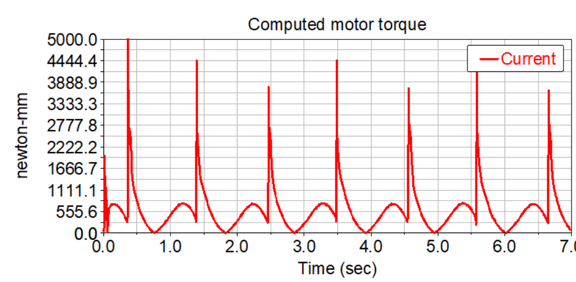

Fig. 9. Computed angular variation of motor torque.

V. Design of CAD model and dynamic simulation

A mechanical design of a proposed exoskeleton is represented in Figs. 10 and 11. The links shape has to be designed to permit adjustments of mechanism links in accordance with different human body constitution. A dynamic simulation has been developed by using a proper model for operation tests in ADAMS environment (Adams 2013). Contact, stiffness, damping coefficients, and friction force coefficients have been set accordingly, as listed in Table 1, with links made of steel.

The exoskeleton consists of two mechanisms for the left and right legs. The legs are composed of 7 links connected by 10 kinematic rotating joints. The electric motor with gearbox reducer (9), which is mounted on the upper frame (10), and chain (12), is used to drive the two mechanisms.

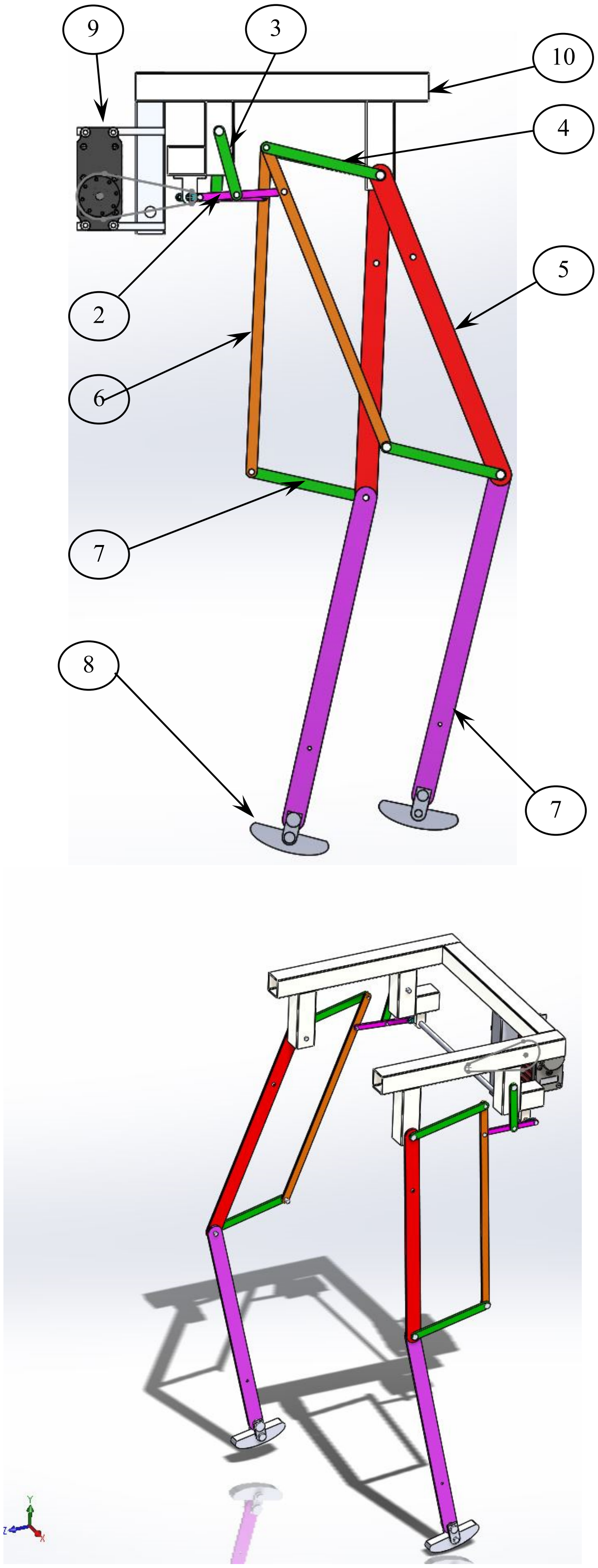

Fig. 10. A mechanical design of the proposed exoskeleton.

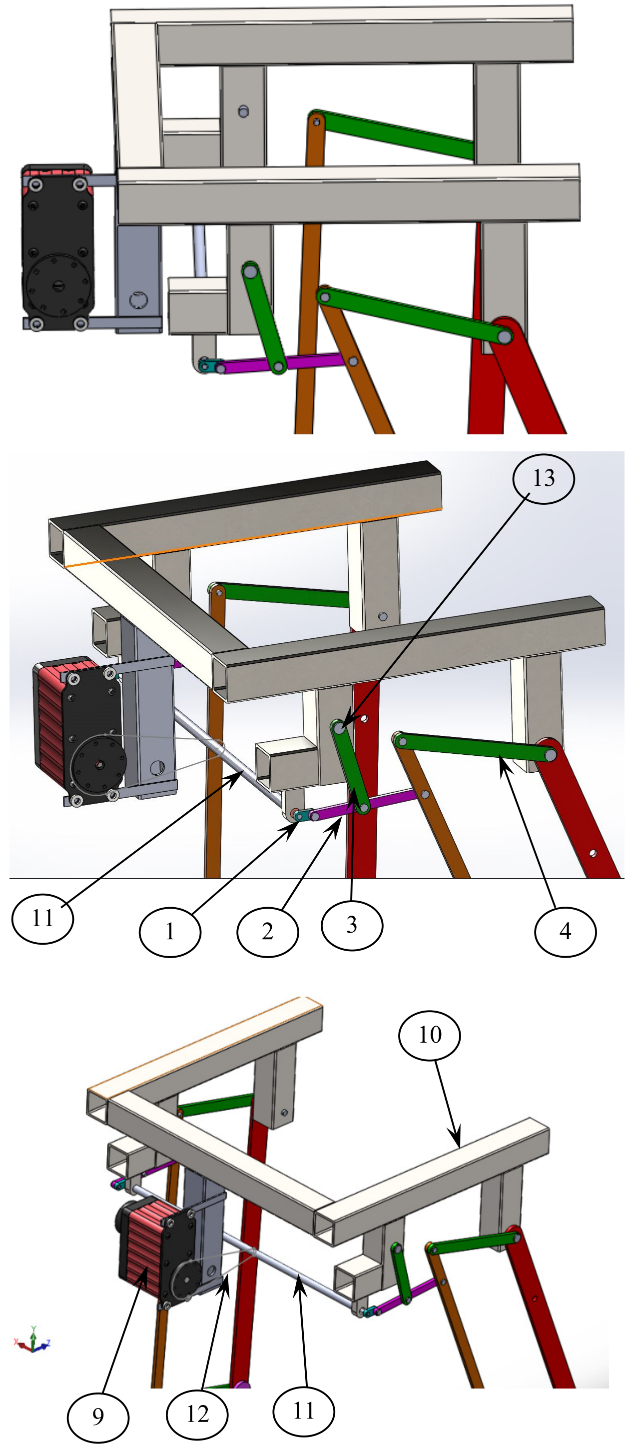

Fig. 11. A mechanical design of the proposed exoskeleton (detail of upper part).

By means of a chain wheel drive, the motion is transmitted to the shaft (11), which is mounted on the upper frame (10) by means of two radial-axial ball bearings. The motor elements (1) of the two leg mechanisms are connected to the drive shaft (11) and are oriented 180 degrees. On the upper frame, the elements (3) and (5) are connected by means of the rotation (with bolts) C and H. The element (7) consists of two segments (GI) and (IM) mounted (welded) at an angle of 90 degrees. The exoskeleton has a human foot-like structure: the joint (H) represents the hip joint, the joint (I) represents the knee joint and the (HI) and the (IM)

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segments represent the femur and the tibia. The simulation model is completed with a human virtual mannequin. The exoskeleton and mannequin assembly is detailed in fig. 12.

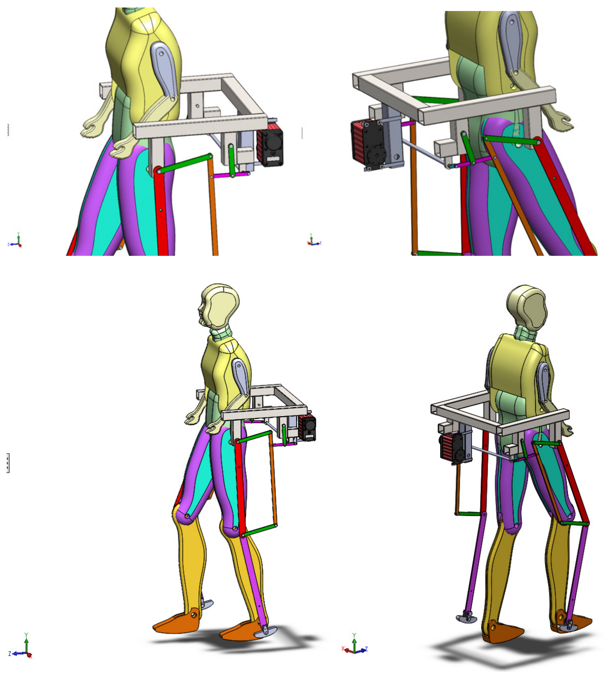

Fig. 12. Aspects of the exoskeleton mechanical design with human mannequin attached.

TABLE 1.
ADAMS PARAMETERS FOR DYNAMIC SIMULATION

Parameter	Value
Elasticity modulus	2.1·105 N/mm2
Density	7.8E-6 kg/mm3
Penetration depth	0.1 mm
Friction force, μs	0.5
Contact force exponent	1.8
Damping	40 Ns/mm;
Stiffness	1200 N/mm

Computed exoskeleton walking sequences are represented in Figs. 13-14 and main kinematic results are shown in Figs. 15 - 23. From Figs. 15 -17 it can be observed that appropriate values of kinematic parameters are obtained as compared with those from experimental tests and numerical kinematic analysis.

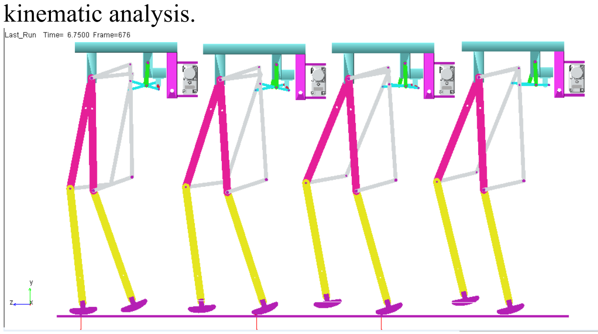

Fig. 13. A walking frames in ADAMS simulation of the exoskeleton.

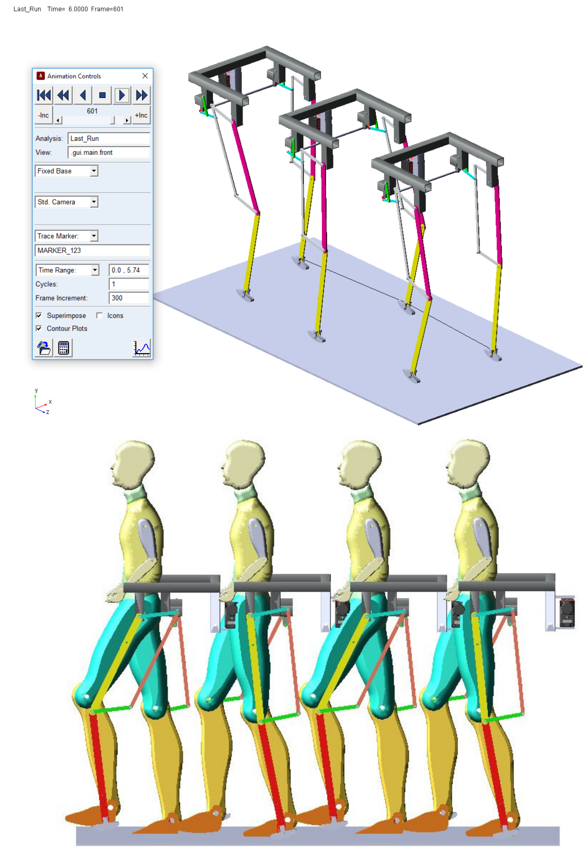

Fig. 14. A walking frames in ADAMS simulation of the exoskeleton and exoskeleton with human mannequin.

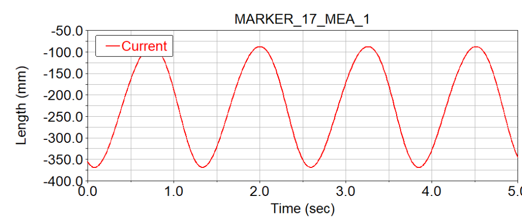

Fig. 15. Translational displacement upon X axis (horizontal) of the exoskeleton right foot.

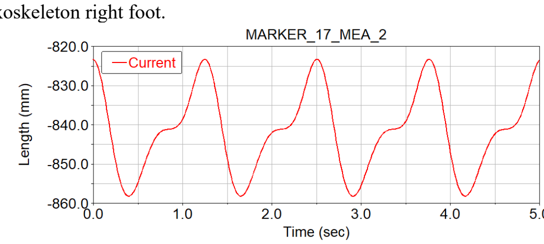

Fig. 16. Translational displacement upon Y axis (vertical) of the exoskeleton right foot.

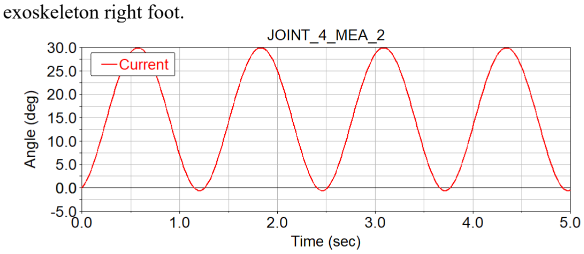

Fig. 17. Computed exoskeleton right knee angle variation.

Translational displacements of the exoskeleton foot, when it's operate on a fixed support, are presented in Figs 15 and 16. When the exoskeleton performs gait, the same parameters are plotted in Figs. 18 and 19.

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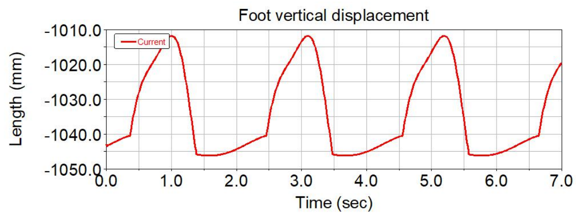

Fig. 18. Computed plot of the exoskeleton right foot vertical displacement.

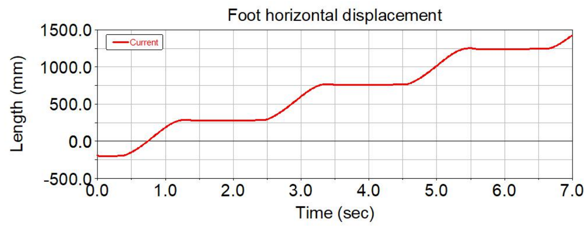

Fig. 19. Computed plot of the exoskeleton right foot horizontal displacement.

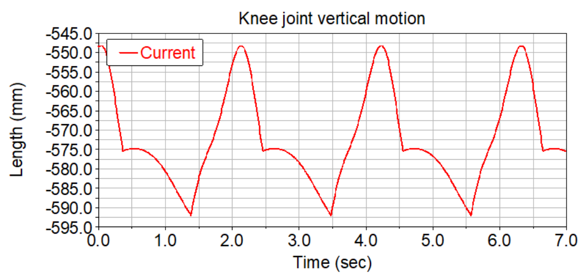

Fig. 20. Computed exoskeleton knee joint vertical motion.

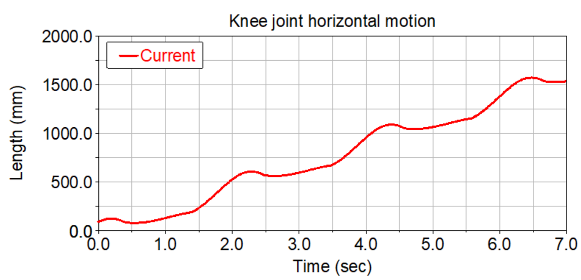

Fig. 21. Computed exoskeleton knee joint horizontal motion.

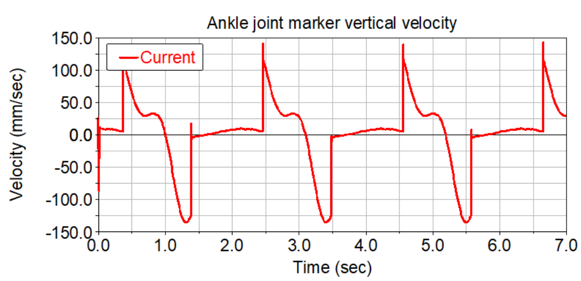

Fig. 22. Computed exoskeleton ankle joint marker vertical velocity.

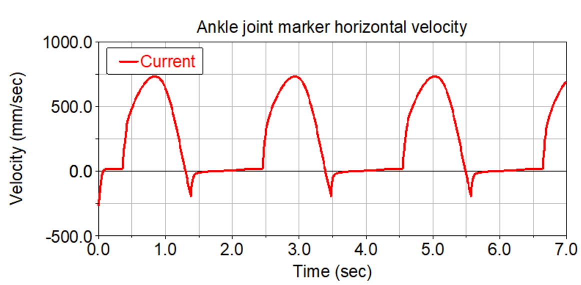

Fig. 23. Computed exoskeleton ankle joint marker horizontal velocity.

VI. Conclusions

In this paper a new prototype of a motion assistance robotic exoskeleton intended for human with disabilities is proposed. The solution features low cost and easy-operation characteristics. Some simulation results obtained with ADAMS, where is developed a dynamic model reveals suitable performance for operation in walking and rehabilitation applications, although its design requires future additional improvements concerning ankle joint motion support. The proposed design is simple, wearable, and easy to adjust on different patients, because it features an anthropomorphic structure. It is operate with only one motor that can be controlled as concerns the angular velocity. The exoskeleton purpose is to assist human gait for purpose of rehabilitation and also enhance human motion capabilities.

Acknowledgment

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