Numerical Simulation and Experimental Characterization of a Leg Exoskeleton for Motion Assistance

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***Abstract*— This paper addresses a numerical and experimental characterization of a leg exoskeleton for motion assistance of human disabled subjects. The introduction part is followed by the description of the design model of exoskeleton to be worn by a human disabled patient. In the third part of the paper is presented a numerical characterization of the leg mechanism when it operates on a supporting stand and when the exoskeleton is performing gait with a human mannequin. Based on the simulated CAD model it's developed an experimental model of the exoskeleton. Its motion is characterized when is performing gait, based on an ultra speed video camera and reflective markers analysis equipment. Obtained results are discussed in order to analyze the exoskeleton kinematic and dynamic features.**

***Index Terms*—human leg, exoskeleton design, simulation.**

I. Introduction

FROM studied literature results that there are many gait rehabilitation systems for human disabled patients.

Worldwide it is a large number of people, which are affected by locomotion disabilities, such as profound muscle weakness or motor control. People with severe muscle problems resulted from neurological disease such as hemiparesis after stroke, have severe walking problems. The principal aim of the human walking rehabilitation after stroke is to regain the walking functions. The medical devices existent on the market to facilitate this need are limited [1, 2]. A part is intended to a single joint motion assistance [3], and other to assist the motion of entire leg joints, and are expensive solutions and difficult to implement on a large scale [3]. These solutions are using joints actuators, expensive command and control hardware and software. As a conclusion these expensive solutions are not accessible to disabled persons, although they assure proper requirements for rehabilitations aim. Developed low cost solution are not fulfilling entire rehabilitation motions for all leg joints, because, in generally they assure active motion for rehabilitation only for the hip and knee joint [4, 5]. Other solutions are intended to assure rehabilitation motions to a specific rehabilitation therapy, intended to recover the gait for a certain leg joint, like hip, knee and ankle, used as passive solutions [6, 7]. They use different types of linear actuators and sensors [8]. Also are developed several solutions of legs, which reproduce human biped locomotion, in generally few of them assure approximately anthropomorphic motions [9].

Recently a few lower-extremity rehabilitation exoskeletons have been developed in order to help humans affected by disease to regain walking capability. These medical devices are not common in rehabilitation clinics. For example, Lokomat is an active powered exoskeleton, used for humans with spinal cord injuries. The patients use Lokomat to walk on a treadmill. The Lokomat (produced by Hocoma AG) is the first medical device exoskeleton used for rehabilitation that is commercially available. ReoAmbulator (Motorika Ltd.) is another example of human body weight support treadmill robotic system.

ReWalk is a commercially available motorized exoskeleton developed by ARGO Medical Technologies Ltd., which is used for rehabilitation therapies. Other human legs power assisted exoskeleton is Berkeley's, which is not intended primary as a rehabilitation device, but more as a soldier's strength amplifier. In 2011, Swortec successfully launched the new high-end device WalkTrainer. The WalkTrainer design consist on a walking frame, pelvic orthosis, a body weight support, two leg orthoses and a real-time controlled electro-stimulation. This rehabilitation device assists patients in their movements, corrects the motion and achieves equilibrium. ALEX (Active Leg Exoskeleton) is a motorized exoskeleton for gait rehabilitation. Its design is based on linear actuators at hip and knee joints. The patient walks on a treadmill and a computer displays visual feedback of the patient gait trajectory. Another existent device is LOPES (Lower Extremity Powered Exoskeleton). This device is a combination of an exoskeleton robot for the legs with an externally supporting robotic system for the pelvis. The joints of the robot (hip and knee) are actuated with cable driven elastic actuators [10, 11]. A limiting characteristic of some of these systems is that they move patients through predetermined movement patterns [12]. Legs are the most significant elements for accomplishing displacement needs of a human. Based on the fact that the human walking gait is repeatable, many researchers proposed open and closed-loop mechanical reproductions of the human legs [7, 9, 12].

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The results of this paper are organized as follows. In the first section, existing solutions of rehabilitation devices are presented. In the second section an experimental human gait biomechanics is performed in order to obtain a reference motion law to be used as an exoskeleton motion comparison. In the third section a leg mechanism is proposed for walking assistance of disabled people. In fourth part, a numerical simulation of exoskeleton worn by a human mannequin is performed, in ADAMS simulation environment. In the last part is presented an experimental numerical characterization of the exoskeleton prototype, and obtained motion laws for the hip and knee joint are compared with those of the human subjects.

II. HUMAN GAIT BIOMECHANICS

For human gait experimental analysis, are used Biometrics electrogoniometers. These sensors are robust, lightweight, flexible and can be worn by subjects without alteration of the movement of the joint [13]. Twin axis goniometers SG series [13], are used to measure joint angles simultaneously in two planes of movement. For example, to measure knee movement, the endblocks of the goniometer are attached on the subject using double sided tape. The goniometer has two separate output connector, one it is used to measure knee flexion/extension and the other connector to measure the valgus/varus.

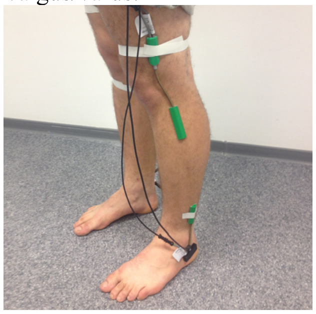


Fig. 1. Goniometers used to study human gait.

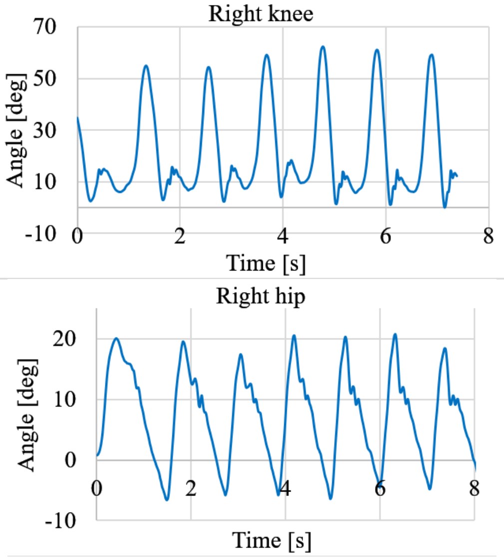


Fig. 2. Experimental measured knee joint and hip joint flexion/extension angle for the right leg.

The purpose of this research is to measure the angle for a single plane of joint (flexion/extension). The analysis procedure, consist in attaching with double size adhesive tape the electrogoniometres on the interest joint, as presented in Fig. 1. The sensors are connected to Biometrics DataLog equipment through which the data are transferred to the computer via Bluetooth interface. Measurement frequency is specified to 500 data registration/second.

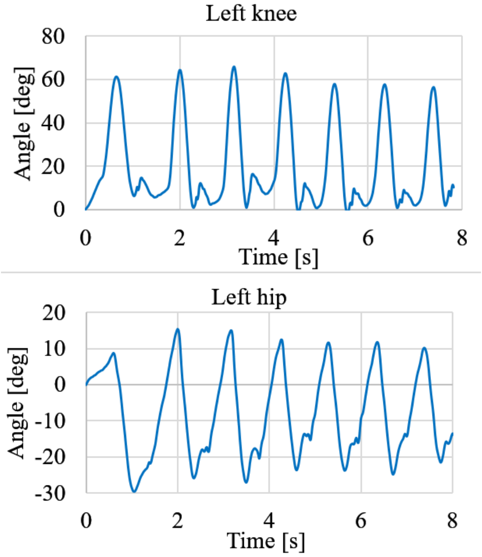


Fig. 3. Experimental measured knee joint and hip joint flexion/extension angle for the left leg.

Experimental gait analysis is focused on healthy subjects. The results obtained for the knee and hip joints angle variation are from a healthy 35 old subject and there are reported with plots in Fig. 2 for the right leg and in Fig. 3 for the left leg. The anthropometric data concerning the gait tested human subject can be summarized in 1.67 m height. Analyzing experimental results, it is observed that duration of one step is about 1.5 second. The knee joint angular maximum amplitude of the medium cycle is 60° and for the hip joint the maximum amplitude value is 35° (Fig. 3). These results are useful in order to make a comparison between achieved joint angles of human subject and joint angles achieved by the exoskeleton.

III. DESIGN OF EXOSKELETON CAD MODEL

Based on the previous work of the authors [14, 15] is designed a kinematic optimized solution of the exoskeleton leg. The design solution is simulated in MSC.ADAMS and the obtained optimized path for the ankle joint trajectory achieved by the new exoskeleton design is shown in Fig. 4.

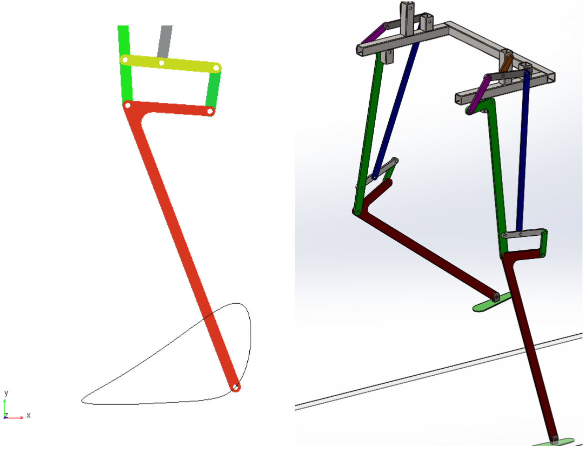


Fig. 4. Trajectory of ankle joint for the optimized solution of exoskeleton.

Considering the optimized kinematic structure of the leg mechanism, a virtual model of the exoskeleton is elaborated and designed, both for simulation purposes and manufacturing of the experimental prototype. A chain transmission is used to actuate the motor link 1 of leg mechanisms, as presented in Fig. 5.

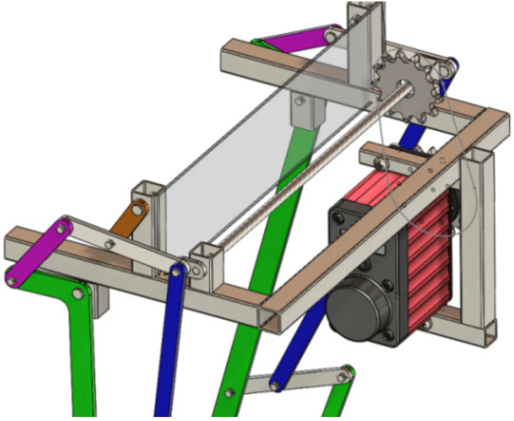


Fig. 5. Exoskeleton CAD model (actuation detail).

A complete drawing of the exoskeleton and mannequin is shown in Fig. 6.

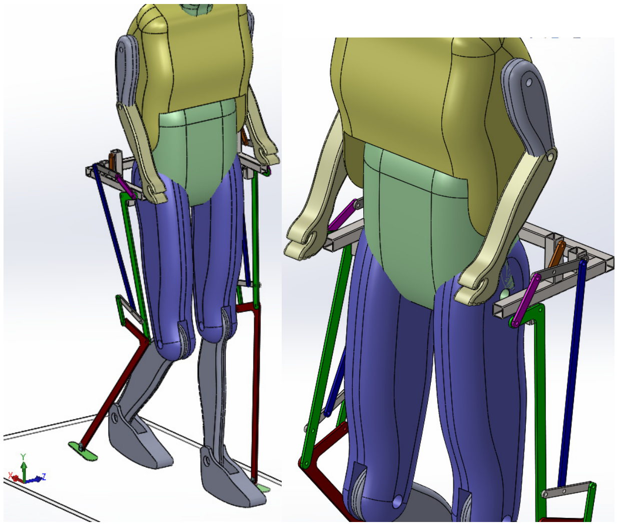
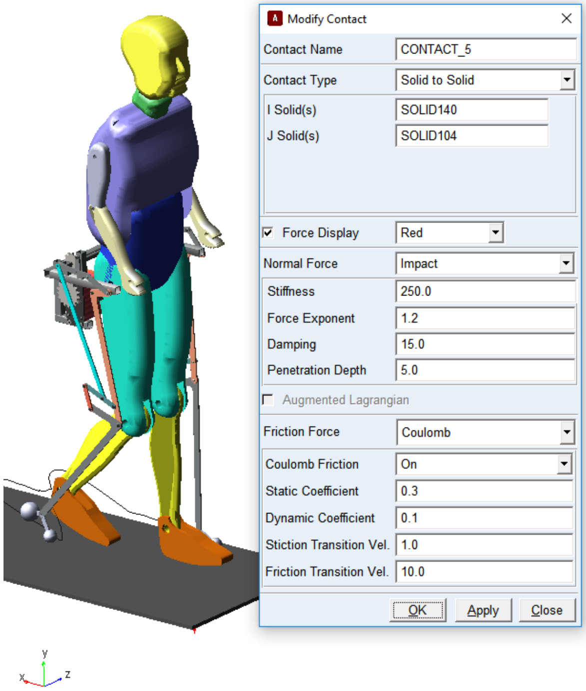


Fig. 6. Exoskeleton worn by a human mannequin.

IV. NUMERICAL SIMULATION IN ADAMS OF EXOSKELETON GAIT

Developed CAD model of the exoskeleton and mannequin is used for numerical simulation in ADAMS, multi-body dynamics software. The exoskeleton parameterized design it is considered for this simulation to be worn by a human mannequin of about 1.70 m height. Other anthropometric dimensions are: the shin length is around 400 mm and femur length 450 mm. The virtual model of the proposed exoskeleton device, designed in Solid Works, based on the kinematic scheme presented in Fig. 4, is used to perform a dynamic simulation in ADAMS. The virtual model details are presented in Fig. 6. In addition, the model presented in Fig. 6 simulates the exoskeleton operation with a human patient, with a body weight of about 65 kg and 1.70 m height. The complete simulation model with proper joints for the exoskeleton and ground contact is presented in Fig. 7. The model operation is considered for an angular velocity of 2 rad/sec. For operation only, one rotational actuator is needed, being positioned in joint A, which moves the mechanism of both, right and left leg. In addition, to the both exoskeleton ankles joint, it is added a torsion spring. All the revolute joints of the exoskeleton have been defined, considering the friction. The contact of legs with ground considers the characteristics presented in Fig. 7.



Modify Contact

Contact Name	CONTACT_5
Contact Type	Solid to Solid
I Solid(s)	SOLID140
J Solid(s)	SOLID104
☑ Force Display	Red
Normal Force	Impact
Stiffness	250.0
Force Exponent	1.2
Damping	15.0
Penetration Depth	5.0
☐ Augmented Lagrangian	
Friction Force	Coulomb
Coulomb Friction	On
Static Coefficient	0.3
Dynamic Coefficient	0.1
Stiction Transition Vel.	1.0
Friction Transition Vel.	10.0

Fig. 7. Simulation model in ADAMS with contact parameters.

Literature shows several studies on the importance of the foot-ground interface. Valiant [16] published investigations on the dynamic characteristics of the plantar surface of the leg. This work has been developed by Meglan [16], who studied the load-deformation parameters of the leg-ground. Meglan developed a general equation for vertical ground reaction force, using optimization techniques to fit Valiant's data to a simple polynomial equation. His obtained equation is, expressed as Eq. (1):

$$F(x,v)=(4.538e10)x^4+(9.719e10)x^4v \tag{1}$$

where: F is the resulting force, x is the penetration depth and v is the velocity of penetration. The ADAMS modeling tools do not allow for such a polynomial function to introduce, but offer instead the cubic function (with IMPACT method for the contact) as it is presented in the Eq. (2):

$$F(x,v)=kx+\left\{c(x/d)^2*\left[3-2x/d\right]\right\}v \tag{2}$$

where: k is a linear spring constant, c is the damping coefficient and d is the depth of penetration. The estimated values of the ADAMS impact coefficients, upon Meglan relations are: k=250 N/mm; c=15 N/mm/sec and d=5 mm. [17, 18]. The exoskeleton leg model includes a shoe element, as a separate part, connected to the shin by a revolute joint.

The torsion spring damper, placed at ankle joint uses the coefficients: $(K_{rot})=1N/rad$; $(C_{rot})=1Nmm/rad$.

The exoskeleton simulation in ADAMS is performed using WSTIF integrator and SI2 formulation.

Obtained results are presented in plots from Figs. 8-15. Exoskeleton translational displacement is quantified by measuring upper body movement, as presented in Fig. 8. From the can be observed the fact that the exoskeleton is moving 550 mm on the negative direction of the OX axis.

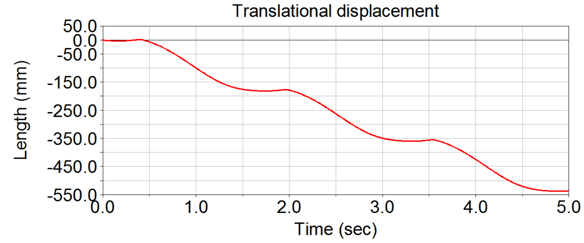


Fig. 8. Computed exoskeleton translational displacement.

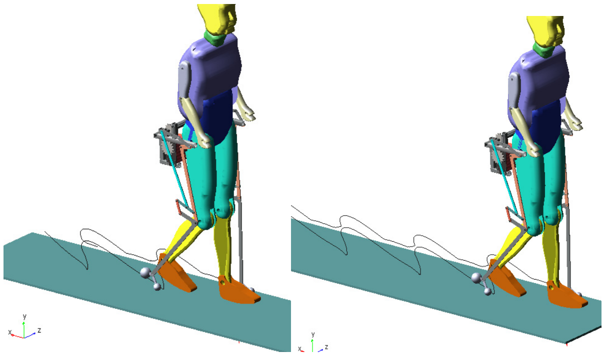


Fig. 9. Snapshots from simulation steps.

The above graphic shows the computed trajectory of the ankle joints for an intermediary phase of the mannequin walking assisted by the exoskeleton. Computed snapshots from exoskeleton gait walking are presented in Fig. 9.

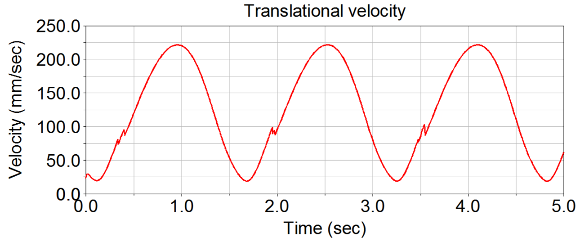
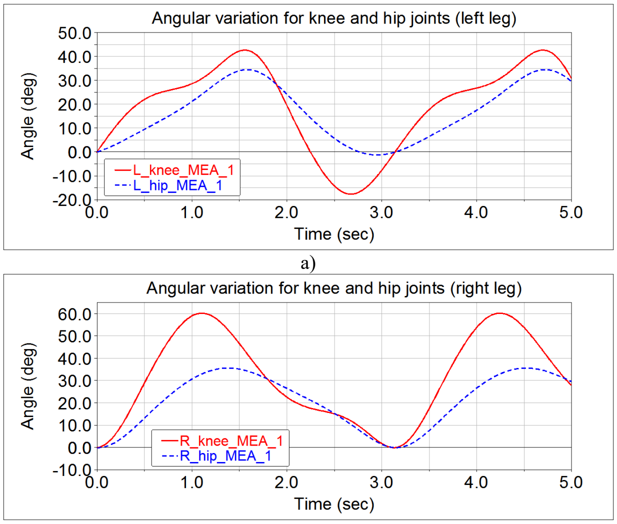


Fig. 10. Computed exoskeleton translational velocity.



a)

b)

Fig. 11. Computed angles for hip joints and knee joints of the exoskeleton legs during simulation.

Exoskeleton translational velocity, computed from ADAMS simulation is plotted in Fig. 10, observing that the maximum velocity is 225 mm/s. Computed plots of knee and hip joints are presented in Fig. 11. Representation from Fig. 11, a), presents the variation angle of the left exoskeleton hip joint, with dotted line and with continuous line for the knee joint of the same exoskeleton leg. The Fig. 11, b) shows the angular variation of the knee and hip joints of the right leg. For the knee joint the variation interval is [0-60] with an amplitude of 60 deg. For the hip joint the variation interval is [0-35] with an amplitude of 35 deg. The angles of variation for the knee and hip joints of the exoskeleton are comparable as time variation with the ones of the human subject presented in Fig. 2, 3.

Computed variation for the hip and knee joints of the exoskeleton as resulted from ADAMS simulation, presented in Fig. 11 there are comparable as maximum amplitude with the results obtained and presented in Fig. 2 and Fig. 3. The knee joint reaction forces components, resulted from simulation, are presented in Fig. 12. The knee joint axes are positioned as Y axis is vertical, and X is horizontal axis. From diagrams presented in Fig. 12, we observe that the force components have greater values during the step sequences when the leg is in contact with the ground. When the leg is in the swing phase the force components have zero value.

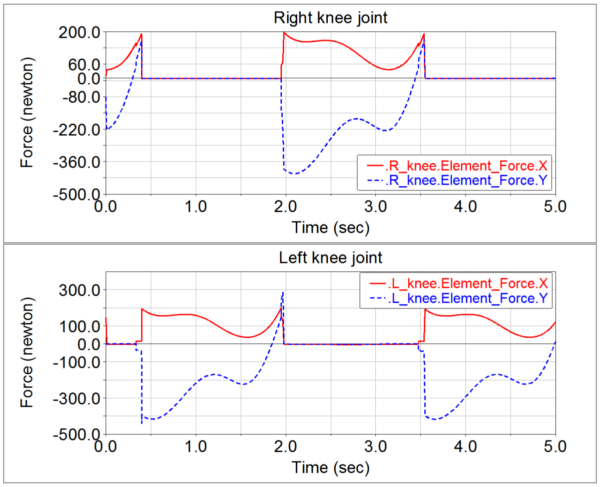


Fig. 12. Knee joints computed reaction forces.

Fig. 13. Computed contact force of the left leg.

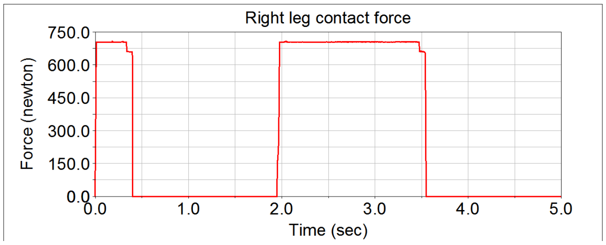


Fig. 14. Computed contact force of the right leg.

Computed ground contact forces, for the left and right leg of the exoskeleton are presented in Fig. 13-14.

The resistant torque, of the actuator, as computed in ADAMS simulation, is shown in Fig. 15. From the variation of resistant motor, it is concluded that the maximum value is 20 Nm, that being useful for the choice of an actuation electric motor for the experimental prototype.

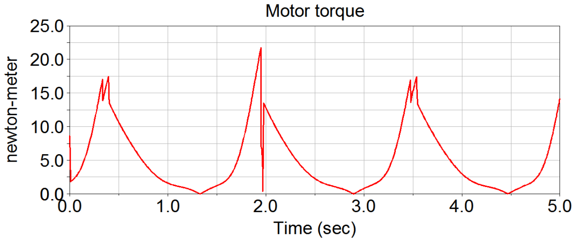


Fig. 15. Computed motor torque for the exoskeleton.

V. EXOSKELETON PROTOTYPE NUMERICAL CHARACTERIZATION

To study proposed exoskeleton kinematic behavior is designed and manufactured a prototype, as shown in Fig. 16. This model is used to perform a motion analysis on ground walking, with motion analysis equipment, such as CONTEMPLAS.

Tests were performed in case when the rehabilitation exoskeleton walks on the ground without the human. In order to keep balance, during experiments, the upper frame is mounted on two vertical supports, equipped with wheels. This motion analysis equipment is based on ultraspeed cameras motion capture and analysis. Reflective markers are attached to the exoskeleton body, as presented in Fig. 16.

Processed images of captured movies are based on tracking markers trajectories, as shown in Fig. 17-18.

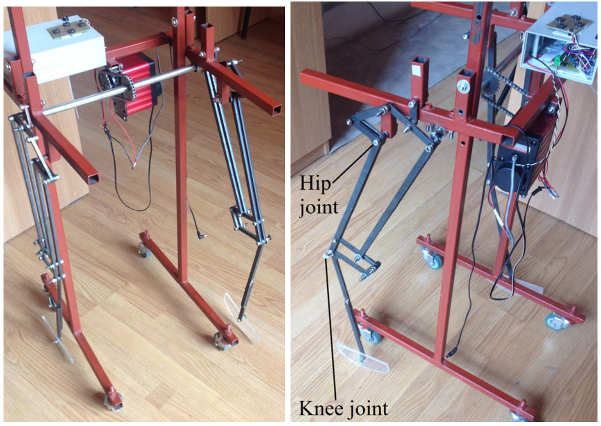


Fig. 16. A prototype of human leg rehabilitation exoskeleton.

In order to compute the variation of the exoskeleton joints angle, are defined the specific angles by corresponding segments. The results obtained for leg joints angular variation, are presented in same graph both for exoskeleton and the human subject.

A comparison between experimental computed knee joint angular variation of the exoskeleton and the measured human subject it is presented in Fig. 19.

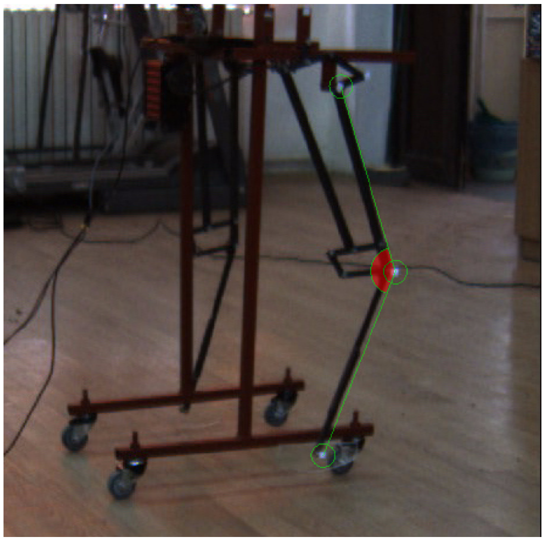


Fig. 17. Marker tracking for knee joint angular calculation, in CONTEMPLAS.

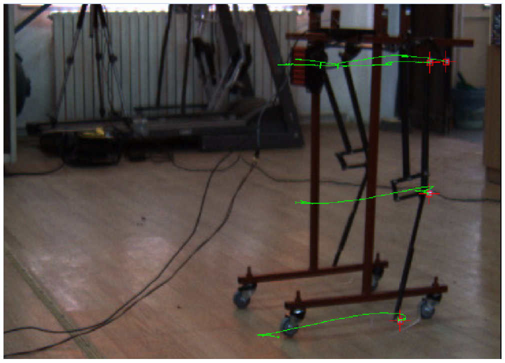


Fig. 18. Marker tracking for kinematic characterization.

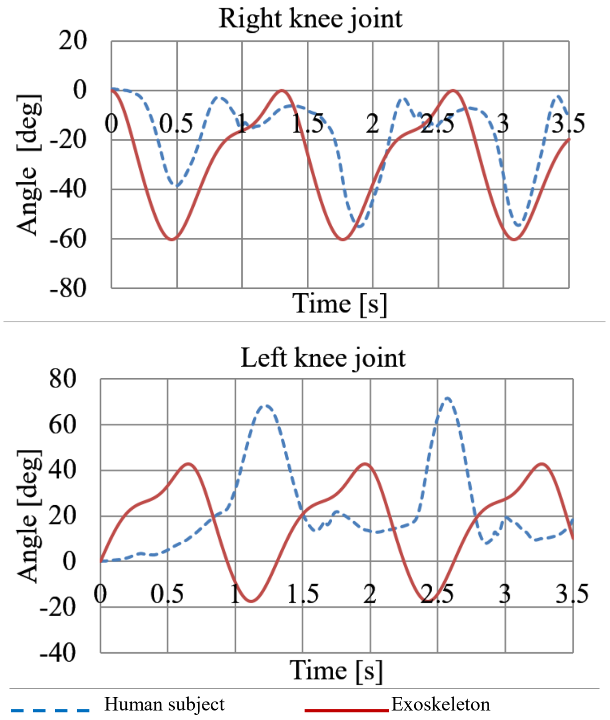


Fig. 19. Comparison of the variation of exoskeleton computed knee joint angle and human subject.

Similar comparison is presented in Fig. 20, for the hip joint, results obtained for the exoskeleton and the results obtained from experimental analysis of human healthy subject. As can be observed from the graphics, the variations are almost similar.

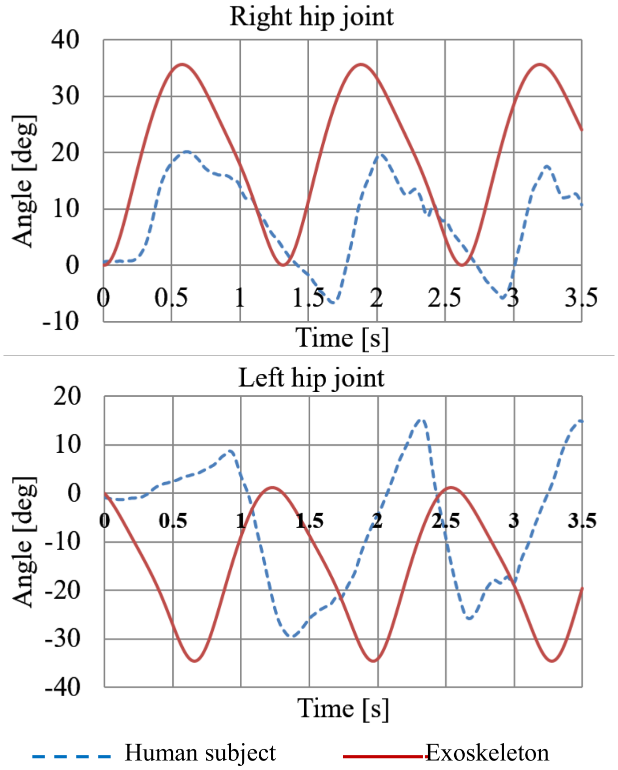


Fig. 20. Comparison of the variation of exoskeleton computed hip joint angle and human subject.

VI. CONCLUSION

In this paper is presented a dynamic simulation in ADAMS completed with an experimental analysis of a one DOF human leg rehabilitation exoskeleton. An experimental model of the proposed mechanism is designed and developed. The prototype is experimentally tested for numerical characterization under ground walking conditions. Experiments are made with Contemplas motion analysis platform equipped with ultraspeed video cameras. The graphics of angular variation for knee and hip joints angles are obtained. Results obtained for the experimental analysis of exoskeleton are compared in Fig. 19 and Fig. 20 with the experimental results obtained from a human healthy subject, and they are similar. From ADAMS dynamic simulation and experimental results, it can be observed that the performance of the proposed rehabilitation exoskeleton is suitable for use of human recovery therapy. The novelty of the design structure consists in the fact that implements a mechanism with only one actuator for assisting the motion of the leg assuring humanoid paths for human gait. Due to its simple design, of using only actuator, this leads to a low cost solution.

REFERENCES

[1] Morecki, A., Human and Machine Locomotion, *Springer 1997*, New York.

[2] I. Dıaz, J. J. Gil and E. Sanchez, "Lower-Limb Robotic Rehabilitation: Literature Review and Challenges", *Journal of Robotics*, Volume 2011, Article ID 759764, 11 pages, doi:10.1155/2011/759764.

[3] N. Koceska, "Review: Robot Devices for Gait Rehabilitation", International Journal of Computer Applications (0975 – 8887), Volume 62– No.13, January 2013.

[4] M. Cenciarini, "Biomechanical Considerations in the Design of Lower Limb Exoskeletons", *2011 IEEE International Conference on Rehabilitation Robotics*, Rehab Week Zurich, ETH Zurich Science City, Switzerland, June 29 - July 1, 2011.

[5] K. Kubo, "Review Article: Gait Rehabilitation Device in Central Nervous SystemDisease: AReview", *Journal of Robotics*, Volume 2011, Article ID 348207, 14 pages, doi:10.1155/2011/348207.

[6] M. Dzahir, "Recent Trends in Lower-Limb Robotic Rehabilitation Orthosis: Control Scheme and Strategy for Pneumatic Muscle Actuated Gait Trainers", *Robotics 2014*, 3, pp. 120-148.

[7] Araidah, O., Conceptual Design of a Single DOF Human-Like Eight Bar Leg Mechanism, *Jordan Journal of Mechanical and Industrial Engineering*, pp.285-289, ISSN 1995-6665, 2011.

[8] Dumitru, N., Malciu, R., Geonea, I., Differential Transmission for Robotizing a Powered Wheelchair, *Proceedings of the OPTIROB* 2010, 28-30 May 2010, pp. 47-51, ISBN 978-981-08-5840-7.

[9] C. Liang, M. Ceccarelli and Y. Takeda, "Operation analysis of a Chebyshev-Pantograph leg mechanism for a single DOF biped robot", *Front. Mech. Eng.* 2012, 7(4): 357–370.

[10] Li T., M.Ceccarelli, An Experimental Characterization of a Rickshaw Prototype, *Mechanisms, Transmissions and Applications*, pp.203-214, Springer 2011, ISBN978-94-007-2727-4.

[11] Dumitru N., Copilusi C., Geonea I., Tarnita D., Dumitrache I., Dynamic Analysis of an Exoskeleton New Ankle Joint Mechanism, *New Trends in Mechanism and Machine Science Mechanisms and Machine Science*, Volume 24, 2015, Springer International Publishing, pp 709-717.

[12] Geonea I., Ceccarelli M. and Carbone G., "Design and Analysis of an Exoskeleton for People with Motor Disabilities", *The 14th IFToMM World Congress*, Taipei, Taiwan, October 25-30, 2015.

[13] Tarniță, D., Geonea I., Petcu A., Tarnita D.N., Experimental Characterization of Human Walking on Stairs Applied to Humanoid Dynamics, *Advances in Robot Design and Intelligent Control, Springer*, 293-301, 2016.

[14] Geonea I., Ceccarelli M. and Copilusi C., "New Assistive Device for People with Motor Disabilities", *Applied Mechanics and Materials*, Vol. 772, pp. 574-579, Jul. 2015.

[15] Geonea I., Alexandru C., Margine A., Ungureanu A., Design and Simulation of a Single DOF Human-Like Leg Mechanism, *Applied Mechanics and Materials* Vol. 332 pp. 491-496 (2013), doi:10.4028/www.scientific.net/AMM.332.491.

[16] Wojtyra, M., "Dynamical Analysis of Human Walking", *15th European ADAMS Users' Conference Technical Papers*, Rome, Italy, 2000.

[17] Tung-Wu Lu, Chu-Fen Chang, "Biomechanics of human movement and its clinical applications", *Kaohsiung Journal of Medical Sciences* (2012) 28, pp.13-25.

[18] Andres Kecskemethy, "Integrating efficient kinematics in biomechanics of human motions", *Procedia IUTAM* 2 (2011) pp. 86–92.