A Knee Exoskeleton Mechanism Dynamic Analysis

Dumitru N., Copilusi C., Dumitru S., Rusu L., Rosu E.

Abstract— **In this paper a human knee mechanism was designed for modeling the human gait as a part of a mechatronic structure namely exoskeleton type. This system will be used for gait rehabilitation in case of persons with neuromotor disorders. Thus, a dynamic analysis will be performed which will be focused on knee equivalent mechanism actuated through a linear actuator. This mechanism dynamic study will be achieved by creating a special interface between an experimental analysis of a human lower limb during walking activity, a mathematical modeling and numerical simulation with MSC Adams software. Through the proposed analysis an actuation mechanism from a leg exoskeleton will be validated.**

***Index Terms*—dynamic analysis, human walking, knee joint, leg mechanism**

I. Introduction

Exoskeletons for human rehabilitation specific programs from medical and biomechanical fields are in a continuous development. Some of them [1, 2] were designed for human walking recovery and it can be remarked the benefits for persons with neuromotor disorders, stroke accidents or other specific locomotion diseases [5, 6]. Some of them have complex mechanisms for actuation and use a minimum number of actuators [3, 8], others have a simple mechanical structure but use a complex command&control components with a large number of actuators [9].

By considering the state-of-the art for human rehabilitation exoskeletons especially designed for walking activity, this research work was focused on the design of a mechanism equivalent with the human knee functionality during walking. In this purpose, experimental tests were performed on human healthy persons presented in the second part of the paper. This assures essential input data used on the design and dynamic analysis of the proposed exoskeleton knee mechanism described in the third section. The knee mechanism functionality was validated through numerical simulations created with the aid of MSC Adams software and the results were reported in the last section of this research work.

At the beginning of this research, a setup was made for the proposed mechanism and the command mechanism actuation for generating the tibia equivalent link motion was performed for two structural solutions: a mechanism with a radial planar cam and oscillating cam follower [3]; a mechanism with a linear actuator which replace the cam mechanism. In this case the research objective is to analyze the second solution, namely the one with a linear actuator.

II. Human Walking Experimental Analyses

The experimental analysis was done with the aid of VICON Equipment existent in University of Craiova biomechanical laboratories [7, 10]. The VICON equipment workflow is easily schematized in Fig. 1.

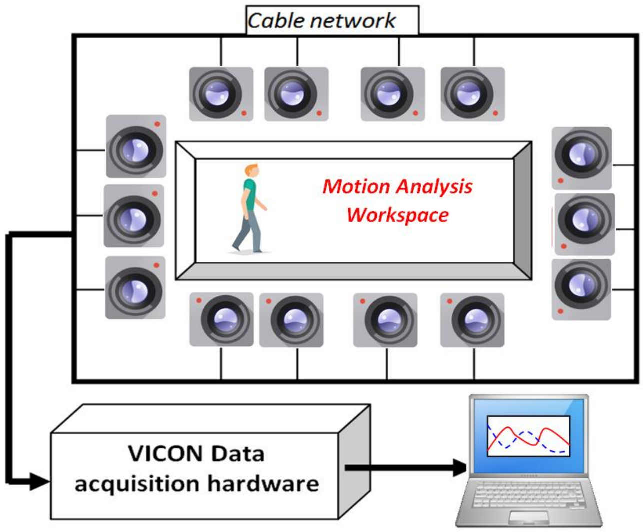

Fig. 1. VICON equipment workflow

This equipment use 14 IR cameras and with this a database was created which consists of 30 human subjects (15 male and 15 female persons) used on walking activity recordings. There were obtained the desired motion laws, for a single gait, from hips, knees and ankles from human locomotion system during walking activity. The obtained results, give essential input data for exoskeleton designs and analyses, like in this case when knee motion law was used as input data for dynamic analysis of the proposed knee equivalent mechanism. Thus, a chosen male with known anthropometric data was considered as input data for this

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research (age 47, 72 kilograms, 1,70 meters height). A snapshot during video analysis with VICON Equipment is shown in Fig. 2. The developed knee motion law is presented in Fig. 3.

Fig. 2. Snapshot during a complete gait of the analized human subject

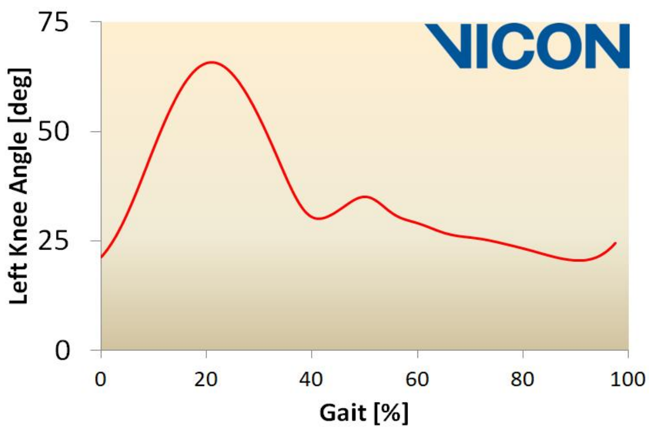

Fig. 3. Knee angle variation during a complete gait

III. Knee Mechanism Dynamic Analysis

Similar dynamic models of the human lower limb were analyzed according with [4], by using inverse dynamic analysis based on Newton-Euler method completed with Lagrange multipliers. By having these as reference points, a dynamic model of an equivalent knee mechanism was elaborated and this is shown on Fig. 4.

The proposed leg exoskeleton mechanism it was analyzed from cinematic viewpoints in [3]. Thus, knee and ankle joints were actuated through a planar linkage designed for each analized joint. The dynamic model of the ankle actuation mechanism was also described in [4].

The knee actuation mechanism is a planar one with DOF equal with two, if the hip joint will be actuated.

From Fig. 4 it can be identified: O, A, B, C, D, E, F, G, H are revolute joints. From these joints it can be remarked: B – hip joint, E – knee joint. The distance between B and E joints is equivalent to femur segment. The drive element, namely the actuator will be the link pair 1-2. The proposed knee actuation mechanism is a parameterized one and will be adaptable to any anthropometric person. Thus, the CD segment and OE segment equivalent with femur have the lengths adjustable. The input data for this analysis were considered known and were represented by the geometric elements (these correspond with the human subject anthropometric data) and generalized coordinates variation law obtained with the VICON Equipment namely knee motion law from Fig. 2. This analysis aim is to obtain the revolute joints connection forces which will be further used on the numerical processing of the equivalent virtual model.

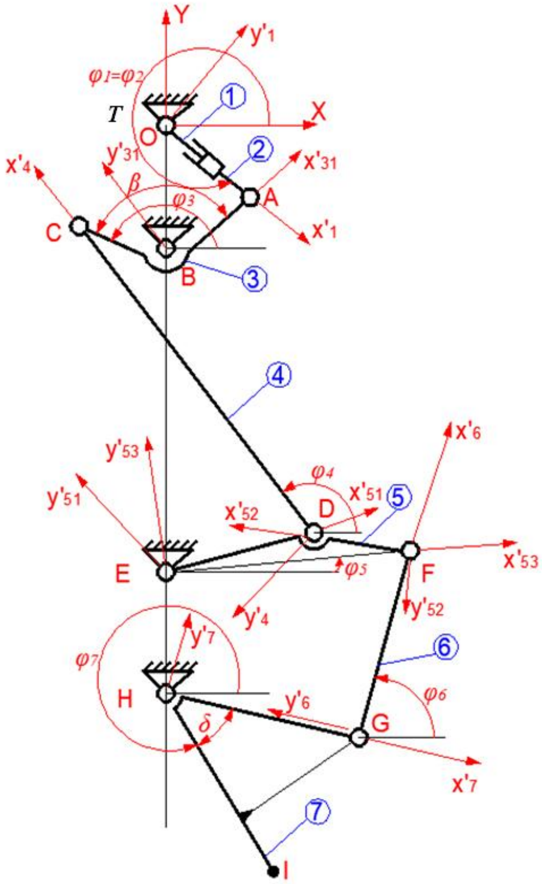

Fig. 4. Knee mechanism kinematic scheme

First it will be identified the generalized coordinate vector as:

$$q = [\varphi_1, \quad S_1, \quad \varphi_3, \quad \varphi_4, \quad \varphi_5, \quad \varphi_6, \quad \varphi_7]^T , \tag{1}$$

Where: S_1 represents the linear motion of the linear actuator namely OA segment; φ_1, φ_2, φ_3, φ_4, φ_6, and φ_7 are the proper angles of the cinematic links depending on global reference coordinate system T(X, Y).

The constraint equations are:

$$\mathrm{E(q,t) = 0} \tag{2}$$

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By differentiating Eq. (2) it will be obtained:

$$J_q \ddot{q} + \sum_{k=1}^{nc} \frac{\partial^2 E_i}{\partial q_j \partial q_k} \dot{q}_k + 2\frac{\partial^2 E_i \dot{q}}{\partial q_j \partial t} + \frac{\partial^2 E_i}{\partial t^2} = 0 \quad (3)$$

The following notation will be made:

$$a = J_q \ddot{q} = \sum_{k=1}^{nc} \frac{\partial^2 E_i}{\partial q_j \partial q_k} \dot{q}_k$$
$$-2\frac{\partial^2 E_i \dot{q}}{\partial q_j \partial t} - \frac{\partial^2 E_i}{\partial t^2} \quad (4)$$

Where: J_q is the Jacobian matrix depending on generalized coordinates which accomplish the requirements for Eq. (2). The Jacobian matrix form for this model is:

$$J_q = \frac{\partial E}{\partial q} = \frac{\partial E_i}{\partial q_j} \quad (5)$$

With: $i = \overline{1, n_h}$; $j = \overline{1, n_c}$, n_c – number of generalized coordinates; n_h – number of kinematic constraints equations; q–generalized coordinates vector.

The Jacobian matrix depends on generalized coordinates characterized by (2).

The motion equations expressed in Newton –Euler formalism completed with Lagrange multipliers are:

$$M \cdot \ddot{q} + J_q^T \cdot \lambda = Q^g \quad (6)$$

By combining the Eq. (4) and (6) it will be obtained:

$$\begin{bmatrix} M & J_q^T \\ J_q & 0 \end{bmatrix} \cdot \begin{bmatrix} \ddot{q} \\ \lambda \end{bmatrix} = \begin{bmatrix} Q^g \\ a \end{bmatrix} \quad (7)$$

Where: M – mass matrix; Q^g – generalized forces vector; λ - Lagrange multipliers vector, J_q – Jacobian matrix, a – matrix from Eq. (4).

By considering the scheme from Fig. 3, the proper kinematic constraints equations are:

$$E(\mathrm{q,t}) = \begin{cases} x_H + l_{GH} \cdot \cos(\varphi_7 + \delta) + \mathrm{l}_{GF} \cdot \cos\varphi_6 - x_E - l_{EF} \cos\varphi_5 = 0 \\ y_H + l_{GH} \cdot \sin(\varphi_7 + \delta) + \mathrm{l}_{GF} \cdot \sin\varphi_6 - y_E - l_{EF} \sin\varphi_5 = 0 \\ x_E + l_{ED} \cdot \cos(\varphi_5 + \alpha) + \mathrm{l}_{CD} \cdot \cos\varphi_4 - x_B - l_{BC} \cos\varphi_3 = 0 \\ y_E + l_{ED} \cdot \sin(\varphi_5 + \alpha) + \mathrm{l}_{CD} \cdot \sin\varphi_4 - y_B - l_{BC} \sin\varphi_3 = 0 \\ x_O + (S_1 + L_2) \cdot \cos\varphi_1 - x_B - l_{AB} \cdot \cos(\varphi_3 - \beta) = 0 \\ y_O + (S_1 + L_2) \cdot \sin\varphi_1 - y_B - l_{AB} \cdot \sin(\varphi_3 - \beta) = 0 \\ \varphi_7 - p_1(t) = 0 \end{cases} \quad (8)$$

Thus, the proper Jacobian matrix for q generalized coordinates which matches with Eq. (8) have the following form:

$$J_q = \begin{bmatrix} [(\mathrm{S}_1 + \mathrm{L}_2)\cos\varphi_1, \sin\varphi_1, -l_{AB}\cos(\varphi_3 + \beta), 0,0,0,0] \\ -(S_1 + L_2)\sin\varphi_1, \cos\varphi_1, -l_{AB}\sin(-\varphi_3 + \beta), 0,0,0,0] \\ 0,0,-l_{BC}\cos\varphi_3, l_{CD}\cos\varphi_4, l_{ED}\cos(\varphi_5 + \alpha), 0,0] \\ 0,0,0,-l_{EF}\cos\varphi_5, l_{GF}\cos\varphi_6, l_{GH}\cos(\varphi_7 + \delta)] \\ 0,0,0,0, l_{EF}\sin\varphi_5, -l_{GF}\sin\varphi_6, -l_{GH}\sin(\varphi_7 + \delta)] \\ [0,0,0,0,0,0,1] \end{bmatrix} \quad (9)$$

By differentiating the Eq. (8) it will be obtained:

$$a = \begin{cases} l_{GH} \cdot \dot{\varphi}_7^2 \cdot \cos(\varphi_7 + \gamma) + \dot{\varphi}_6^2 \cdot l_{GF} \cdot \cos\varphi_6 - l_{EF} \cdot \dot{\varphi}_5^2 \cdot \cos\varphi_5 \\ l_{GH} \cdot \dot{\varphi}_7^2 \cdot \sin(\varphi_7 + \gamma) + \dot{\varphi}_6^2 \cdot l_{GF} \cdot \sin\varphi_6 - l_{FE} \cdot \dot{\varphi}_5^2 \cdot \sin\varphi_5 \\ l_{ED} \cdot \dot{\varphi}_5^2 \cdot \cos(\varphi_5 + \alpha) + l_{CD} \cdot \dot{\varphi}_6^2 \cdot \cos\varphi_4 - l_{BC} \cdot \dot{\varphi}_3^2 \cdot \cos\varphi_3 \\ l_{ED} \cdot \dot{\varphi}_5^2 \cdot \sin(\varphi_5 + \alpha) + l_{CD} \cdot \dot{\varphi}_6^2 \cdot \sin\varphi_4 - l_{BC} \cdot \dot{\varphi}_3^2 \cdot \sin\varphi_3 \\ 2 \cdot \dot{S}_1 \cdot \dot{\varphi}_1 \cdot \sin\varphi_1 + (\mathrm{S}_1 + \mathrm{L}_2) \cdot \dot{\varphi}_1^2 \cdot \cos\varphi_1 - l_{AB} \cdot \dot{\varphi}_3^2 \cdot \cos(\varphi_3 - \beta) \\ -2 \cdot \dot{S}_1 \cdot \dot{\varphi}_1 \cdot \cos\varphi_1 + (\mathrm{S}_1 + \mathrm{L}_2) \cdot \dot{\varphi}_1^2 \cdot \sin\varphi_1 - l_{AB} \cdot \dot{\varphi}_3^2 \cdot \sin(\varphi_3 - \beta) \end{cases}$$

The active generalized forces vector form is:

$$Q^g = \begin{bmatrix} -\dfrac{m_1 \cdot g \cdot (S_1 + L_2)}{2} \\ m_1 \cdot g \\ \dfrac{m_3 \cdot g \cdot l_{AB}}{2} \\ -\dfrac{m_4 \cdot g \cdot l_{CD}}{2} \\ -\dfrac{m_6 \cdot g \cdot l_{GF}}{2} \\ -\dfrac{m_7 \cdot g \cdot l_{GH}}{2} \end{bmatrix} \quad (10)$$

The mass matrix has the following form:

$$M = diag(I_1, \quad m_1, \quad I_3, \quad I_4, \quad I_5, \quad I_6) \quad (11)$$

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Where: I_i are the inertia momentums of "*i*" element with $i = \overline{1,7}$; m_i – mass of "*i*" element.

The Lagrange multipliers are:

$$\lambda = J_q \cdot \left(Q^g - M \cdot \ddot{q} \right) \tag{12}$$

The connection forces from kinematic joints depending on the global coordinates system are:

$$F_k = -\lambda_k \; ; \tag{13}$$

Where: k – represents the assigned letter of the kinematic joints.

Thus, the motion variation laws for q generalized coordinates were determined from Eq. (8), with Newton – Raphson method.

By considering the mathematical model obtained through the dynamic analysis for the proposed exoskeleton knee mechanism, a computational algorithm was processed in MAPLE environment. For this, the following parameters were taken into account: OA – linear actuator with a variable length of 10 to 100 millimeters; AB –component of element (3) with a length of 39.18 millimeters; BC – component of element (3) with a length of 63.8 millimeters; CD – actuation mechanism element (4) with a length of 392 millimeters; DE – component of element (5) with a length of 39.18 millimeters; DF – component of element (5) with a length of 29.41 millimeters; FG - element (5) with a length of 90 millimeters; GH – a component of element (7) equivalent to tibia segment with a length of 30 millimeters.

The size identification of all components is mandatory for numerical processing in case of virtual simulations for the proposed leg exoskeleton mechanism.

Through this numerical processing with MAPLE, the connection forces components for B joint, which will appear during a complete gait, were obtained and their variations are shown in Fig. 5 and Fig. 6. These were processed depending on global coordinate system and there are presented as a comparative study with the ones obtained through numerical simulations outputs with MSC Adams soft.

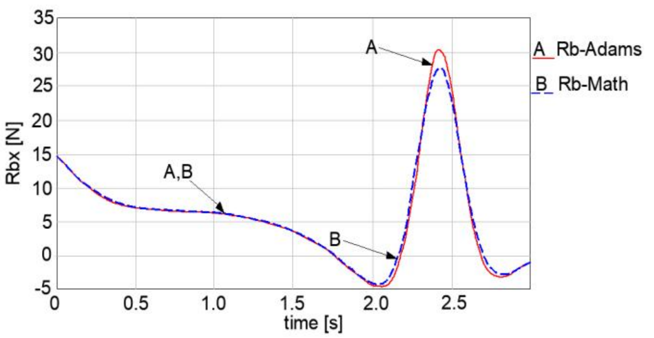

Fig. 5. Connection force component on X-axis [N] variation from B kinematic joint depending on time [sec]

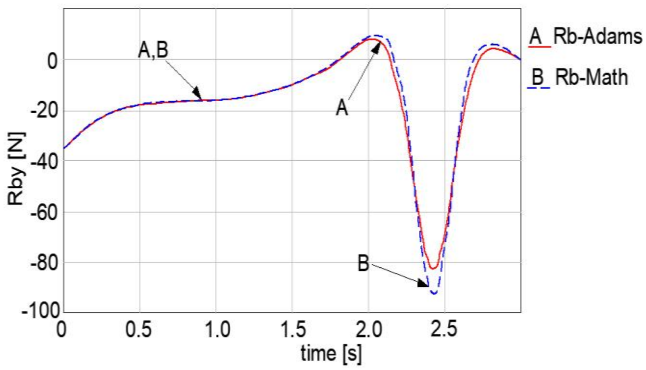

Fig. 6. Connection force component on Y-axis [N] variation from B kinematic joint depending on time [sec]

The obtained path certifies that the obtained results are correct ones and the accuracy between the obtained trajectories is quite small due to the influence of the mechanism linkage architecture.

The accuracy between both curves from Fig. 5 is around 2.03% and in case of curves from Fig. 6, this is around 1.63%.

IV. Knee Mechanism Numerical Simulations

Based on kinematic scheme from Fig. 4 and taking into account the anthropometric data of the human subject from experimental database, a virtual prototype was elaborated and this will be inserted in a new leg exoskeleton proposal for human neuromotor walking rehabilitation. This is represented in Fig. 7 and it has a complete actuation mechanism for a single leg exoskeleton. It can be remarked a similar actuation mechanism in case of ankle joint actuation with a similar linear actuator. This mechanism was also analyzed in [4]. Thus, the DOF for a single leg exoskeleton will be equal with 3, namely on rotational actuator for hip joint (this will be placed straight on hip). The virtual model conceptual solution motivation for using linkages was imposed by the actuators size and control.

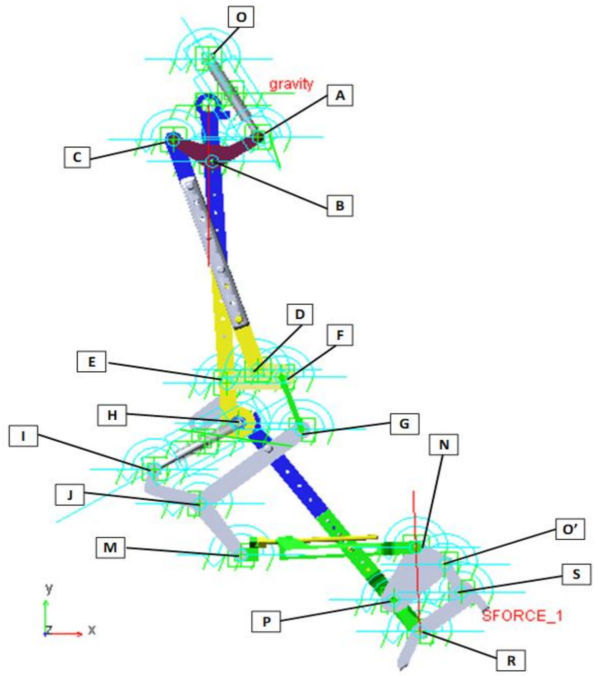

Fig. 7. A 3D model of the leg exoskeleton with the analyzed knee actuation mechanism

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Also it can be observed the revolute joints correspondence between Fig. 4 and Fig. 7 and also two linear actuators placed at the level of the hip joint for knee joint actuation and the other placed at the level of knee joint for actuating the ankle joint. Proper materials parameters were defined for the leg exoskeleton links, namely aluminum alloys and the structure of each link was a solid one. In this way, the leg exoskeleton weight reaches a value of 8.74 kilograms. The leg exoskeleton has 17 revolute joints, according with the model from Fig. 7. The exoskeleton position corresponds with the one of the analyzed human subject. The friction forces were neglected and also the ground-foot contact was not considered. The simulation sequence was equal with 2.8 seconds and corresponds to a complete gait developed on the experimental analysis.

By taking into account the obtained results through dynamic analysis and also the input data from experimental data (knee motion law – Fig. 2), the generalized coordinate variation law of translational actuation joint was successively implemented, namely link no. 2 from Fig. 4.

By accomplishing the proposed numerical simulations carried out on MSC Adams environment, it will be determined the motion variation laws depending on time for the kinematic parameters which defines the tibia equivalent link motion.

Some snapshots were taken during virtual simulations with MSC Adams – Adams View module and these are presented in Fig. 8.

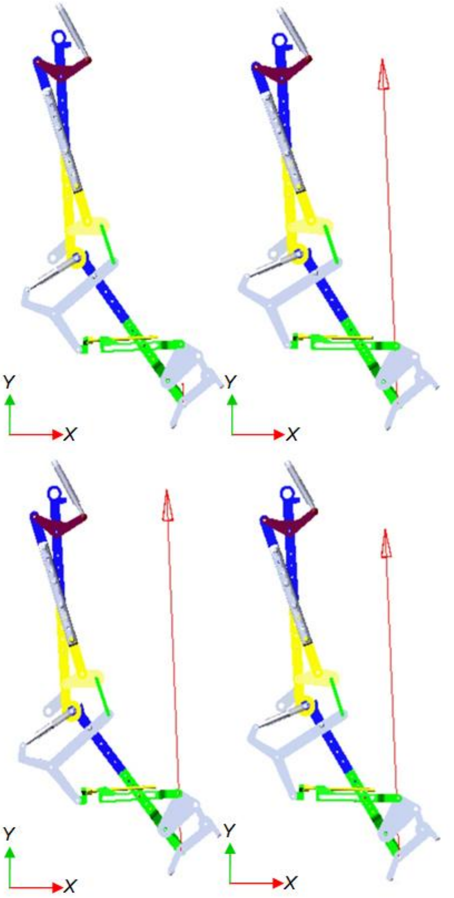

Fig. 8. Snapshots during numerical simulations of the knee exoskeleton geometric model

For this, the post-processed results performed under MSC Adams environment were obtained, namely x-y trajectory components of tibia equivalent link of the proposed knee mechanism.

In order to validate the mathematical model created through dynamic analysis and the proposed knee mechanism virtual model, a comparative study was done and the objective was to determine the x-y trajectory components for point I (see Fig. 4) with the one located on the tibia equivalent link from MSC Adams. These results are shown in Fig. 9 and Fig. 10.

Thus, the time interval was 2.8 seconds which corresponds for a complete gait cycle [100%].

By having in sight the diagram from Fig. 9 it can be observed the trajectory component path for both models are almost the same and it fits on the same numerical values. In case of the computed mathematical trajectory it has a small difference and the accuracy between both paths is equal with 2.98%. The displacement obtained for this trajectory was equal with 180 millimeters.

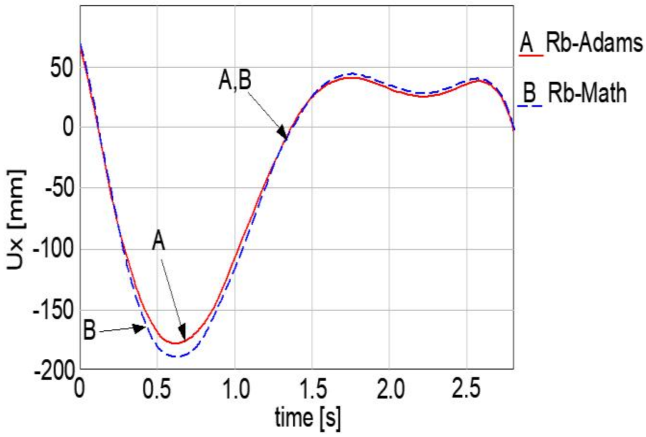

Fig. 9. Comparative analysis of the X-component displacement [mm] for I point identified on tibia segment vs. time [sec] (A – displacements corresponding to the MSC Adams virtual model; B – displacements corresponding to the analyzed mathematical model).

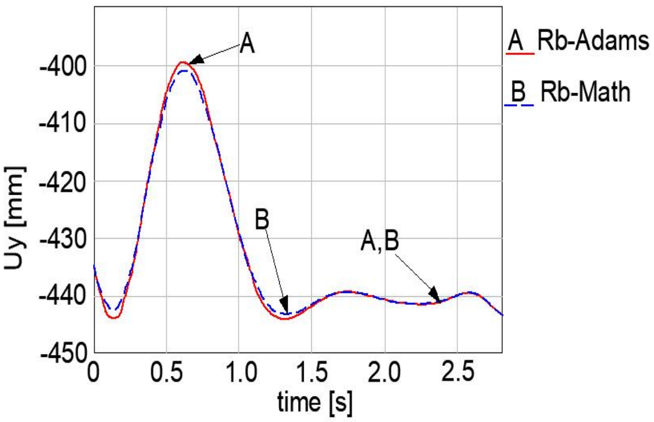

Fig. 10. Comparative analysis of the Y-component displacement [mm] for I point identified on tibia segment vs. time [sec] (A – displacements corresponding to the MSC Adams virtual model; B – displacements corresponding to the analyzed mathematical model)

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Considering the diagram from Fig. 10 it can be remarked similar paths for both analyzed models and an accuracy of 1.96% it was obtained. The highest value for both models in case of Y- trajectory component was equal with 43 millimeters.

V. Conclusion

In this paper a human knee equivalent mechanism from a leg exoskeleton was analyzed and also validated through a dynamic analysis. It was performed an experimental analysis, where a database was created and characterized by human locomotion system motion for walking activities. The obtained results were represented through interest points and segments angular variations and trajectories.

A parameterized leg exoskeleton was designed by taking into account the correlation between the segments geometry and anthropometric data of a human lower limb. It was performed an inverse kinematic analysis for determine the analytical motion variation law of the translational actuation joint. For this an algorithm was created in order to process the numerical results of the elaborated kinematic and dynamic mechanism models.

A dynamic model was elaborated with Newton-Euler formalism completed with Lagrange multipliers. Through this there were identified the generalized coordinates variation laws during time and also the connection forces variations from kinematic joints. These were done through mathematical modeling and also numerically with the aid of MSC Adams. Finally, the whole analysis was validated through a comparative study represented in Fig. 8 and Fig. 9, where a point from tibia segment was considered and the displacement vector component variation during time were obtained. It can be remarked that there are small differences between the mathematical modeling and virtual simulations and this confirm the knee mechanism for the proposed leg exoskeleton validation.

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