Human Locomotion System Design Based on Cam Mechanisms

S.I. Dumitrache, N. Dumitru and I. Geonea

***Abstract*— This paper presents a new design of exoskeleton for human locomotion system, based on a cam mechanism. Cam profile is determined by the main joints motion laws of the human locomotion system. Constructive solution adopted is validated by virtual simulation software package made by Adams software. The results obtained through virtual simulations consist in mass centres, displacements, velocities and accelerations of the exoskeleton kinematic elements.**

***Index Terms*— cam-mechanisms, exoskeleton, laws-of-motion**

I. Introduction

Beginning with the 19th century, scientists like N. Yagn in patent [1], [2] paid a significant attention to the mechanism that improve the human locomotion system performance, as we can see in figure 1.

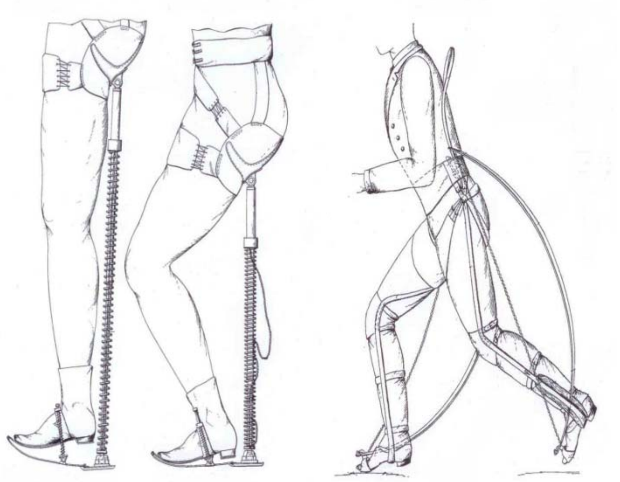

Fig. 1. The two “apparatus to facilitate walking, running and jumping” developed by N. Yagn

An exoskeleton for lower limbs can benefit the people who have suffered a stroke or suffering from paralysis. After studding the work of a researchers group from Massachusetts Institute of Technology in publication [3] we concluded that by analyzing biomechanical data, design principles for efficient actuation strategies can be extracted.

In our opinion the exoskeleton must have a structure for supporting the weight of the wearer similar with the solution chose by T. Koshiishi shown in figure 2, taken from patent [5].

Fig. 2. Walking support system developed by T. Koshiishi

The system must also be capable of varying its position and impedance in a comparable manner to that of a normal, healthy biological limb. Applying the appropriate torque and power at the joints it has to assist in forward locomotion as is shown in paper [6] (figure 3).

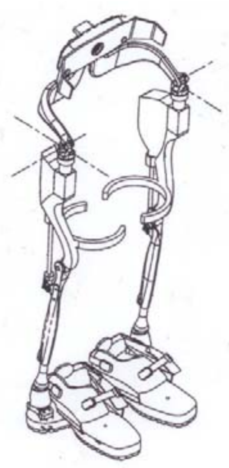

Fig. 3. Lower extremity exoskeleton developed for The Regents of the University of California

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To determine the angular amplitudes developed by each exoskeleton joint, we experimentally determined the angles amplitudes developed for each joint of interest in the human lower limb during walking. Correlating laws of motion of each joint, we can determine the general law of human limb movement, setting the cams profiles.

II. HUMAN LOCOMOTION SYSTEM EXPERIMENTAL ANALYSIS

Taking into account the experimental research aim, the motions developed by the human body will be evaluated experimentally by using motion analysis equipment, which is called CONTEMPLAS. It has two high speed cameras for capturing and recording sequences and a DELL notebook for sequences analysis in real time with Tempo Standard module software, [11]. The University of Craiova-Faculty of Mechanics owns this special equipment, which is used for the experimental research presented in figure 4.

Fig. 4. CONTEMPLAS motion analysis equipment

The high-speed cameras are CCD-Chip 2.1.0 type. This equipment enables us to determinate the desired points trajectories and spatial angular variation into biomechanical mobile systems through successive identifications of the joint centres positions in their structures. How to obtain results with this equipment is shown outlined in figure 5.

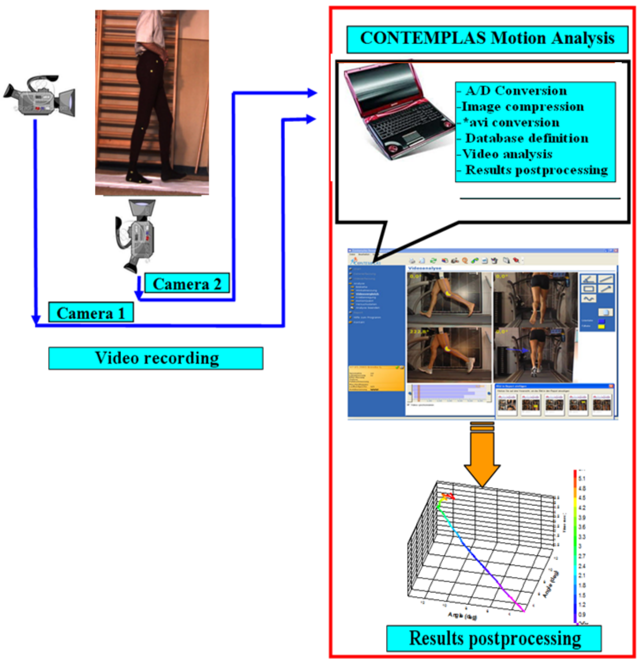

Fig. 5. CONTEMPLAS Motion Analysis scheme

Thus, one attached markers in the rotation joints centres with a view to determining the angular amplitude developed by the human body motions [12].

To reflect the motion laws made at the joints: hip, knee and ankle, were a series of experiments conducted on male volunteers, age - 30years, height - 1.80metres weight - 67 kilograms, $l_{femur} = 403$ millimetres; $l_{tibia} = 332$ millimetres; $l_{foot} = 215$ millimetres. These experiments are to determinate in-vivo joint kinematics for walking.

An overview of the subject's lower limb shows the position of each marker attached to the interest joints (figure 6).

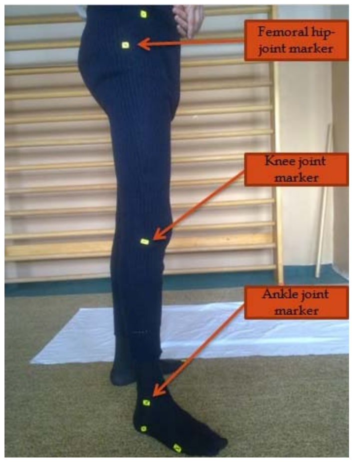

Fig. 6. Subject's lower limb overview with the attached markers

The analysis can measure the angular variations in certain frames of sequences. In figures 7 and 8 two sequences of the experimental analysis using this equipment are shown.

Fig. 7. Angular amplitudes developed by knee joint during flexion

Fig. 8. Angular amplitudes developed by ankle joint during flexion

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The data provided can be exported in *xls files, which are values of the analysis in question. With these we can generate diagrams representing the trajectories of the studied points, or human lower limb segment angular variations.

For hip joint, flexion during walking activity occurs in the range of 156 → 180 degrees, which shows 24 degrees angular amplitude (figure 9).

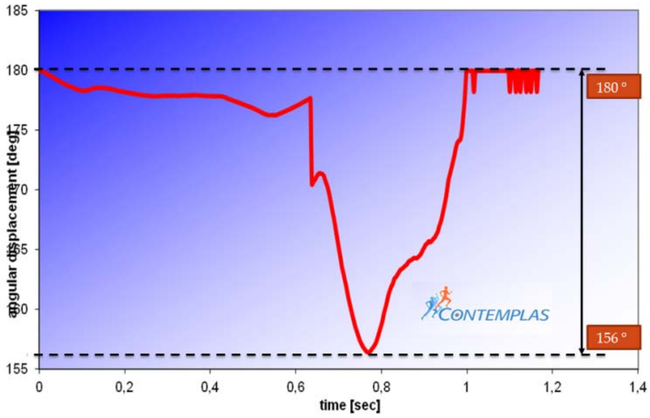

Fig. 9. Angular displacement [degrees], for hip joint during flexion

For the knee joint flexion-extension, during walking activity, occurs within the 120→ 178 degrees, which shows 56 degrees angular amplitude (figure 10).

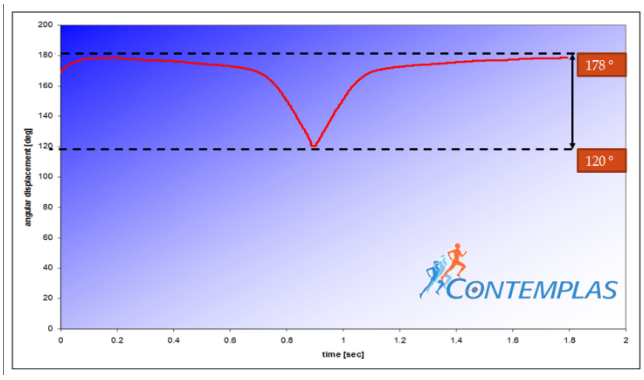

Fig. 10. Angular displacement [degrees], for knee joint during flexion

For the ankle joint, plantar/dorsal flexion during walking activity occurs in the range 113.9 → 137.5 degrees, which shows 24 degrees angular amplitude (figure 11).

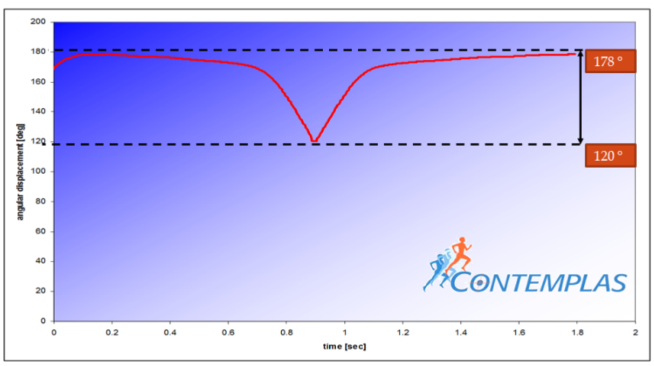

Fig. 11. Angular displacement [degrees], in ankle joint during flexion

III. DESIGN OF A CAM BASED EXOSKELETON MECHANISMS

A variety of solutions have been proposed to overcome problems in human lower limb, for people who have suffered an accident or paralysis.

As we said the exoskeleton must have a structure for supporting the wearer weight. We design a structure that is capable initially to take almost the entire wearer weight and during the rehabilitation progress gradually releases the weight until the wearer can support his weight. This support can be observed in figure 12.

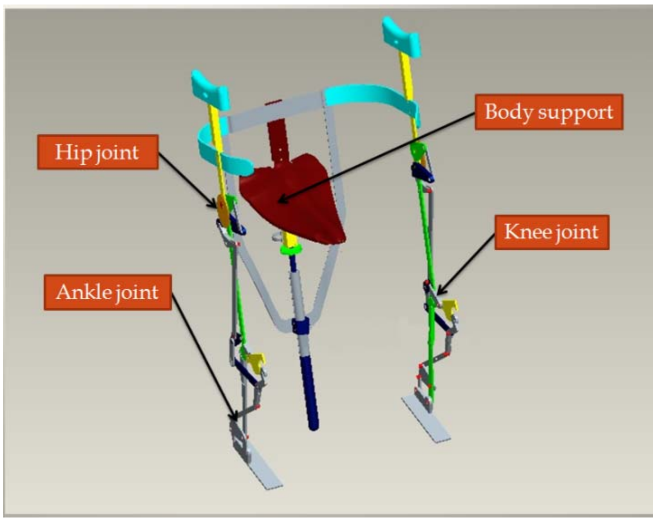

Fig. 12 Exoskeleton virtual model based on cam mechanism

Considering the constructive solution that works only for two joints chosen by researchers [7], we have developed a mechanism that acts on three main human lower limb joints (figure 12).

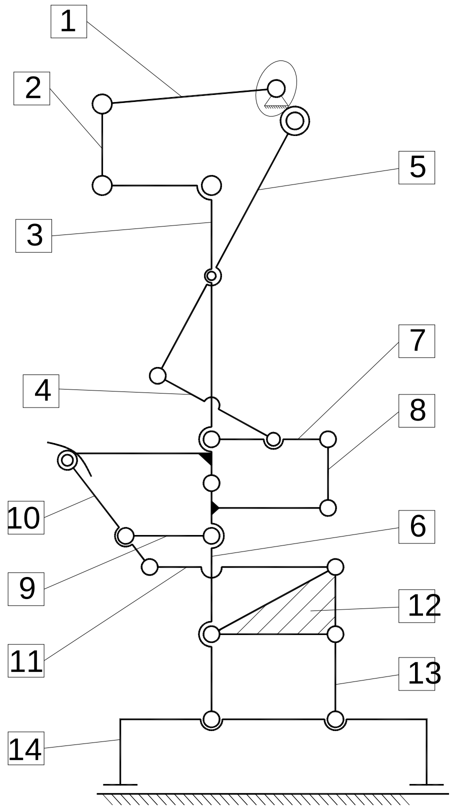

Fig. 13. Mechanism Kinematic scheme for human lower limb

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We considered that the leg is not in contact with the ground, and for this the mechanism family is 3. The mechanism is a planar one, and the motion range in this case is determined by the relation [8]:

$$M = (6 - f)n - \sum_{i=f+1}^{5} (i - f) C_i \quad (1)$$

n –number of moving parts of the mechanism;
f –mechanism family;
c_i –number of kinematic joints by class "i".

For our mechanism we have: n = 14, C_5 = 19, C_4 = 3 and substituting the relation (1), the mobility degree is M = 1. This means that we have 1 motor for driving the entire mechanism.

This exoskeleton is attached to the wearer torso and limbs; the right limb virtual mechanism is identical with the left limb mechanism so that only the left limb mechanism will be presented in this frame.

The hip movement is generated by a four link which rotates the element 5 equivalent to the femur.

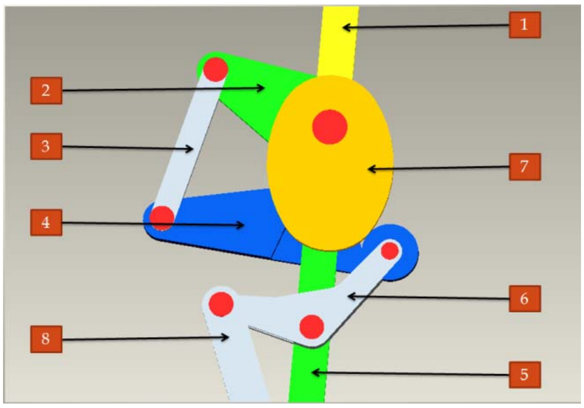

Fig. 14. Exoskeleton hip joint with components identification

The four link mechanism (figure 14) is composed from element 1, fixed with exoskeleton lombar support. This is connected by a driven shaft with element 2 that is pivotally connected with element 3. The element 3 is also pivotally connected to element 4 at one end. At the other end element 4 is connected pivotally up to a rotation of 10 deg with element 5 equivalent with femur. When the shaft rotate the element 4, after pivoting 10 deg to the femur, the element 5 starts to push. This will generate the exoskeleton hip joint movement. The motion follows the lowest of movement law in the human hip joint.

For knee movement we transmit the driven shaft rotation to a cam 7 (figure 14). The cam no 7 profile is determinate by the lowest motion in the knee joint, and the hip rocker 6, acts as a cam follower by rolling on the outer surface of cam 7.

The hip rocker is pivotally connected in the middle with femur element 5 and at the other end with element 8, transmitting the back and forth rocker 6 motions to the element 9.

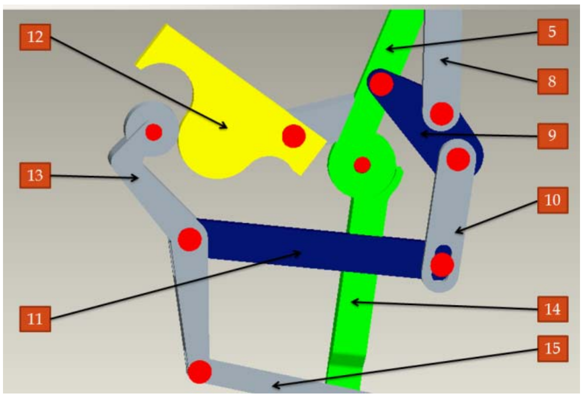

Fig. 15. Exoskeleton knee joint with components identification

Element 9 is pivotally connected with femur element 5. Also this is connected with element 8 and 10. In this way the element 8 motion is transmitted to a floating element 10 (figure 15), which is pivotally mounted and connects the element 9 with element 11. The element 11 is rigidly mounted on tibia element 14. The exoskeleton knee rotation is imposed by the profile of cam 7, which follows the motion laws in the human knee joint.

Ankle movement during walk is also established by a cam follower mechanism, as follows in this description. On the femur element 5, using a connection element we have a rigidly mounted cam 12 (figure 15). When the knee mechanism is making the flexion-extension movement during walking activity, the rocker 13, connected pivotally in the middle with element 11, acts as a cam follower by rolling on the outer surface of knee cam 12. Knee rocker 13 is pivotally connected at the other end with element 15, transmitting the back and forth rocking movement of the rocker 13 to the element 16 (figure 16).

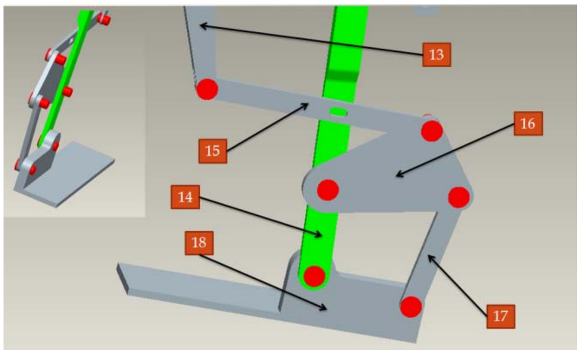

Fig. 16. Exoskeleton ankle joint with components identification

The element 16 is pivotally connected with tibia element 14 and this is also pivotally connected with element 15 and 17. In this way the element 15 motion is transmitted to element 17. Element 17 is pivotally mounted and connects the element 16 with support element 18 that is connected pivotally with tibia element 14 in the middle.

Responsible for the exoskeleton's ankle joint plantar/dorsal flexion, during walking is the profile of cam 12.

The profile of cam 12 must respect the laws of movement in the human ankle joint during walking activity.

IV. Constructive Solution Validation by Virtual Simulation with MSC ADAMS Software

To validate the mechanism functionality, we propose to achieve a kinematical simulation, using MSC Adams software. For this, we realized a kinematic model, based on mechanism geometry. We defined the elements material properties, kinematics joints, and the moving law of cam 7, which acts as an actuation element.

The mechanism elements motion laws, are corresponding with human limb movements for walking, thus fulfils the mechanism functional role for rehabilitation procedures. In the figures below, virtual mechanism sequences are shown, namely the initial position, figure 17, and the extreme positions of the mechanism for walking, figure 18.

Fig. 17. Mechanism into initial position

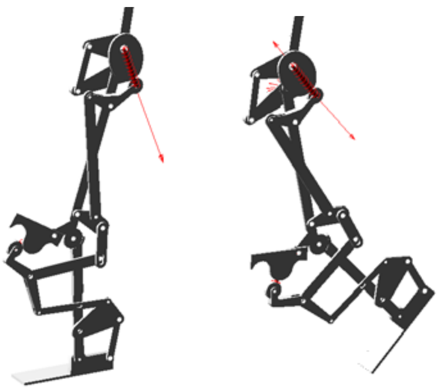

Fig. 18. Positions of the mechanism into extreme phases

For element 5, which acts as a structural femur, we presented in figure 19 the rotation angle law depending on time in x-y plane, which has angular amplitude of 45 degrees.

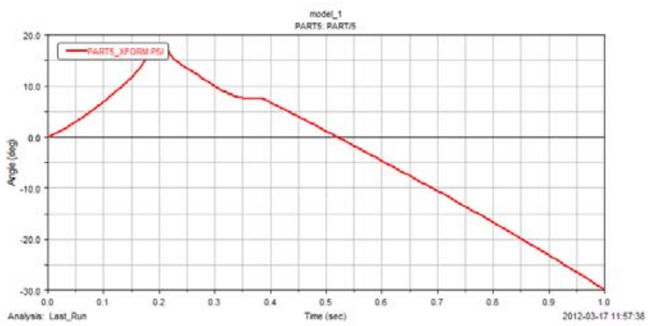

Fig. 19. Femur no 5 angular displacement law depending on time

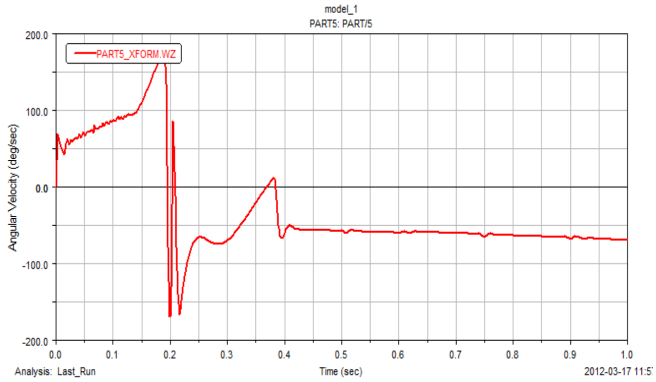

Fig. 20. Femur no 5 angular velocity law depending on time

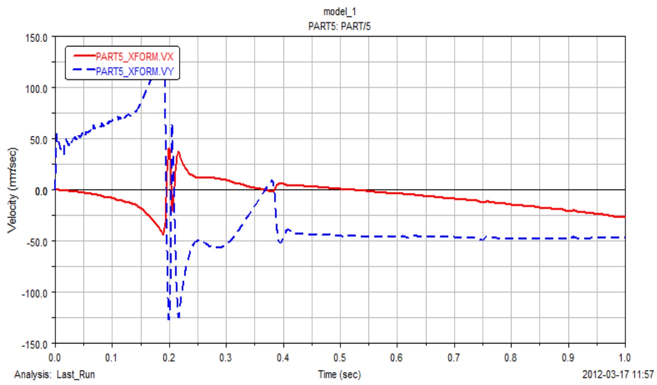

Fig. 21. Centre mass velocity components of the femur element 5

In Figure 21 the femur centre mass velocity components is presented, for a single gait.

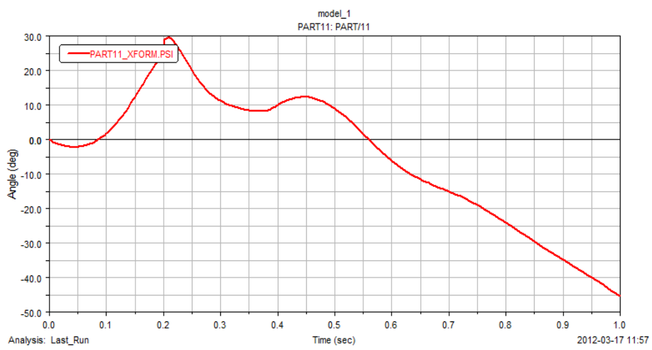

Fig. 22. Element no 14 equivalent with tibia angular displacement law depending on time

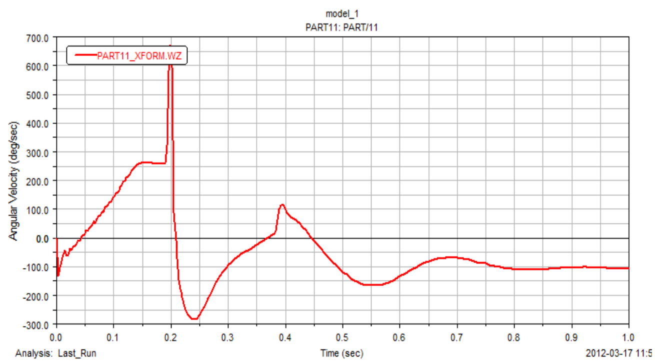

Fig. 23. Element no 14 equivalent with tibia angular velocity law depending on time

For element 14, equivalent with tibia, angular motion law in figure 22 is shown. Also the angular velocity is shown in figure 23 and the velocity components of mass centre are presented in figure 24.

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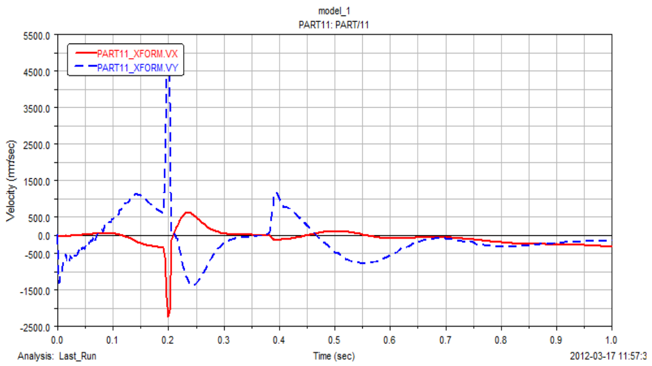

Fig. 24. Element no 14 equivalent with tibia centre mass velocity components law depending on time

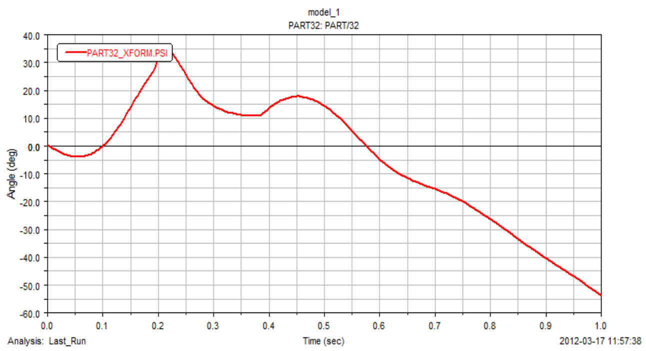

Fig. 25. Foot no 18 element angular displacement law depending on time

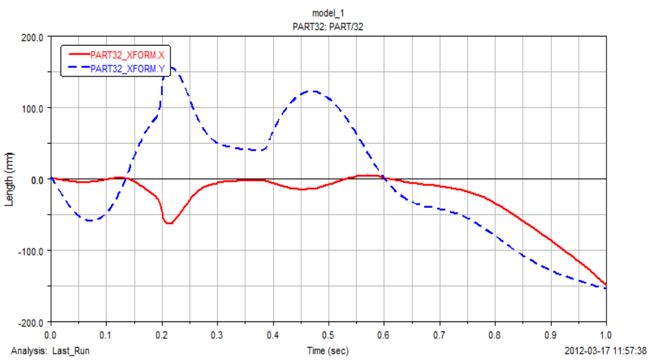

Fig. 26. Element no 18 equivalent with foot centre mass displacement components law depending on time

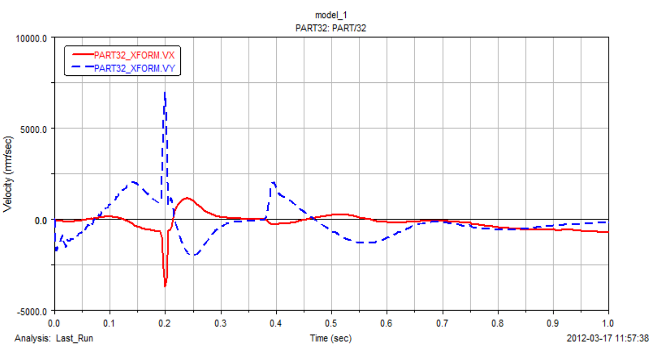

Fig. 27. Element no 18 equivalent with foot centre mass velocity components law depending on time

For element 18, equivalent with the human foot, angular motion law in figure 25 is shown. Also the angular velocity is shown in figure 26 and the velocity components of mass centre are presented in figure 27.

V. Conclusion

This paper presents a new design of an exoskeleton for human locomotion system, based on a cam mechanism. By a human lower limb structural analysis, we decided to develop a kinematic chain equivalent in terms with a real one. The aim is to create a mechanical system, such as a human limb exoskeleton for rehabilitation.
Cam profile is determined by the motion laws of the human lower limb main joints. Constructive solution adopted here is validated by virtual simulation software package made by MSC ADAMS.

Following the mechanical system simulation, we present results in a graphs form, the variation of kinematic parameters and sequence of the working mechanism.

The conclusion drawn is that the structure and mechanism construction fulfils its functional role, performing the movements necessary to comply with work done by walking human locomotion system.

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