Locomotion System Dynamic Analysis with Application on Children Orthotics and Prostheses Devices

C. Copilusi, M. Marin, N. Dumitru and L. Rusu

Abstract— **A study concerning the children locomotion system is presented through this research. The research aim is to obtain the motion laws developed by the children locomotion system's articulations and connection forces which are produced in their structure in the walking activity. These parameters are useful for orthotic and prosthetic systems design for children with ages between 4-7 years. The study is based on an experimental analysis developed with ultra high-speed video equipment on 20 children and a dynamic analysis achieved on analytical way by using the results obtained from the experimental analysis. A new knee modular orthosis and a parameterized lower limb are designed through this research.**

Index Terms— **dynamics, locomotion system, orthotics, prosthesis**

I. INTRODUCTION

THE main motivation for these analyses was given by the prosthesis and orthotics devices development restriction for children. It is known that the restriction is imposed by the fact that children are in growth continuously especially between 4-7 years. Due to this fact modular orthotics devices and parameterized prosthetics can be developed in order to improve the locomotion system and to satisfy the ability to move. For this it is necessary to perform experimental, analytical, and design analyses in order to create databases useful in this research direction. It can be mentioned similar research work in this field by [2], [3], [6], [8], [9] and [13]. Similar dynamic analyses with remarkable result can be found in [1], [6], [7], and [10]. The research main aim was to obtain the connection forces from each human locomotion system articulation when the healthy subject will perform the walking activity. This will serve as input data for dynamic analysis developed on analytical way.

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II. EXPERIMENTAL RESEARCH

Taking into account the experimental research aim, the motions developed by the human locomotion system [1], [7] presented here will be evaluated experimentally by using motion analysis equipment, which is called CONTEMPLAS. This has two high speed cameras for capturing and recording sequences and a DELL notebook for sequences analysis in real time with Templo Standard module software [4]. The University of Craiova-Faculty of Mechanics owns this special equipment, which is used for the experimental research presented in figure 1. This equipment enables us to determine the desired points trajectories and spatial angular variations onto either mechanical or biomechanical mobile systems through successive identifications of the joint centers positions in their structures. The general procedure for experimental determinations is shown in figure 1.
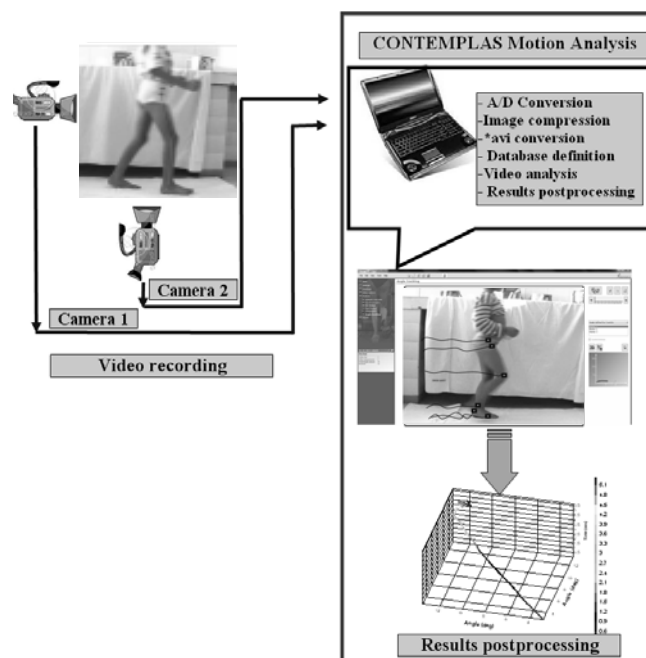

Fig. 1. CONTEMPLAS Motion equipment and analysis scheme

Thus, one attached markers in the rotation joints centers with a view to determining the angular amplitude developed by the human locomotion system. A sequence of the experimental analysis using this equipment is shown in figure 2. In this sequence children have to perform 3 steps

for walking activity. For this experimental research a number of 20 children with ages between 4-7 years were used. Markers have been attached on human locomotion system's articulations centers, in order to determine trajectories and angular amplitudes. These motion laws forms a database which consists in a number of 4 segments, each segment consists in 5 healthy children with the same age.
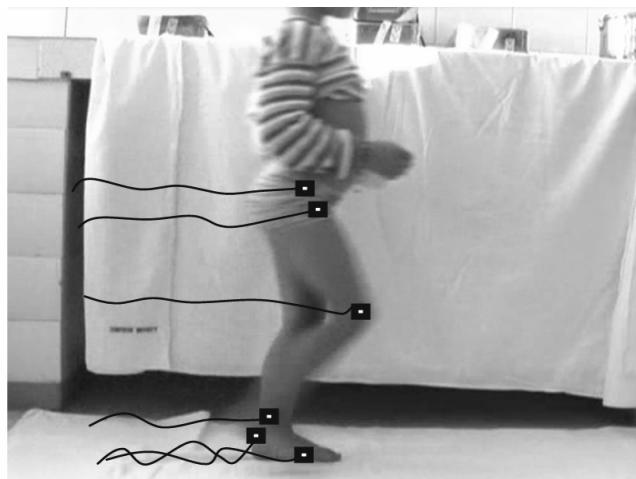

Fig. 2. Experimental analysis sequence

Also the height interval for all the analyzed children was: 95-136 cm. Weight of these subjects was between 21-36 kilograms. In each segment was 1 girl and the rest of the subjects were boys. The cameras record simultaneously the markers trajectories and angular amplitudes for each lower limb. As an example of the final results, one presents the motion laws for the analyzed articulations in diagrams from Fig. 3, Fig.4, Fig.5 and Fig.6.
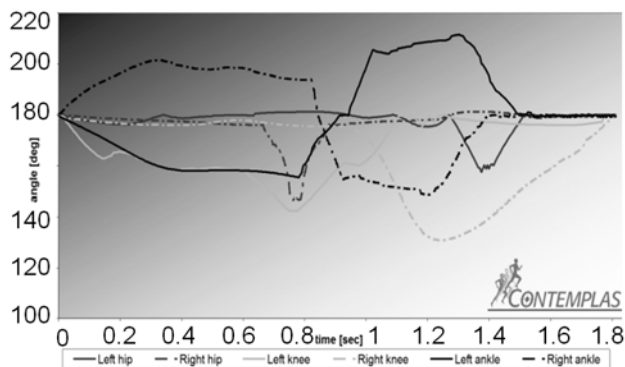

Fig. 3. Locomotion system's angular amplitudes average for children at 4 years for walking activity
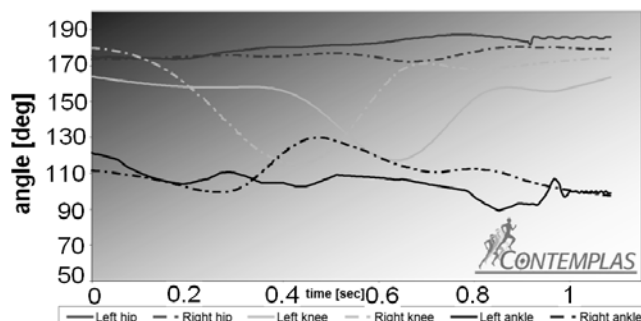

Fig. 4. Locomotion system's angular amplitudes average for children at 5 years for walking activity

The angular amplitude of each joint is a functional angle for lower limb joints, means useful angle for develops movement from ADL scale (activity daily living scale) present by the trajectories of the joints.
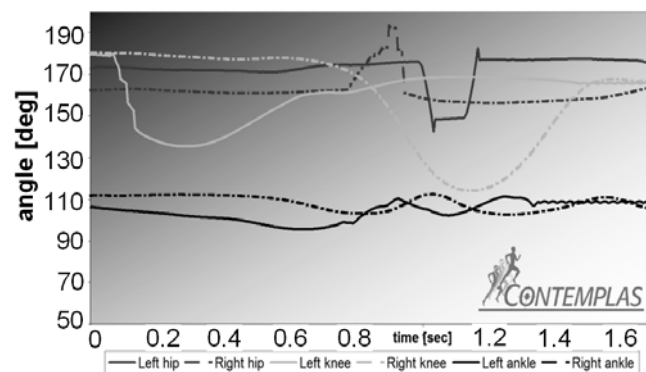

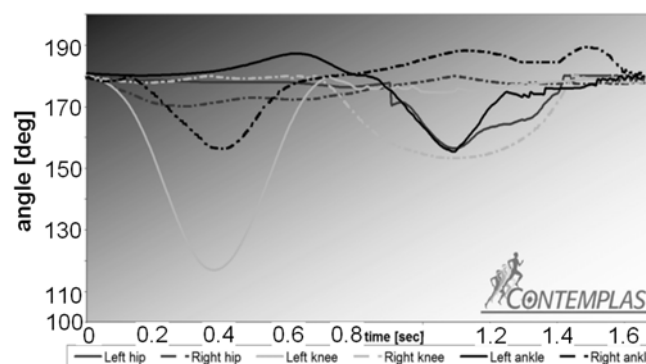Fig. 5. Locomotion system's angular amplitudes average for children at 6 years for walking activity

Fig. 6. Locomotion system's angular amplitudes average for children at 7 years for walking activity

The average angular amplitudes during the gait cycle on the examined children segments are presented in Table 1, where: IC-Initial Contact, LR-Loading Response, MSt-MidStance, TSt-Terminal Stance, PSw-PreSwing, ISw-Initial Swing, MSw-MidSwing, TSw-Terminal Swing.

TABLE I
AVERAGE ANGULAR AMPLITUDES FROM ANALYZED HUMAN SUBJECTS

Joints Gait phase	Segment 1 with 4 years age			Segment 2 with 5 years		
	Hip	Knee	Ankle	Hip	Knee	Ankle
IC	19.71°	4.23°	-6.51°	19.85°	4.78°	-6.56°
LR	14.08°	13.76°	-15.48°	14°	13.82°	-15.9°
Mst	-14.5°	0.87°	-5.37°	-15.62°	1.02°	-5.42°
Tst	-22.7°	3.08°	-2.17°	-23.01°	5.23°	-1.95°
PSw	-16.4°	39.35°	27.39°	-16.51°	40.02°	27.44°
ISw	10.9°	53.68°	14.29°	10.93°	52.16°	14.44°
MSw	17.01°	15.08°	11.78°	16.98°	15.59°	12.35°
TSw	16.17°	7.83°	10.21°	16.23°	6.42°	11.52°
	Segment 3 with 6 years age			Segment 4 with 7 years age		
IC	19.98°	5.23°	-7.03°	20.36°	6.36°	-10.5°
LR	14.52°	14.11°	-16.35°	15.87°	15.99°	-18.9°
Mst	-14.9°	1.12°	-5.98°	-16.64°	0.52°	-7.36°
Tst	-23.2°	6.49°	-0.87°	-25.61°	7.83°	0.12°
PSw	-17.5°	42.23°	28.39°	-19.22°	46.29°	30.21°
ISw	11.01°	54.63°	15.92°	12.21°	55.31°	16.05°
MSw	17.23°	16.32°	13.62°	18.34°	17.58°	14.21°
TSw	16.69°	8.42°	12.96°	18.48°	9.13°	13.62°

III. CHILDREN LOCOMOTION SYSTEM DYNAMIC ANALYSIS

A mathematical model used for inverse dynamic analysis of the human lower limb, will be elaborated by taking in account the ground contact (Fig. 7). Similar analysis and procedures can be found in [5], [6], [11], [12] and [15]. Input data: For an inverse dynamic analysis one consider known the geometric elements (L_{OT}, L_1, L_2... L16) and generalized coordinates variation laws from cinematic joints: q_1, q_2, q_3,…,q_{16} obtained with the CONTEMPLAS equipment's aid.
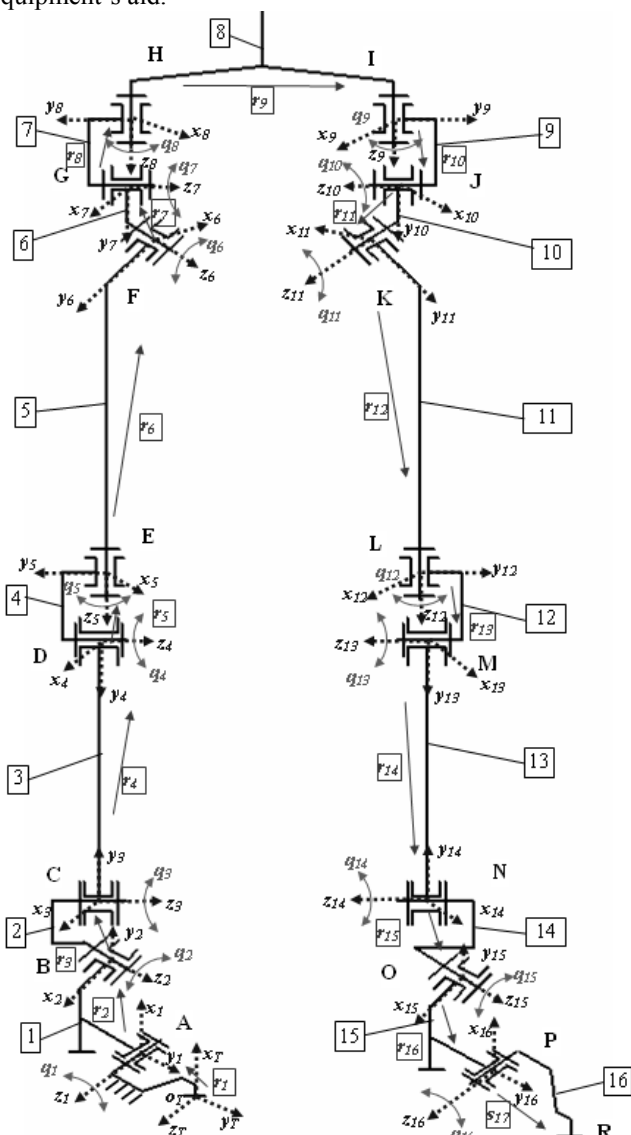

Fig. 7. Mathematical model for inverse dynamic analysis of the human locomotion system

A calculus algorithm was elaborated with MAPLE software's aid. Output data: It will be followed to obtain the connection forces components, which will appear in the walking activity, for a gait cycle, at the each joint level from the mathematical model structure which is equivalent to human locomotion system. The constraint equations are:

$$\Phi(q,t) = 0. \tag{1}$$

q_r - Generalized coordinates vector considered when the elements are rigid ones; t- time. The motion equation has the following form:

$$\begin{bmatrix} M & J_q^T \\ J_q & 0 \end{bmatrix} \begin{bmatrix} \ddot{q} \\ \lambda \end{bmatrix} = \begin{bmatrix} Q_a \\ a \end{bmatrix}. \tag{2}$$

Where: M, represents the mass matrix with:

$$M = diag\ (m_i, J_i);\ i = \overline{1,16}. \tag{3}$$

We obtain the Lagrange's multipliers are:

$$\lambda = \left[J_q\right]^{-1}\left[Q_a - M \cdot \ddot{q}\right]. \tag{4}$$

The motion laws are known: $q(t)$, $\dot{q}(t)$ and $\ddot{q}(t)$, from the experimentally analysis accomplished in dynamic mode. From (4) relations we determine λ Lagrange's multipliers, with the aid of a programming algorithm accomplished in MAPLE software. With these it will be process an inverse dynamic analysis from it were obtained cinematic joint connection forces. These forces were determined by taking into account the Lagrange multipliers:

$$F_i^{"r(i,j)} = \left[R_{i,i"}\right]^T \cdot \left[A_{oi}\right]^T \cdot \left[\lambda\right]^{r(i,j)} \tag{5}$$

Based on the elaborated algorithm the connection forces for each joint were obtained. The joints are from the model presented above, and the connection forces components are oriented on 3 directions for a xyz coordinate system.

The force components for knee joint are presented in figures 8 and 9, and are used to design orthotic and prosthetic mechanisms especially for children on 4-7 years age. The high values and high oscillations onto these diagrams are from the foot with ground contact when the analyzed subjects are in the Tst and Tsw gait phases.
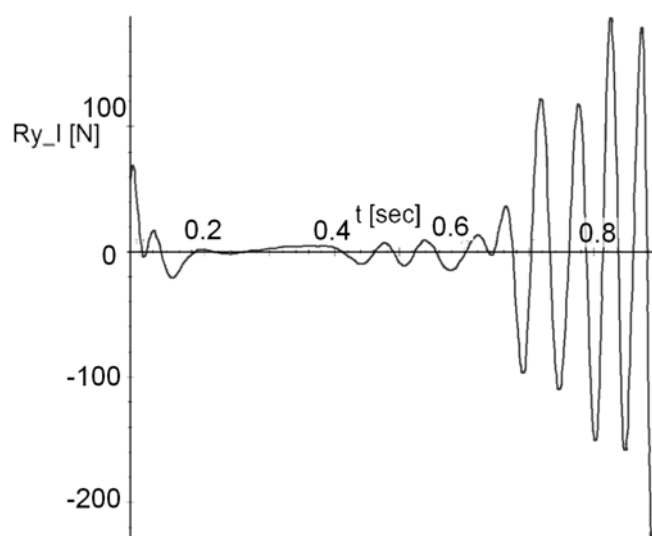

Fig. 8. Connection force component on Y direction for knee articulation (I-joint) [Newton] vs. time [sec] for 4 years children segment
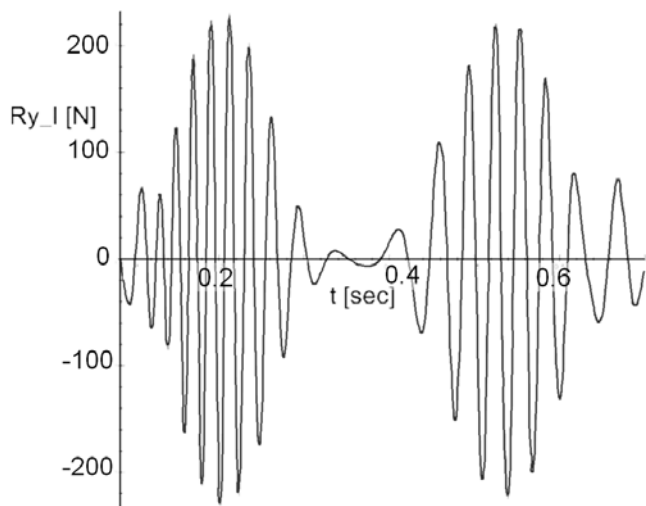
Fig. 9. Connection force component on Y direction for knee articulation (I-joint) [Newton] vs. time [sec] for 7 years children segment

The knee connection force value in case of a 4 year old child is 9.845N on swing phase. In case of a 7 year old child, the knee connection force is 18.908N on swing phase. This data help us to design orthotics and prosthesis mechanisms. In order to validate these mechanisms is necessary to simulate with Dynamic Module from MSC Adams environment.

IV. ORTHOTICS AND PROSTHESIS DESIGN BASED ON DYNAMIC CONSIDERATIONS

Based on the dynamic analysis presented here, the obtained results are useful for design a knee modular orthosis for 4-7 years old children and a parameterized knee prosthesis which has a cam mechanism in his structure. The virtual models are presented in Fig. 10 and Fig. 11.

For virtual simulations the knee modular orthosis was imported in MSC Adams Environment by creating an export interface from SolidWorks. Two virtual models were created, one for a 4 years old child and other for 7 years old. As a dynamic view point for knee modular orthotics through virtual simulations it wants to be determinate the cable forces for both cases. For this the connection forces components from Fig. 8 and Fig. 9 were applied on knee orthotics final module. The connection force from figure 9 was applied in case of the modular knee orthosis from Fig. 10-a, and the other connection force from Fig. 8 for the virtual model from Fig. 10-b. In Fig. 11, an aspect of virtual models in the MSC Adams environment is shown. The forces from cables are presented in Fig. 12 and Fig. 13. It can be observe that the maximum value is 112.5N for a 7 years old child, which means that the cable diameters are correctly choose. The diameter in this case is a 1.75 millimeters stainless steel. In the 4 years old child case this was smaller and the obtained value was 68.75N (Fig.13).

In the knee parameterized prosthesis case, presented in Fig. 14, the component identification is: 1-femur component, 2-cilindrical joint, 3- cam follower, 4- cam, 5- tibia component, 6-FESTO shock absorber, 7-aditional shock absorber mechanism. For this through VisualNastran simulations dynamic response of this was determined.

Fig. 10. modular orthosis virtual model with components (a-case of a 7 years old child; b-case of a 4 years old child).
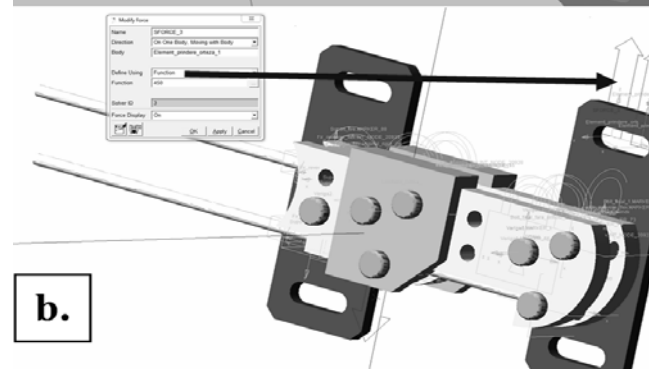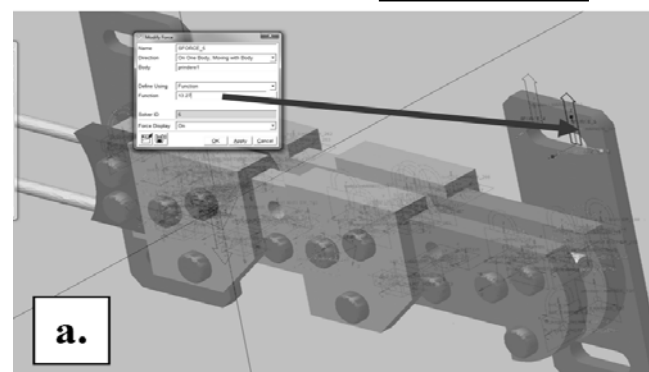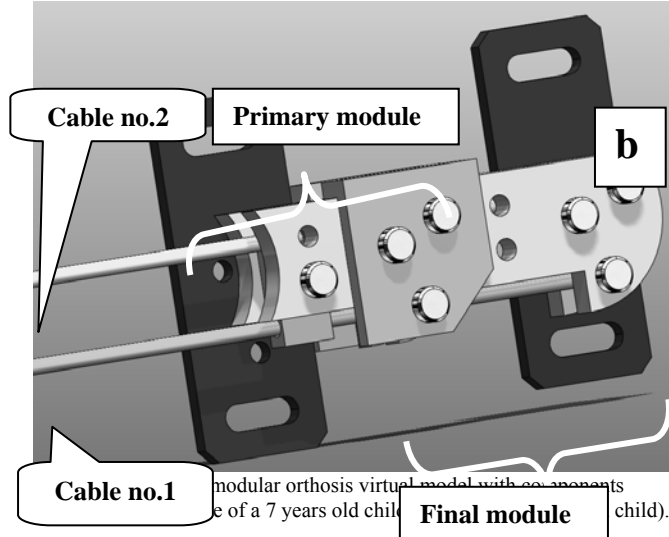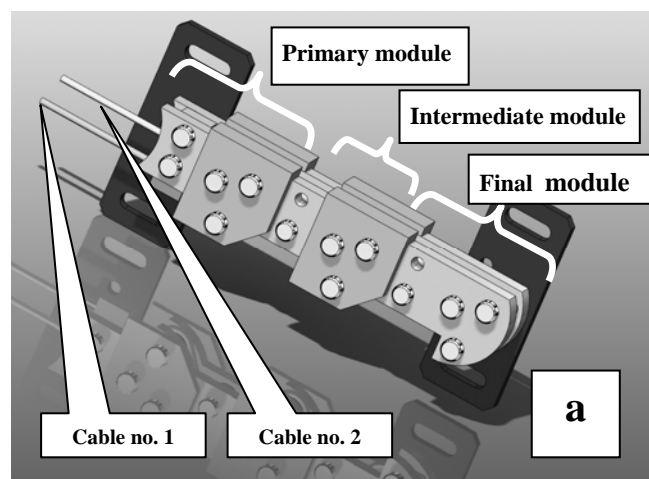

Fig. 11. Aspects regarding the applied force laws (a-case of a 7 years old child; b-case of a 4 years old child).
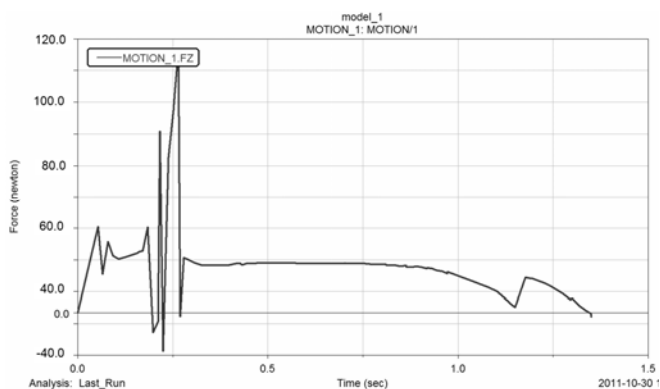
Fig. 12. Force variation diagram for cable no. 1 of the knee modular orthosis in a 7 years old child case.
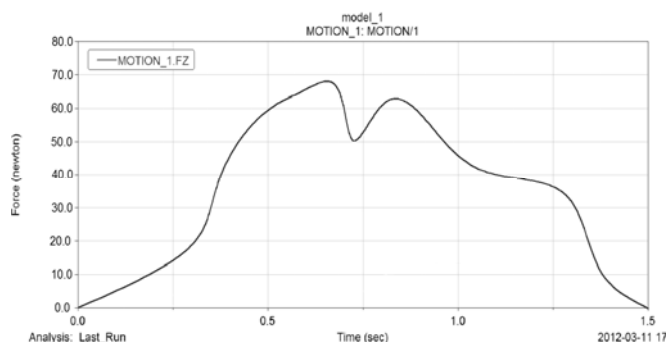

Fig. 13. Force variation diagram for cable no. 1 of the knee modular orthosis in a 4 years old child case.

The dynamic response was represented through von Misses stress, displacements and deformations of the knee prosthesis mechanism. These results were obtained in a dynamic mode by applying the connection forces from figure 9 onto cam element, and the knee motion law from figure 6 was applied onto the drive element for a single gait. The drive element was the Festo shock absorber. The results are shown in Fig. 15, Fig. 16 and Fig. 17. Von Misses stress highest value was 21 MPa, displacements were 0.034milimeters and total deformations were 0.000061. These values were obtained for aluminum alloys which confer a small weight and can be easy to wear for the children with one amputated leg.
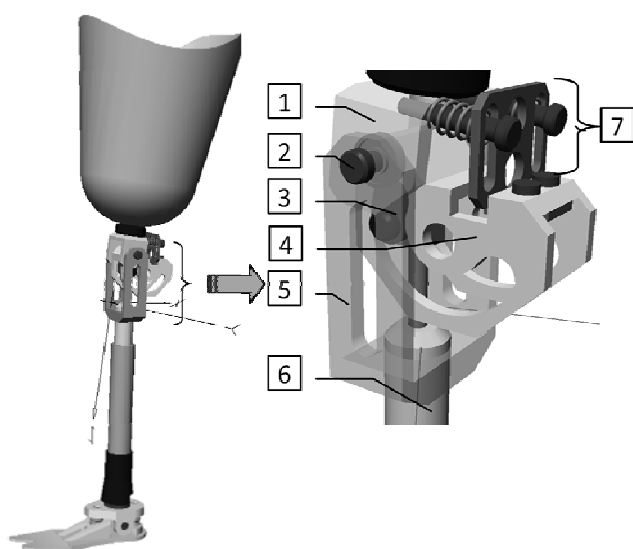

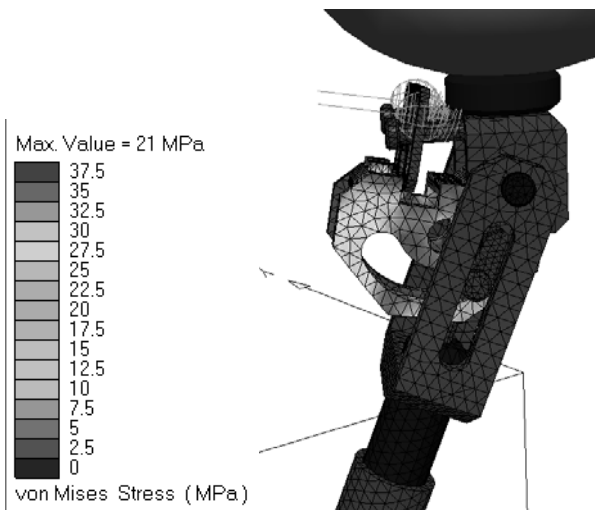Fig. 14. Parameterized knee prosthesis for 4-7 years old children with component identification

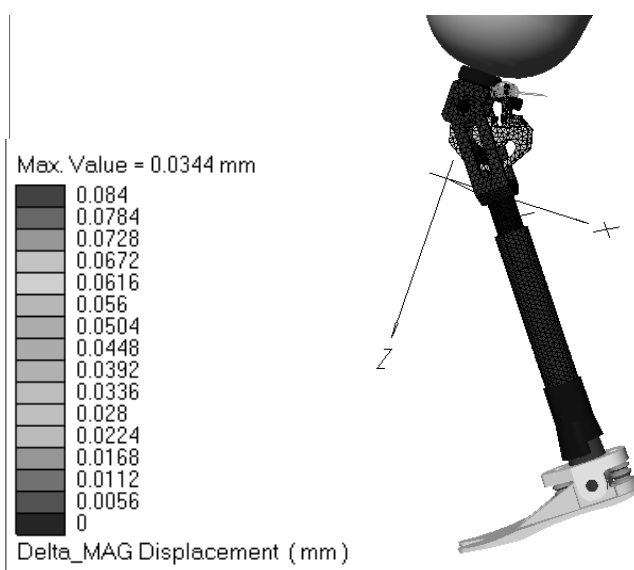Fig. 15. Von Misses stress of the parameterized knee prosthesis

Fig. 16. Displacements of the parameterized knee prosthesis

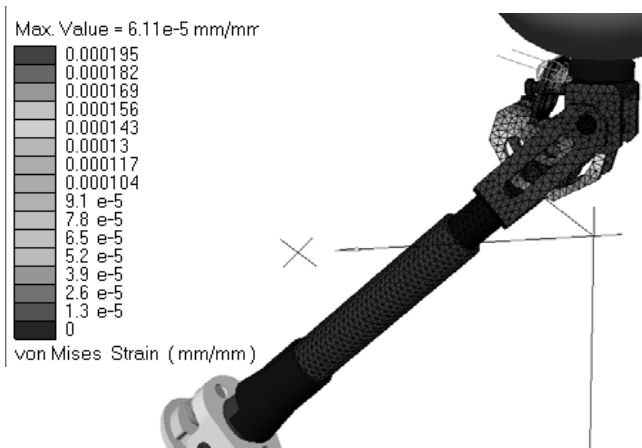Fig. 17. Deformations of the parameterized knee prosthesis

V. CONCLUSION

As final conclusions it can be mentioned that this type of analysis has an original approach because it was started by creating a database from an experimental research and finally to obtain connection forces diagrams used for orthotics and prosthesis design. With these it can be presented here real models of a modular knee orthotic

device (Fig. 18) and parameterized knee prosthesis (Fig. 19).

The angular amplitudes and lower limb segments dimensions are used as entry data for dynamic analysis. Also the angular amplitudes represent the motion laws which dictate the prosthetic and orthotic devices motions specially designed for children.

The motion laws developed through the experimental research can be useful to joint actuators program and control from an exoskeleton structure specially designed for children with temporal locomotion disabilities according with biomechanical features of children.

If we analyzed the joints values movement during the gait cycle we can observe difference between group of age and this is important for design the assistive devices in according with biomechanical features of children.

Fig. 18. Prototype experimental research in case of a 4 years old child (a) and 7 years old child (b)

The database that we try to create beginning from healthy people, in this research, help us to design the assistive devices for children with neuromotor pathology, depending of age and anthropometric features that means an improvement and development of fast and well rehabilitation program.

Fig. 19. Real model of parameterized knee prosthesis for children

Analyzed of joints kinematics for each phase of gait help us for modulate the construction of assistive devices and improvement the motor control for each joint in according with biomechanical rules. That means to improve the movement and stability of joint without decrease the role of dynamic stability involved by muscle system. Much more is possible to integrate the movement pattern of child in normal pattern of gait and to improve the balance during gait.

Analyzing the forces from figure 8 and 9, it help us to training the muscle group close to normal pattern of gait, because the assistive devices can involve a normal pattern of gait. So is possible to restore or to improve the normal central nervous system activity in the situations o cerebral palsy. The system of assessment the gait phase using biomechanical assessment can help to monitoring the rehabilitation program and to develop the skills for each phase of gait, at each joint.

The major problem for knee prosthesis mechanical system is the fabrication procedures, which are expensive. In the knee orthosis case the problems consists in its size, which is bigger than some children knee articulation size. On the future the research presented here will be continued in order to increase the mechanical systems performances.

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