Abstract—In this paper a human locomotion system cinematic analysis is presented, in order to obtain the cinematic joints motion laws. This cinematic analysis is performed for a 4 years old child in the walking activity case. The obtained results are used for a new knee modular orthosis prototype validation.

Index Terms—cinematic, modular orthosis, human locomotion system, biomechanics

I. INTRODUCTION

DIFFERENT human locomotion system cinematic analyses have been developed through diverse methods [1], [2], [3], [5], [12] and [14].

In this paper a human locomotion system cinematic analysis is performed in the walking case of a 4 years old child. The research aim is to design a new knee orthosis which will be used by children that needs a temporal recovery through therapeutic procedures only for walking activity. The children are permanently in growth and that is the main fact that restricts the orthosis design research area. For this we propose here the development of a new orthosis type which consists in modules that can be modified by depending the childs age, sex, weight, height, etc. For this is necessary to study the whole locomotion system from a cinematic viewpoint when perform a single gait.

A cinematic analysis of a mechanical model consists in solving two important problems: cinematic direct problem and cinematic inverse problem. The cinematic direct problem’s frame, the displacements from cinematic joint are known, and it will be determined the positions – orientation, speeds and accelerations of the mechanism elements or some characteristic points onto the analyzed mechanism.

The cinematic inverse problem, cinematic parameters for some characteristic points motion are known, and it will be determined the cinematic joints relative motions parameters. With these, in the cinematic analysis context, we identify many problems such as: positional problem, speed problem, accelerations problem. Each of these problems presents a direct or inverse aspect.

II. HUMAN LOCOMOTION SYSTEM CINEMATIC ANALYSIS

The method used here has a flexible character and assures an interface for dynamic analysis especially for finite element modeling of spatial and planar mobile mechanical systems [6], [7], [8] and [9].

For the cinematic analysis the cinematic model presented in figure 1, will be considered. The cinematic analysis will be performed for walking; only one gait when a foot is fixed with the ground and the other perform the desired motion. The cinematic parameters variation laws were obtained by processing with the MAPLE software aid the mathematical models which are defining the human locomotion system experimentally cinematic analysis.

From a structural viewpoint, the cinematic chain it consists in 16 rotation joints.

Fig. 1. Human locomotion system cinematic model.
By analyzing (3) to (19) we observe that:

\[
\begin{align*}
[A_{OT2}]_{1} & = [A_{12}]_{1} \cdot \{ W_{OT1} \} \\
[A_{OT4}]_{1} & = [A_{34}]_{1} \cdot \{ W_{OT1} \} \\
[A_{OT6}]_{1} & = [A_{56}]_{1} \cdot \{ W_{OT1} \} \\
[A_{OT8}]_{1} & = [A_{78}]_{1} \cdot \{ W_{OT1} \} \\
[A_{OT10}]_{1} & = [A_{910}]_{1} \cdot \{ W_{OT1} \} \\
\end{align*}
\]

(20)

Based on (20) we identify the coordinates transformation matrices for each cinematic joints, with \( \alpha_{i,j+1} = 90^\circ \), and \( i = 1, \ldots, 6 \). Point: \( A, B, C, D, E, F, G, H, I, J, K, L, M, N, O, P \) and \( R \) positions in rapport with \( T_{OT} \) coordinate system, bounded to the left foot, will be identified through the (21) to (28). Similarly, we obtain the displacements of other joint centre points. The displacement for \( R \) point is given by (29).
\[
\{v\}_{R}^{\text{OT}} = \begin{bmatrix}
[r_{1x}^{\text{OT}}] & \cdots & [r_{16x}^{\text{OT}}] & \cdots & [r_{21x}^{\text{OT}}] & \cdots & [r_{26x}^{\text{OT}}]
\end{bmatrix} - \begin{bmatrix}
[w_{1x}^{\text{OT}}] & \cdots & [w_{16x}^{\text{OT}}] & \cdots & [w_{21x}^{\text{OT}}] & \cdots & [w_{26x}^{\text{OT}}]
\end{bmatrix} + 
\begin{bmatrix}
[r_{2x}^{\text{OT}}] & \cdots & [r_{26x}^{\text{OT}}] & \cdots & [r_{31x}^{\text{OT}}] & \cdots & [r_{36x}^{\text{OT}}]
\end{bmatrix} - \begin{bmatrix}
[w_{2x}^{\text{OT}}] & \cdots & [w_{26x}^{\text{OT}}] & \cdots & [w_{31x}^{\text{OT}}] & \cdots & [w_{36x}^{\text{OT}}]
\end{bmatrix} + 
\begin{bmatrix}
[r_{3x}^{\text{OT}}] & \cdots & [r_{36x}^{\text{OT}}] & \cdots & [r_{41x}^{\text{OT}}] & \cdots & [r_{46x}^{\text{OT}}]
\end{bmatrix} - \begin{bmatrix}
[w_{3x}^{\text{OT}}] & \cdots & [w_{36x}^{\text{OT}}] & \cdots & [w_{41x}^{\text{OT}}] & \cdots & [w_{46x}^{\text{OT}}]
\end{bmatrix} + 
\begin{bmatrix}
[r_{4x}^{\text{OT}}] & \cdots & [r_{46x}^{\text{OT}}] & \cdots & [r_{51x}^{\text{OT}}] & \cdots & [r_{56x}^{\text{OT}}]
\end{bmatrix} - \begin{bmatrix}
[w_{4x}^{\text{OT}}] & \cdots & [w_{46x}^{\text{OT}}] & \cdots & [w_{51x}^{\text{OT}}] & \cdots & [w_{56x}^{\text{OT}}]
\end{bmatrix} + 
\begin{bmatrix}
[r_{5x}^{\text{OT}}] & \cdots & [r_{56x}^{\text{OT}}] & \cdots & [r_{61x}^{\text{OT}}] & \cdots & [r_{66x}^{\text{OT}}]
\end{bmatrix} - \begin{bmatrix}
[w_{5x}^{\text{OT}}] & \cdots & [w_{56x}^{\text{OT}}] & \cdots & [w_{61x}^{\text{OT}}] & \cdots & [w_{66x}^{\text{OT}}]
\end{bmatrix} + 
\begin{bmatrix}
[r_{6x}^{\text{OT}}] & \cdots & [r_{66x}^{\text{OT}}]
\end{bmatrix} - \begin{bmatrix}
[w_{6x}^{\text{OT}}]
\end{bmatrix}.
\]

B. Speed calculus

We follow to determine the \( R \) point speed depending on \( T_{\text{OT}} \) reference system. For this we differentiate successively (21) to (29), but for achieves this calculus is necessary to build the anti symmetric matrices for each joint, like the form from (30).

\[
\begin{bmatrix}
0 & -\omega_{ci} & -\omega_{ci} \\
\omega_{ci} & 0 & -\omega_{ci} \\
-\omega_{ci} & \omega_{ci} & 0
\end{bmatrix}, \quad \text{with } i, j = 1, \ldots, 6.
\]

For this:

\[
\begin{bmatrix}
\cdot \\
A_{\text{OT1}} \cdot & -\omega_{ci} & -\omega_{ci} \\
\cdot & A_{\text{OT1}} & 0 & -\omega_{ci} \\
\cdot & -\omega_{ci} & A_{\text{OT1}} & 0
\end{bmatrix} = \begin{bmatrix}
0 & -\omega_{ci} & -\omega_{ci} \\
\omega_{ci} & 0 & -\omega_{ci} \\
-\omega_{ci} & \omega_{ci} & 0
\end{bmatrix},
\]

\begin{equation}
(30)
\end{equation}

By differentiating (21) to (29) for each joint centre point we obtain the speed equations. For \( A, B \) and \( C \) we will obtain the speed (32), (33) and (34). Similarly, we obtain the velocities of other joint centre points. The velocity for \( R \) point is given by (35).

\[
\begin{bmatrix}
\cdot \\
\omega_{ci} & -\omega_{ci} & -\omega_{ci} \\
\cdot & \omega_{ci} & 0 & -\omega_{ci} \\
\cdot & -\omega_{ci} & \omega_{ci} & 0
\end{bmatrix} = \begin{bmatrix}
0 & -\omega_{ci} & -\omega_{ci} \\
\omega_{ci} & 0 & -\omega_{ci} \\
-\omega_{ci} & \omega_{ci} & 0
\end{bmatrix}.
\]

\begin{equation}
(31)
\end{equation}

\[
\begin{bmatrix}
\cdot \\
A_{\text{OT1}} \cdot & -\omega_{ci} & -\omega_{ci} \\
\cdot & A_{\text{OT1}} & 0 & -\omega_{ci} \\
\cdot & -\omega_{ci} & A_{\text{OT1}} & 0
\end{bmatrix} = \begin{bmatrix}
0 & -\omega_{ci} & -\omega_{ci} \\
\omega_{ci} & 0 & -\omega_{ci} \\
-\omega_{ci} & \omega_{ci} & 0
\end{bmatrix},
\]

\begin{equation}
(32)
\end{equation}

\[
\begin{bmatrix}
\cdot \\
A_{\text{OT1}} \cdot & -\omega_{ci} & -\omega_{ci} \\
\cdot & A_{\text{OT1}} & 0 & -\omega_{ci} \\
\cdot & -\omega_{ci} & A_{\text{OT1}} & 0
\end{bmatrix} = \begin{bmatrix}
0 & -\omega_{ci} & -\omega_{ci} \\
\omega_{ci} & 0 & -\omega_{ci} \\
-\omega_{ci} & \omega_{ci} & 0
\end{bmatrix},
\]

\begin{equation}
(33)
\end{equation}

\[
\begin{bmatrix}
\cdot \\
A_{\text{OT1}} \cdot & -\omega_{ci} & -\omega_{ci} \\
\cdot & A_{\text{OT1}} & 0 & -\omega_{ci} \\
\cdot & -\omega_{ci} & A_{\text{OT1}} & 0
\end{bmatrix} = \begin{bmatrix}
0 & -\omega_{ci} & -\omega_{ci} \\
\omega_{ci} & 0 & -\omega_{ci} \\
-\omega_{ci} & \omega_{ci} & 0
\end{bmatrix},
\]

\begin{equation}
(34)
\end{equation}

\[
\begin{bmatrix}
\cdot \\
A_{\text{OT1}} \cdot & -\omega_{ci} & -\omega_{ci} \\
\cdot & A_{\text{OT1}} & 0 & -\omega_{ci} \\
\cdot & -\omega_{ci} & A_{\text{OT1}} & 0
\end{bmatrix} = \begin{bmatrix}
0 & -\omega_{ci} & -\omega_{ci} \\
\omega_{ci} & 0 & -\omega_{ci} \\
-\omega_{ci} & \omega_{ci} & 0
\end{bmatrix},
\]

\begin{equation}
(35)
\end{equation}

C. Acceleration calculus

These will be obtained by differentiating successively the speed equations. For \( A, B \) and \( C \) we will obtain the accelerations (36) and (37). Similarly, we obtain the accelerations of other joint centre points. The acceleration for \( R \) point is given by (38).

\[
\begin{bmatrix}
\cdot \\
\omega_{ci} & -\omega_{ci} & -\omega_{ci} \\
\cdot & \omega_{ci} & 0 & -\omega_{ci} \\
\cdot & -\omega_{ci} & \omega_{ci} & 0
\end{bmatrix} = \begin{bmatrix}
0 & -\omega_{ci} & -\omega_{ci} \\
\omega_{ci} & 0 & -\omega_{ci} \\
-\omega_{ci} & \omega_{ci} & 0
\end{bmatrix},
\]

\begin{equation}
(36)
\end{equation}

\[
\begin{bmatrix}
\cdot \\
\omega_{ci} & -\omega_{ci} & -\omega_{ci} \\
\cdot & \omega_{ci} & 0 & -\omega_{ci} \\
\cdot & -\omega_{ci} & \omega_{ci} & 0
\end{bmatrix} = \begin{bmatrix}
0 & -\omega_{ci} & -\omega_{ci} \\
\omega_{ci} & 0 & -\omega_{ci} \\
-\omega_{ci} & \omega_{ci} & 0
\end{bmatrix},
\]

\begin{equation}
(37)
\end{equation}

\[
\begin{bmatrix}
\cdot \\
\omega_{ci} & -\omega_{ci} & -\omega_{ci} \\
\cdot & \omega_{ci} & 0 & -\omega_{ci} \\
\cdot & -\omega_{ci} & \omega_{ci} & 0
\end{bmatrix} = \begin{bmatrix}
0 & -\omega_{ci} & -\omega_{ci} \\
\omega_{ci} & 0 & -\omega_{ci} \\
-\omega_{ci} & \omega_{ci} & 0
\end{bmatrix},
\]

\begin{equation}
(38)
\end{equation}
Fig. 2. Generalized coordinate motion law equivalent with the hip joint for walking activity in the case of a 4 year old child: a-left lower limb; b-right lower limb.

III. NUMERICAL PROCESSING

For cinematic analysis, the geometrical elements are known. The computing algorithm was elaborated with the MAPLE aid. The geometrical elements dimensions are in millimeters: L_{OT} = 70; L_1 = 65; L_2 = 65; L_3 = 200; L_4 = 5; L_5 = 225; L_6 = 5; L_7 = 220; L_8 = 5; L_9 = 225; L_{10} = 200; L_{11} = 65; L_{12} = 65; L_{13} = 70. The generalized coordinate system variations for the equivalent locomotion system active joints in walking activity’s case are presented in Fig. 3, 4 and 5. These were processed in a 4 years old child. The angular amplitudes of these motion laws were validated by consulting specialty literature data [10].
IV. MODULAR KNEE ORTHOSIS DESIGN

The main requirements for a child orthosis are: to have a simple construction and a reduced weight, easy to achieve the angular amplitude for knee flexion in the walking activity, easy to adjust the dimensions, especially when it is used for children, easy to wear. This knee orthosis model will be used for children locomotion recovery through kinetotherapeutic procedures after some bone fractures or surgical interventions at the lower limb’s level. Also this will be a passive one. For these, an orthosis modular structure was designed in order to add or remove modules for increase or decrease in size. The material which will be used for components is aluminum alloys. For this modular orthosis’ command and control a step by step actuator will be used, and an Arduino microcontroller board. These two elements will form the command and control unit and will be placed in a special box with a backpack. The module design was achieved by taking into account the knee modular orthosis cinematic scheme from figure 5. The orthosis cinematic model has a single mobility degree. The virtual model with all the geometric parts was created in SolidWorks and is shown in figures 5 and 6. A link between the command-control unit and the modular orthosis will be made through flexible cables, one for pull up – cable no: 1 and the other for roll back – cable no: 2. For a 4 years old child, the intermediate module was eliminated from his structure in order to decrease his size. For this, as a geometric model remains only primary and final module, and it will be simulated in MSC ADAMS. An interface between SolidWorks and MSC ADAMS/Autoflex was created, for this model. For simulations, the right limb motion law from Fig. 3-b was applied on the Cable no.1. The femur component of primary module was fixed and a load force equal with 450 Newton was applied on final module (this force was determined in a previous work of the authors according with literature data [9], [10]).

Fig. 4. Generalized coordinate motion law equivalent with the ankle joint for walking activity in the case of a 4 year old child: a-left lower limb; b-right lower limb.

Fig. 5. Knee modular orthosis cinematic scheme and virtual model with components identification.

Fig. 6. The modular orthosis virtual model – lateral view for pulley visualization.

Fig. 7. Cables Von Misses stress, final module angular variation and modular orthosis prototype.

Flexible cable Von Misses stress was obtained and the final module angular variation was also determined (Fig. 7).
The maximum Von Misses stress value was 18.0635MPa, which is not so high, and the final module angular motion value was 68.7 degrees (Fig. 7). Also for this virtual model, the final module angular displacement has 46.754 degrees.

V. EXPERIMENTAL TESTS

In order to validate the modular orthosis prototype, a 4 years old child with locomotion disability will perform flexion/extension exercises and the motion laws will be achieved with CONTEMPLAS High Speed Motion Analysis equipment (Machine Elements laboratory - Faculty of Mechanics, University of Craiova). This child has a trauma at the right shank’s level, and also the knee joint was affected. The modular orthosis prototype is presented in Fig. 8. As a template from a database developed in this way, for a healthy 4 years old child the knee angular amplitude on a single gait is represented in Fig. 9. The knee angular amplitude developed by a healthy child for walking was 55 degrees, and in the knee modular orthosis case was 48 degrees.

Fig. 8. Knee modular orthosis prototype images from experimental tests.

![Fig. 8. Knee modular orthosis prototype images from experimental tests.](image)

Fig. 9. Knee angular amplitude analyzed with CONTEMPLAS Motion Equipment in a 4 year old healthy and invalid child case for a single gait.

VI. CONCLUSIONS

Through this research, a new orthosis type was validated. The novel elements in this research are: a modern cinematic viewpoint parameters in 3D or 2D environments. This modular orthosis can be modified by adding or removing modules depending on child leg’s size.

The result of this research helps the specialist from neuromotor rehabilitation field, to develop a rehabilitation program for 4 years children lower limbs. So in according with this system gait and posture rehabilitation include specific muscle training, balance training and coordination. Gait and posture rehabilitation can be assess by CONTEMPLAS system and after can be create individual model for modular orthoses that make more easy the lower limb rehabilitation especially at children because in the same time specific rehabilitation technique include the muscle groups that are involved in devices function. We conclude that existence of mathematic model based on cinematic analysis helps increase the results of gait and posture rehabilitation by helping the locomotion system function.

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REFERENCES