UNIVERSITY OF CRAIOVA
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PHD thesis abstract:

RESEARCHES REGARDING SOME MECHANICAL SYSTEMS APLIABLE IN MEDICINE

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The technological progress rhythm was very slow for the major part of the world's history – in past, a person could live an entire life without been witness at any significant changes. If exists a direction to follow the world in that time, this could be outwards from time, on myth realm or on supernatural interventions.

But if exists an observatory of our times, this will be the witness which will assists at some radical technological changes, in just 10 years, or even slightly in some sectors.

One of these sectors is the Medical Engineering or Bioengineering. This represents a multidisciplinary sub domain which integrates professional engineering activities with a mode agreement of how a human subject does work when this is completely healthy, seek or hurt.

Articulations replacement, pacemaker, medical imagistic, surviving systems and medical lasers are only few results examples of medical engineer's activity.

The Phd. Thesis subject is a very expansive one, and for this reason, the research direction was oriented from a medical viewpoint to an important domain of the orthopedics personalizing the human lower limb's amputee aspect from the human locomotion system. From a mechanical viewpoint the research attention was concentrated on elaboration and study of a mechanical system which can satisfy the equivalent conditions which must accomplish the human healthy lower limb's articulations (knee, ankle and foot articulations).

And so, this domain constitutes an immense challenge for practical realization.

Through Phd. thesis called „Researches regarding some mechanical systems apliable in medicine" I propose for the study, analisys and achievement, the following objectives:

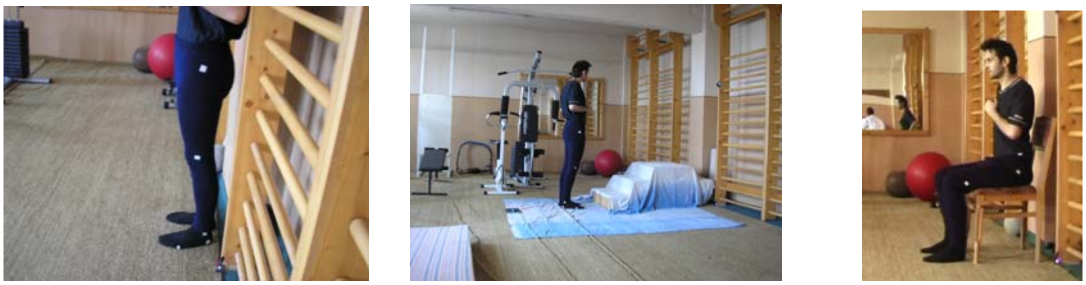
- The study of some mechanical endoprosthetic systems (implants) used through implantation at the human lower limb's articulations level, and the study of some exoprosthetic mechanical systems used in some segments amputation of this limb;
- Experimental analysis realization of the human locomotion apparatus in order to obtain some kinematic parameters which characterize the articulations from his structure;
- A kinematic model attainment equivalent to human lower limb, based on a human locomotion apparatus anatomic functional study;
- An inverse dynamic analysis realization of the mathematical model equivalent to human lower limb, in order to obtain the connection forces for each joint from this model's structure;
- Virtual modeling and simulation in dynamic regime of an endoprosthetic model used in human lower limb implants;
- Database achievement, characterized through kinematic parameters determined from a human subject experimental analysis which has a lower limb amputated;
- Elaborating and testing on virtual and experimental way of a new exoprosthetic system which has in his structure a cam mechanism;
- Mechanical systems study from some medical robots structure used in some mini invasive surgical interventions;

The achievement mode of the proposed objectives is presented in 9 capitols which will be presented as it follows.

In ***Chapter I*** – "*Actual stage of the researches regarding some mechanical systems applicable in medicine*" a few introductive notions regarding the essential factors interdependence are presented, which concurs at diagnostic, recuperation/rehabilitation techniques improvement, etc. At the beginning a short description of the Phd. thesis is elaborated, in order to establish the main objectives which will be accomplish in the sight of obtaining some significant results in the interdisciplinary domain called biomechanics.

In this chapter's frame a general presentation of the mechanical systems used in human locomotion apparatus is presented. These are the endoprosthetic mechanical systems used in some articulations prosthesis from the human lower limb structure through surgical procedure called arthroplasty, and the exoprosthetic mechanical systems used in human lower limb amputation through some segments replacements. The first chapter was finalized by presenting some medical robotic units which posses flexible elements in order to perform some mini invasive surgical procedures. From this study was obtained new premises in the sight of endoprosthetic and exoprosthetic mechanical systems improvement, by accentuating the modern calculus and modeling techniques applied on these, but also some new research directions elaboration regarding the medical robotic units with flexible elements, used in some surgical interventions achievement.

In the ***Chapter II***, called “*Experimental determination of some kinematic parameters from the human locomotion apparatus*”, I performed a human locomotion experimental analysis for three types of activities (figure 1): walking, stair climbing, changing the human body position, in order to determinate some kinematic parameters (displacements, speeds and accelerations) characteristic to the joints from the human lower limb structure. In order to obtain this motion laws, it was used an acquisition data system and image processing called SIMI Motion. The analyzing process of these parameters through video capture is described in figure 2.



a. *b.* *c.*

Figure 1. Aspects regarding the experimental analysis (a – walking activity; b – stair climbing activity; c – changing the body position)

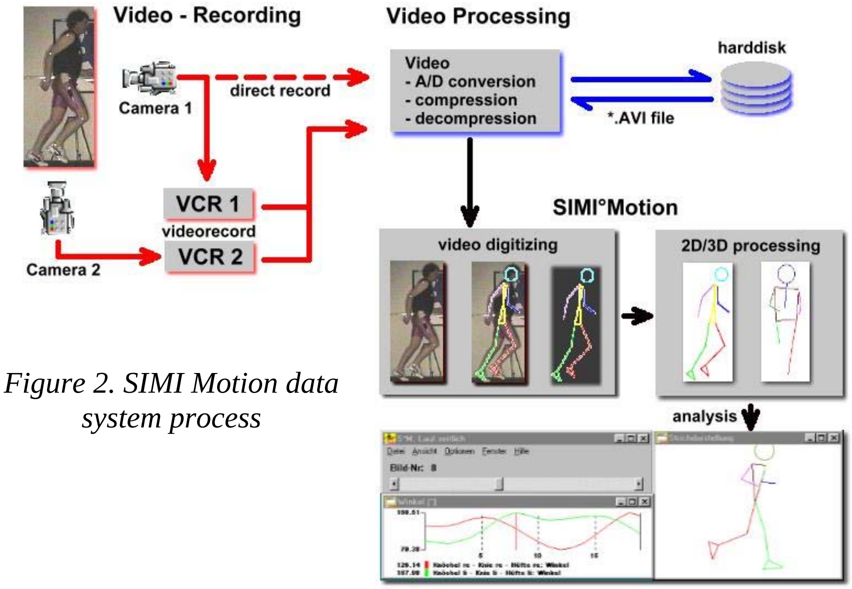


Figure 2. SIMI Motion data system process

Also the experimental analysis constitutes a database enough solid which will serve as a template in the sight of comparison with the ones obtained in the following chapters frame. This database it was useful to achieve an inverse dynamic analysis for the human lower limb. In figures 3, 4 and 5 are presented, in an exemplified mode, the ankle joint variation laws diagrams for the proposed activities mentioned above. From these diagrams it can be observed the angular amplitudes developed at this joint’s level.

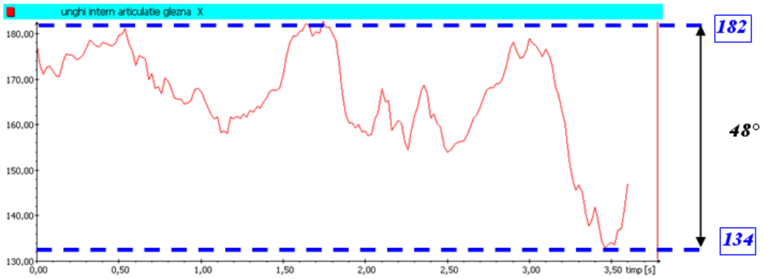


Figure 3. Ankle joint angular amplitude for walking activity [degrees]

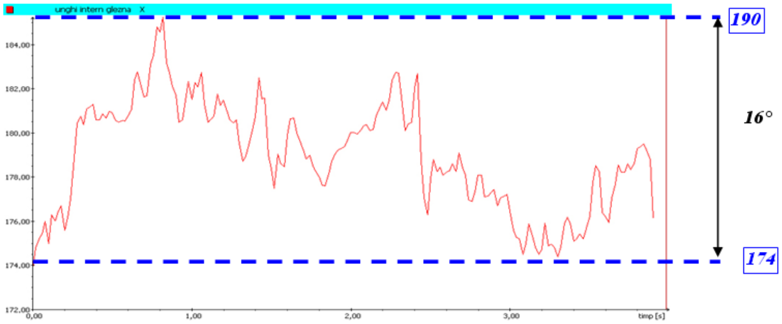


Figure 4. Ankle joint angular amplitude for stair climbing activity [degrees]

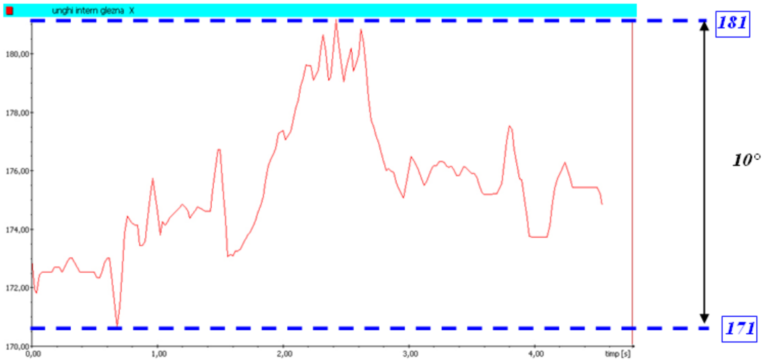
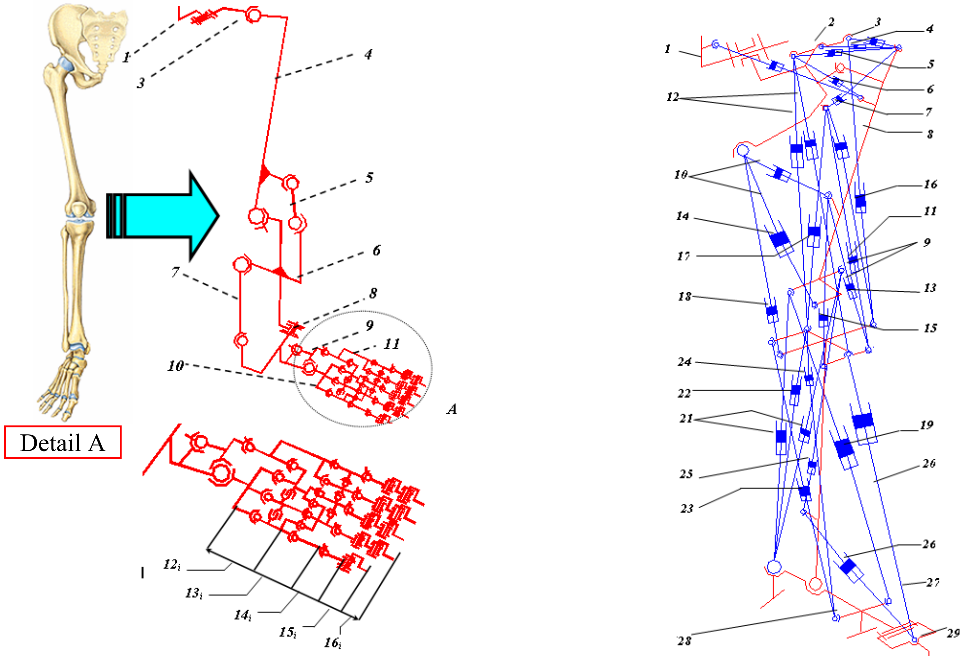


Figure 5. Ankle joint angular amplitude for changing the body position [degrees]

From the diagrams presented in figure 3, 4 and 5, an exoprosthesis must have the same angular amplitudes developed at ankle joint's level.

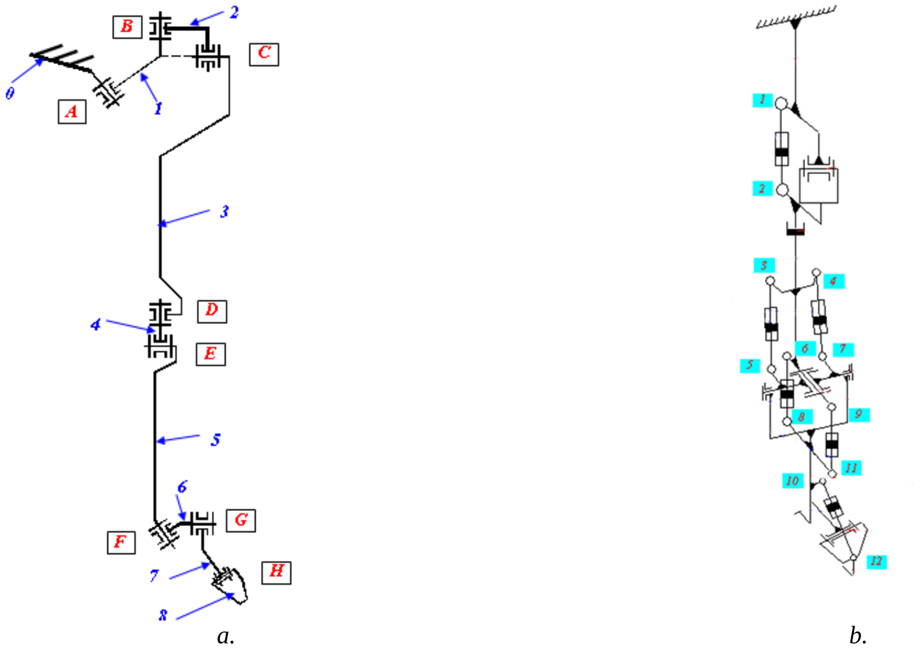
Based on these data obtained on experimental way, we follow to elaborate some biomechanism human lower limb structural models corresponding to the three activity types mentioned above. This represents the ***Chapter III*** main objective, called „*Human locomotion apparatus. Functional anatomic analysis*". In this chapter's frame it was followed to identify the motions developed on each human lower limb joint, the origins and muscle insertion points. And so, it was developed two equivalent human lower limb models – one osteoarticular model, and the other osteoarthromuscular, which are very difficult to study from a kinematic viewpoint (figure 6).



a. *b.*

Figure 6. Presenting the two biomechanism human lower limb structural models (a – modelul osteo-articular model; b –osteo-artro-muscular model)

These two models were simplified by taking account the imposed criteria from the three activity types studied on experimental way (Criteria 1 – adapting the structural model at the followed locomotion type; Criteria 2 – reconsidering the tars-ground rolling motion, by neglecting the elastic character from foot and ground contact elements). After these models simplification, the number of elements and kinematic joints were reduced. Considering only the simplified osteo-articular model, equivalent to human lower limb, we follow to realize a kinematic and inverse dynamic analyses of this, for walking activity. The simplified models are presented in figure 7.



a. *b.*

Figure 7. The human lower limb's simplified models (a –osteo-articular model; b –osteo-artro-muscular model)

The simplified osteo-articular model constitutes the necessary support for an inverse dynamic analysis realization which was elaborated in the next chapter for walking activity studied in chapter 2.

The human lower limb kinematic and dynamic analyses constitutes the Chapter IV main objectives, called "Human lower limb kinematic and dynamic analysis". In this chapter we follow to obtain the generalized coordinates variation corresponding to the equivalent kinematic joints of this limb (figure 8).

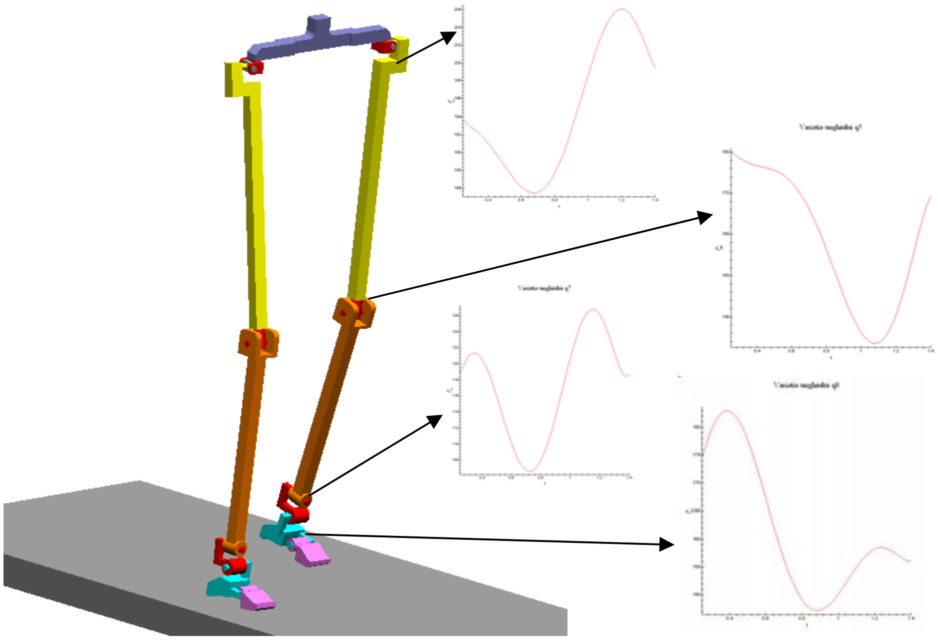
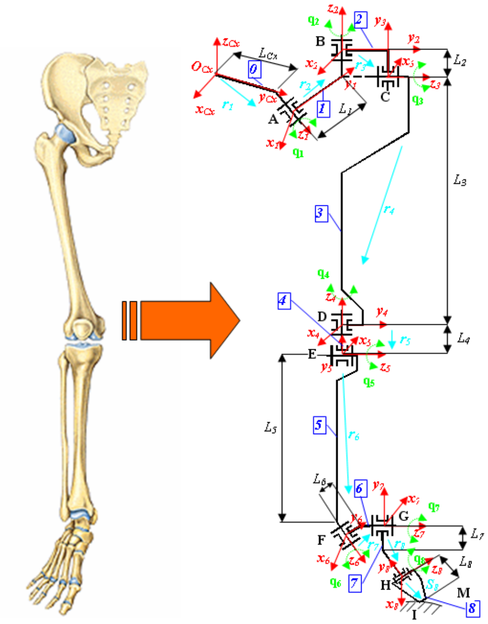


Figure 8. 3D model, realized through numerical processing of the generalized coordinates variations corresponding to the equivalent kinematic joints of the human lower limb

These laws are useful in order to perform an inverse dynamic analysis of the mathematical model equivalent to the human lower limb. This analysis has the Newton-Euler formalism on its base, which was completed with Lagrange's multipliers method, applied on the developed model. Also was taken in account the foot-ground contact (figure 9).



a. b.

Figure 9. Mathematical model proposed for inverse dynamic analysis of the human lower limb: a – anatomic model; b – the equivalent human lower limb model

The purpose of this human lower limb's inverse dynamic analysis is the one of obtaining the connection forces developed on three directions at the level of each joint from his structure. For inverse dynamic analysis we go through following steps:

1. we build the mechanism kinematic model;
2. we identify the constrain kinematic equation: $\Phi(q,t)=0$;
3. we determine the Jacoby corresponding to the equation system which governs the kinematic mechanism;
4. we build the mass matrix;
5. we identify the generalized forces vector: $\lambda=[\lambda_1,\lambda_2,\dots,\lambda_{36}]^T$;
6. we define the generalized forces vector and we build the equation system which governs the kinematic mechanism;
7. we identify the Lagrange's multipliers vector: $\lambda=\left[J_q\right]^{-1}\left[Q_a-M\cdot\ddot{q}\right]$;
8. We determine the connection forces from each kinematic joint in dynamic regime.

With the generalized coordinates variation laws corresponding with the human lower limb's joints and with the connection forces obtained at the level of each joint, was formed a database useful to study with the finite element method the endoprosthetic and exoprosthetic systems in the sight of monitoring the behavior of these in dynamic regime through a virtual simulations. In figure 10, the connection force variation law on Z axis direction, for ankle joint is presented. This law was useful to complete the studies from the following chapters.

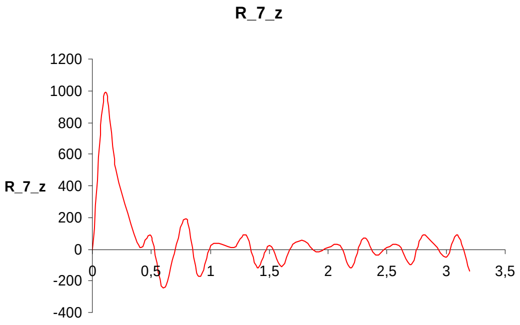


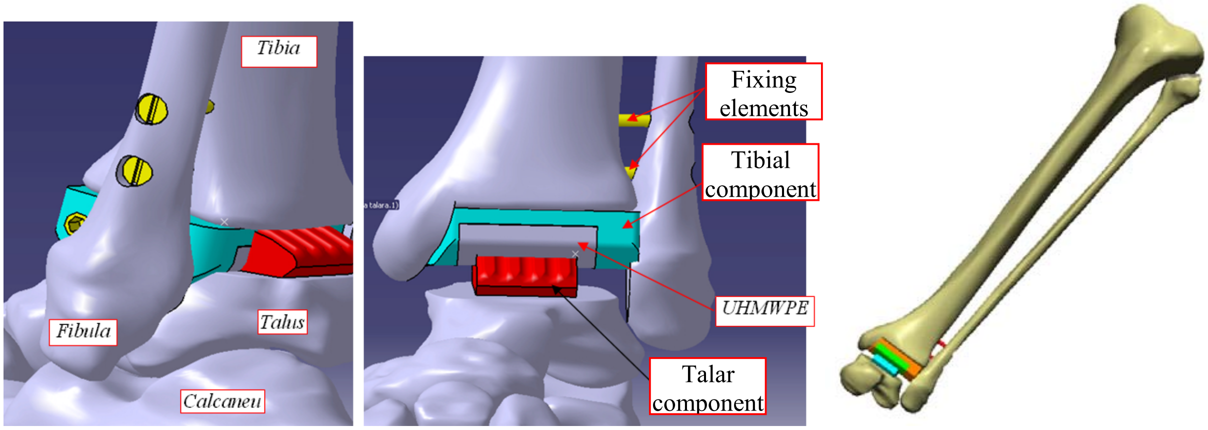
Figure 10. Connection force variation on Z axis direction, for G joint equivalent to the human ankle joint (for a single step developed in the walking activity)

In ***Chapter V***, called "*Parametric modeling of some bony elements from the human locomotion apparatus*" we obtain the human lower limb virtual model, which was useful in the sight of endoprosthetic and exoprosthetic systems implementation, for some virtual simulations realization in dynamic regime. In figure 11 is presented the human lower limb virtual model.

Figure 11. Reconstructive aspect of the virtual human lower limb

The bony elements parametric modeling from the human lower limb structure was achieved by consulting two main methods based on CT-series. These methods are laborious and the time allocated for this virtual modeling is relatively long.

Based on the human virtual lower limb model, and by take in account the obtained results from the previous chapters, we achieved a virtual endoprosthetic model study in dynamic regime used in the surgical procedure called arthroplasty, which is applied in case of ankle replacement with implants. This study constitutes the main objective for ***Chapter VI*** called "*Finite element analysis in dynamic regime of a endoprosthetic model*". Through this analysis was obtained the equivalent stress, deformations and displacements values, with von Mises method, through virtual simulations. In figure 12, the virtual endoprosthetic model is presented, but also the virtual model of the prosthetic shank.



A. *B.*

Figure12. A – virtual endoprosthetic model; B – virtual model of the prosthetic shank

By obtained results from the finite element method in dynamic regime (figures 13, 14 and 15), it can be observed that the maximum stress and deformations with von Mises method are for sequence when time t=0,1 seconds, corresponding to the maximum value of connection forces F_{ankle}= 985 N, and for time t= 2,8 seconds of a 160° angular displacement values.

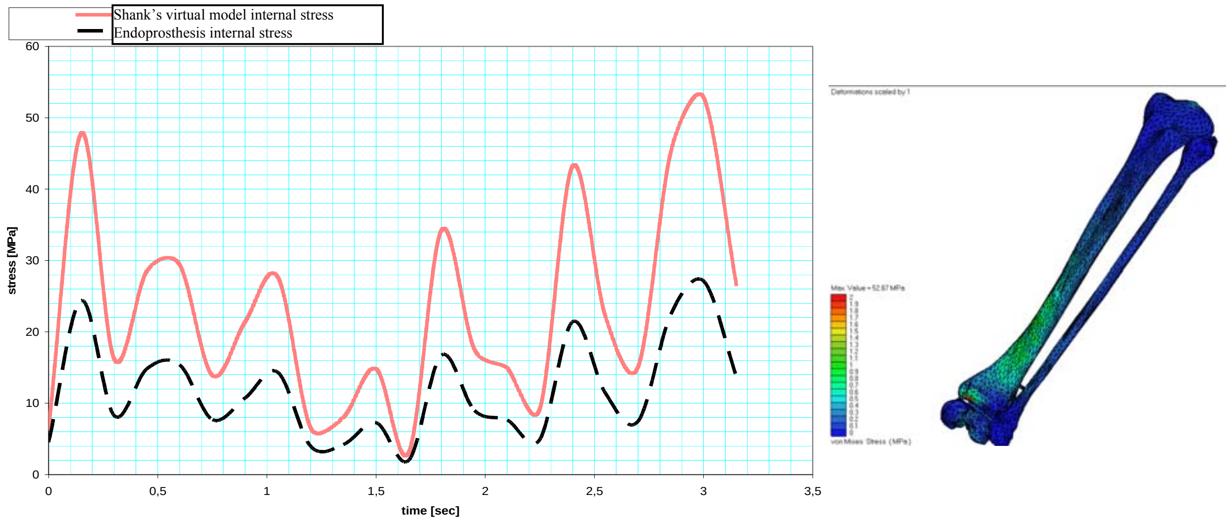


Figure 13. The internal equivalent von Mises stress variation depending on time

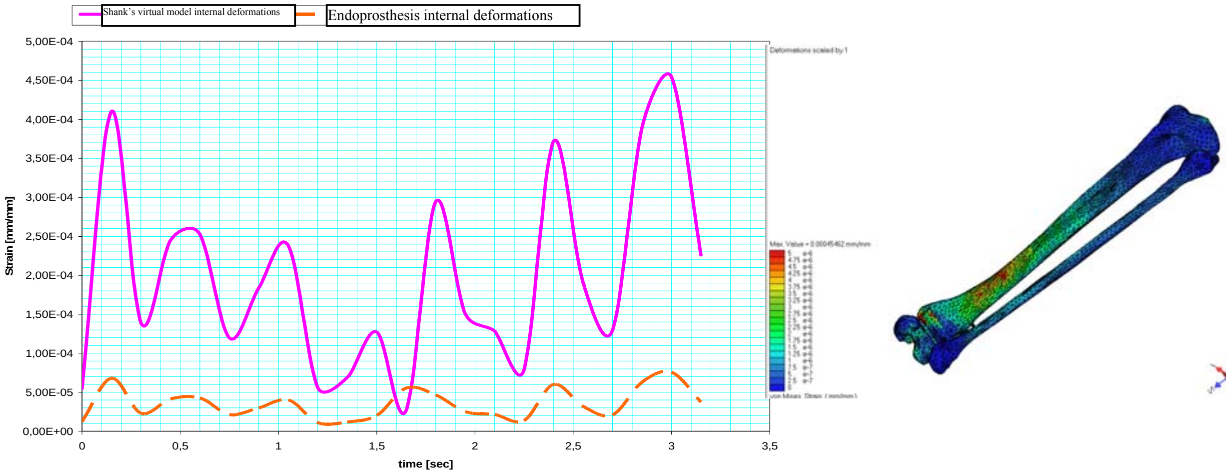


Figure 14. The equivalent von Mises deformations

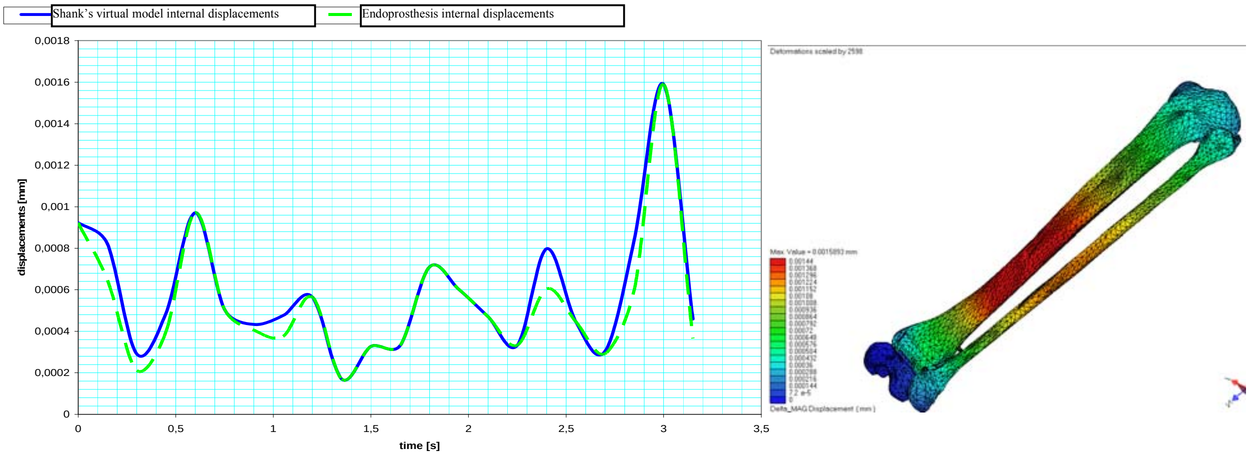


Figure 15. Displacements variation depending on time

By taking in account the thesis objectives and the study regarding the mechanical systems which exists in the exoprostheses structure, the research was continued by an experimental analysis realization which was emphasized in ***Chapter VII*** called "*Experimental determination of some kinematic parameters from the human locomotion apparatus on a subject with locomotion disabilities*"

So it was followed to determine on experimental way some kinematic parameters such as displacements, speeds, and accelerations. This parameters characterize the kinematic joints from the exoprosthetic mechanism's structure. The experimental analysis was achieved on a human subject with the lower limb amputated above the knee articulations for three activities (walking, stair climbing, changing the body position – figure 16).


a. *b.* *c.*

Figure 16 Aspects regarding the experimental analysis on a human subject with lower limb amputated (a – wlaking activity; b – stair climbing; c – changing the body position)

Also, this experimental analysis is correlated with the one from Chapter II of this thesis. The main objective of this chapter is to identify the same parameters in order to establish the angular amplitude for the exoprosthetic mechanical system, and at the level of all joints from the prosthesis structure. This parameters was useful to compare with the ones obtained in the human subject experimental analysis without locomotion disabilities from chapter II (figures 17, 18 and 19).

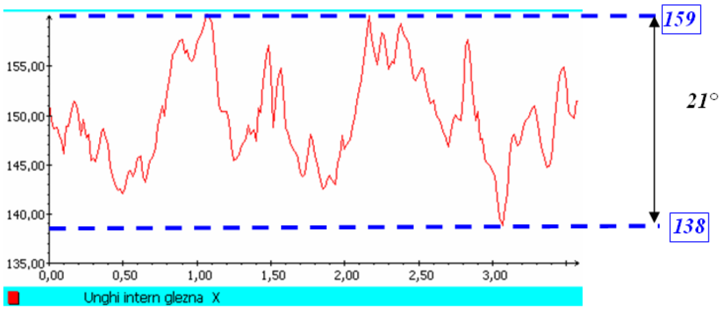


Figure 17. Ankle joint angular amplitude for walking activity – amputee's case [degrees]

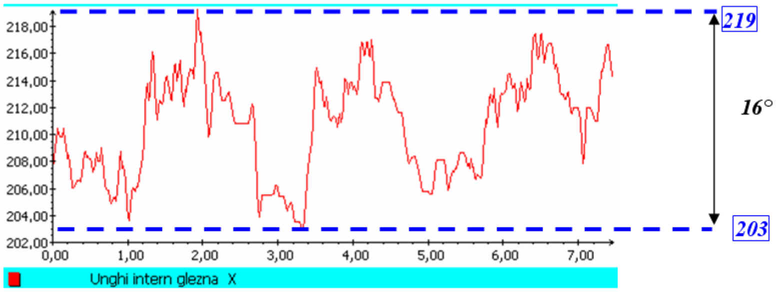


Figure 18. Ankle joint angular amplitude for stair climbing activity – amputee's case [degrees]

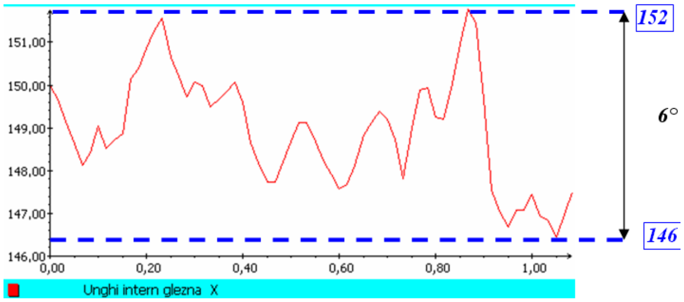


Figure 19. Ankle joint angular amplitude for changing the body position – amputee's case [degrees]

Based on the diagrams presented above, we conclude that an Otto Bock 3R95 prosthesis adverse in the stair climbing activity. This aspect confirms that the angular amplitudes are relatively small comparative with the ones from a human subject without locomotion disabilities (Chapter II). In ankle joint's case, the C-Walk foot develops angular amplitude relatively small in the walking activities; the value is 21 deg, which represents ½ from the real value developed by the ankle joint from the human subject without locomotion disabilities.

Also, for the stair climbing, the angular amplitude developed at the ankle level is the same in both human subjects' cases. It can be observed an angular amplitude difference in the activity of changing the body position, the difference was very small (4 degrees). This difference results from the C-Walk foot's stiffness (Chapter II).

The improvement of these exoprosthetic systems will be made by taking in account the obtained results from the experimental analyses performed on both human subjects. This improvement was realized by implementing a cam mechanism which permits to develop appropriate angular amplitude at the ankle level with the one in the natural ankle joint achieved on a human subject without locomotion disabilities.

This represent the ***Chapter VIII*** main objective, called "*A new exoprosthetic system elaboration destined to ankle disarticulations from the human lower limb structure*". In this chapter we were trying, on analytical way, to determine the cam profile and the cam follower displacement in such manner that the angular amplitude must be appropriate with the one developed in the natural ankle joint. This amplitude must be correlated with a proper amortization in the foot dorsal/plantar flexion. The new prosthetic system has in his structure a cam mechanism which was modeled and simulated in the sight of assuring a corresponding functionality to the natural ankle, and the geometrical conditions imposed by this articulation structure (figure 20 and 21).

Based on virtual simulations, the exoprosthetic system was experimentally tested in order to determine some kinematic parameters (displacements, speeds and accelerations), which were served as a database for a comparative study with the other ones obtained from Chapter II and VII (figures 22 and 23). The comparison was realized in order to emphasize the exoprosthetic system improvement, more precisely the implementation of some mechanism in the prosthetics domain of the human lower limb – cam mechanisms.

The exoprsthetic system develops an angular amplitude appropriate with the one of a healthy human subject's case, in walking activity process this has a value of 42 degrees. Also, for the stair climbing, the angular amplitude is identical with the one develop in healthy human subject. It can be remarked a difference of the angular amplitude at the ankle joint's level in the body changing position's case, where the difference was very small – 4 degrees. This difference results from the C-Walk foot's stiffness (Chapter II).

In the new prosthetic system's case, the dorsal/plantar flexion in the walking activity was produced in 147°→189°. From this it results an angular amplitude of 42° (figure 24). This is an appropriate angular amplitude for the one develop in case of a healthy human subject. In fact these aspects confirm the improvement of the exoprosthetic systems destined to human lower limb prostheses for amputated segments from above the knee joint.

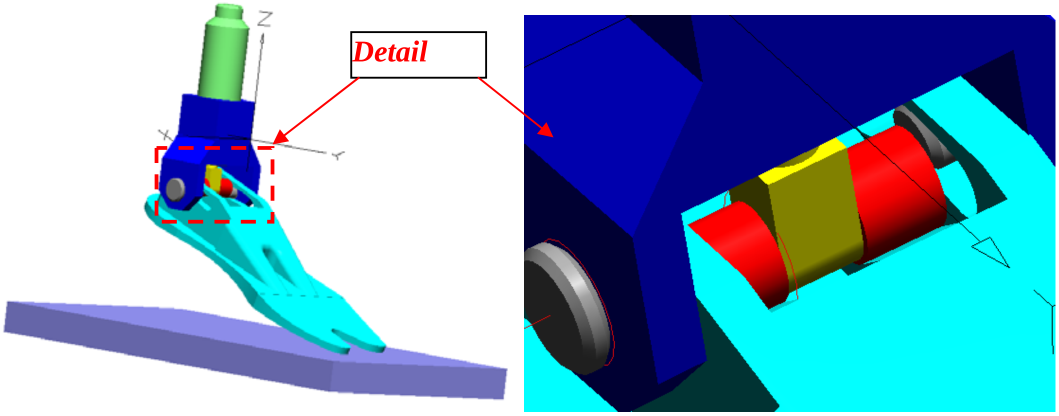


Figure20. The virtual exo-prosthetic system proposed for practical achievement (cam mechanism detailed view)

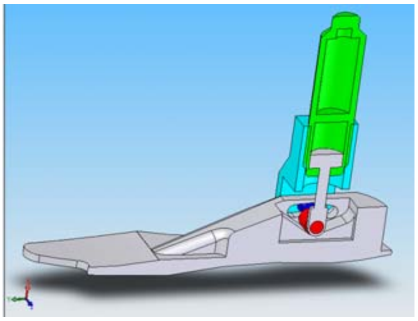


Figure 21. The virtual exo-prosthetic system proposed for practical achievement (cam mechanism sectioned view)

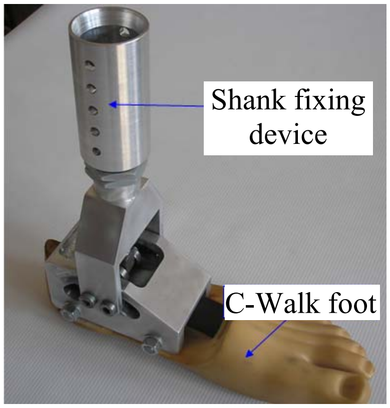


Figure 22. The exo-prosthetic system achieved for the experimental tests

Figure 23. The exo-prosthetic system in the experimental tests

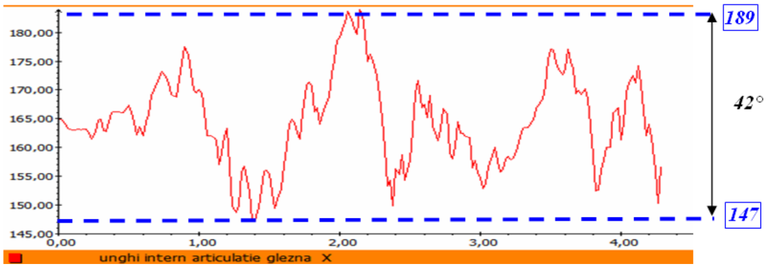


Figure 24. Ankle joint angular amplitude for walking activity – amputee's case with the new prosthetic system (final stage): dorsal flexion angle , angular displacements depending on time [degrees]

The thesis was finished through ***Chapter IX,*** called "*General considerations, original contributions and new research directions*", where are presented the final conclusions, the original contributions brought in some mechanical systems research, applicable in medicine, but also new research directions which can be further developed based on this thesis.

It can be consisted that in the first chapter, some robotic units used in some surgical interventions are presented. Based on this robotic units with flexible elements' actual phase, which posses in the structure a flexible spine formed from vertebras, it was elaborated an experimental and virtual model of such robotic units. This has in his structure three flexible module which can create a curvature radius simultaneously on three directions. In figure 25, a virtual model of such poliarticulated robotic unit is presented.

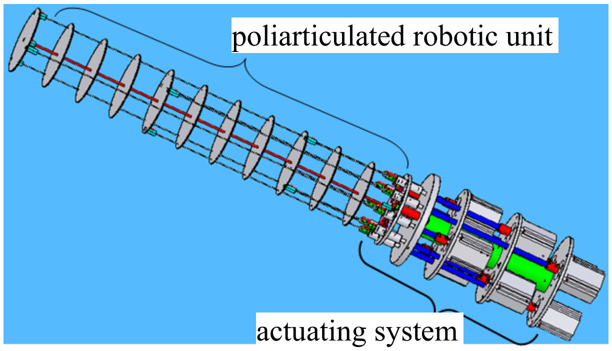


Figure 25. The poliarticulated robotic unit virtual model

It was performed three calculus algorithm which were processed with the MAPLE software's aid, 12 experimental kinematic analysis projects developed with the aid of SIMI Motion software and equipment, and numerous virtual simulations on endo/exo-prostheses systems performed with the NASTRAN software's aid.

Through this thesis finalization, it was consulted a number of ***106*** bibliographical references which consists in books, Phd. theses, scientific papers, author participation as a collective member in some research grants with derivative thematic from biomechanics, web pages, catalogs and atlases. Also this phd. thesis was elaborated through a grant financed from ***CNCSIS TD - type no.597/2007, with title „Researches regarding some mechanical systems applicable in medicine".***