

Dynamic Analysis of a Human Ankle Joint Prosthesis

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Abstract. This research addresses a human ankle joint prosthesis design based on a cam mechanism. Thus, a dynamic analysis of the entire human lower limb was performed in order to obtain the input data for numerical simulations of an ankle joint prosthesis. For this, experimental analysis was accomplished in order to obtain input and reference data for human ankle joint motion laws. These human ankle joint motion laws were considered from a healthy human subject and an amputee. A virtual model of the ankle joint prosthesis was designed with the aid of CATIA software and the working principle was based on a cam mechanism. This virtual model was simulated in dynamic conditions, similar to the imposed ones onto a mathematical model. Results represented through stress and deformations will validate the proposed ankle prosthesis prototype. Finally the proposed prosthesis prototype was manufactured and experimentally tested on the proposed amputee through a comparative analysis for validation.

1. Introduction

In the field of human lower limb prosthesis design it is well known the fact that prosthesis are in continuous growth and these should be resized or redesigned very often. Thus it can be remarked prosthetic systems with applications on human walking recovery especially designed on simple criteria like the ones from [1]. These can be purchased at low prices due to their simple functions and also it cannot contribute to a human natural motion achievement. For this inconvenient there were developed complex prostheses based on mechatronic systems like the ones from [2, 3, 4]. For these ones, in background, can be remarked complex analyses like kinematics and dynamics, by analyzing the whole human lower limb for certain activities like walking or running. Thus, by having in sight the state-of-the-art from similar researches like [1, 5] it can be remarked the starting research point, which was to obtain input data for dynamic analysis of the proposed human subject. In this case, the input data are represented by the ankle joint motion law of a person with the same anthropometric data like the amputee, which is presented in second part of the paper. With the obtained data, a human lower limb dynamic model was elaborated and the obtained theoretical results are represented by ankle connection forces. The used method with the obtained results, which is applicable on a parameterized model, is presented in third part of this research. Theoretical results are important for virtual simulations for the proposed ankle prosthesis concept as input data. Thus, by using MSC Nastran, the proposed ankle prosthesis functionality was verified and approved by developing numerical simulations on dynamic modes similar with the real ones. These are described in the fourth section of this research and important results are synthesized on final conclusions.

2. Human lower limb experimental analysis

An experimental analysis was performed by taking into account a human subject with similar anthropometric data with the amputee (age, weight, height, gender). The amputee has the right lower limb amputated from above the ankle joint area. The analysis aim was to obtain specific human lower

limb angular variations during walking for a single gait in case of hip, knee and ankle joints. These results represent the input data for a whole human lower limb dynamic analysis. On the other hand, a comparative analysis was performed in case of one analyzed amputee with a usual ankle joint prosthesis. This analysis was performed in specific clinical conditions by using high speed camera motion analysis equipment called CONTEMPLAS [6]. The workflow is schematized in figure 1.

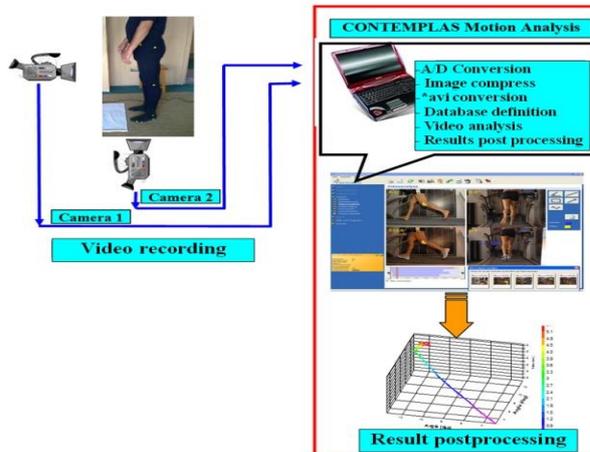


Figure 1. CONTEMPLAS Motion Analysis workflow [6].

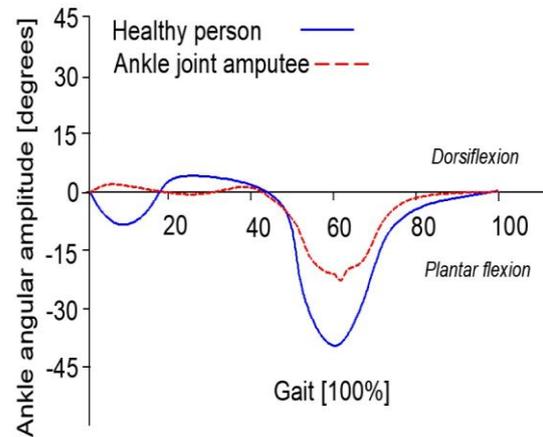


Figure 2. Knee angular amplitude for a complete gait of the analyzed human subjects.

The analyzed human subjects perform several walking steps in the defined workspace and from these steps were extracted only a single gait. It is important to know that the time period is different from an analyzed human subject to the proposed amputee. Thus, in case of a human subject, a complete gait was performed in 2.68 (seconds), and in case of the considered amputee, this was done in 3.42 (seconds). These time intervals are important to retain for dynamic computations and also virtual simulations.

The obtained results are materialized through graphs and a comparative graph is represented in figure 2, where it can be remarked the difference between a healthy subject angular variation and the chosen amputee. These results are reported for a 100 percent full gait in both cases. The obtained results were validated by considering similar researches reported in [7, 8].

From figure 2 it can be remarked that in case of an amputee ankle angular amplitude has some distortion zones on the resulted curve. A maximum obtained value was equal with 2.962 (degrees) for dorsiflexion and a minimum of 21.423 (degrees) for plantar flexion. In case of the analyzed healthy human subject, the obtained curve is smooth and the maximum values were around 9.674 degrees for dorsiflexion and a minimum one of -34.496 (degrees) for plantar flexion. In this case total ankle angular amplitude will be around 45 (degrees). Thus it can be also observed that curvature path is almost the same in both cases.

3. Human lower limb experimental analysis

The proposed mathematical model was elaborated by having in sight similar researches reported in [8, 9]. We consider the foot ground contact as it shows in figure 3. The kinematic constrain equations are:

$$\phi(q, t) = 0 \quad (1)$$

Where: q - generalized coordinates vector; t - time. By differentiating equation (1) depending on time and it will be obtained:

$$J_q \cdot \dot{q} + \frac{\partial \Phi}{\partial t} = 0 \quad (2)$$

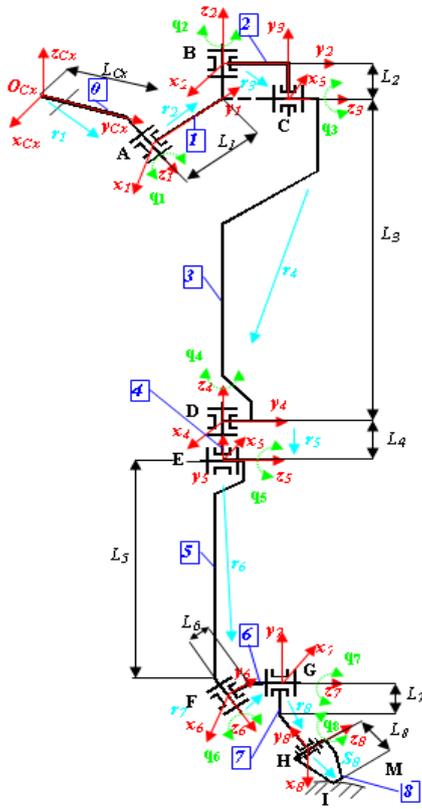


Figure 3. The human lower limb kinematic scheme.

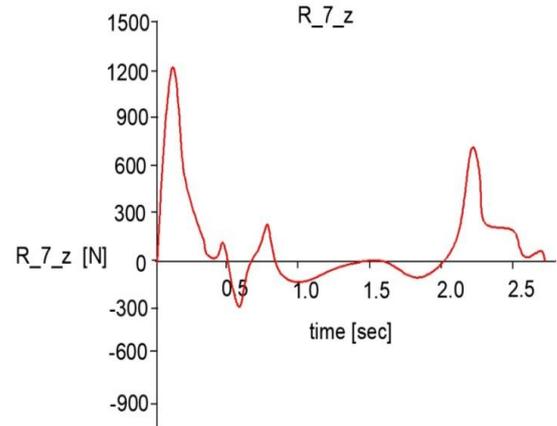


Figure 4. The variation of the connection force (Newton) for the ankle joint on z direction.

The motion equation will have the following form:

$$\begin{bmatrix} M & J_q^T \\ J_q & 0 \end{bmatrix} \cdot \begin{bmatrix} q \\ \lambda \end{bmatrix} = \begin{bmatrix} Q_a \\ a \end{bmatrix} \quad (3)$$

The mathematical equations, which can help for computing these connection forces, by considering the Lagrange multipliers, are:

$$\begin{cases} F_i^{rr(i,j)} = [R_{i,j}^r]^T \cdot [A_{0i}]^T \cdot [\lambda]^{r(i,j)} \\ T_i^{rr(i,j)} = \{S_i^{iM}\}^T \cdot [P_{0i}]^T \cdot [I] - \{S_i^{iM}\}^T \cdot [P_{0i}]^T \cdot [\lambda]^{r(i,j)} \end{cases} \quad (4)$$

Motion laws for ankle joint will be considered as known, namely $q(t)$, $\dot{q}(t)$ and $\ddot{q}(t)$ from the experimental analysis, performed in dynamic modes. From equation (4) it can be determined Lagrange multipliers λ , with the aid of an algorithm performed in MAPLE program. After a numerical processing under MAPLE environment it will be obtained the connection force component variation for the ankle joint. This is shown in figure 4 and it will be further used on virtual simulations of the proposed ankle joint prosthesis as input data for motion variation during one gait. From figure 4 it can be remarked that the connection force reach a maximum value of 1223Newton when the gait was started. During one gait when the foot has lost the ground contact the force connection varies between 0 to -50Newton and it happens between time periods of 1 to 1.95seconds.

4. Ankle prosthesis numerical simulations

For designing an ankle joint prosthesis, this has to accomplish the following conditions: achieving an angular amplitude during gait almost identical with the one which was obtained on healthy human subject (45°). A suitable mechanism which can be implemented on the prosthesis structure was a cam mechanism. Thus, the cam component was fixed to the artificial foot, and the cam follower was fixed with the shock absorber's rod as it can be seen in figure 5. This was elaborated with the CATIA V5 R16 and the components are identified as follow: tibia component (1), which contain the shock absorber's body; shock absorber's support (2); shock absorber's rod (3); role of the cam follower (4) which slide over the cam profile; bolt (5) which glides over a imposed profile described by the motion law from a human subject without locomotion disabilities; foot (6). Also from figure 5 it can be remarked a cross sectional image for a better viewing of the cam mechanism.

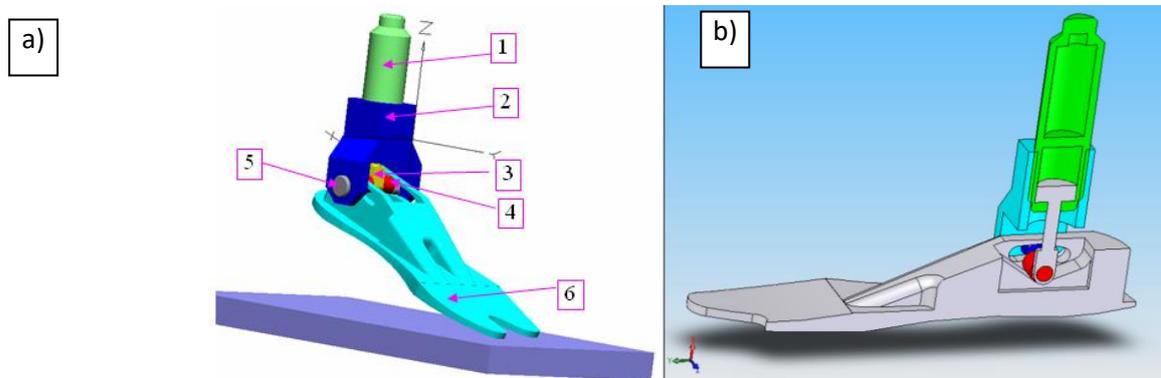


Figure 5. Ankle prosthesis virtual model: a) front view; b) section view.

The entire virtual model was imported under MSC Nastran software for virtual simulations in dynamic conditions. Material properties were defined such as rubber for the foot, aluminum alloys and steel characterized by density elasticity modulus and Poisson ratio. Also friction was taken into account during virtual simulations. For meshing specific operations, there were individually meshed each component by choosing tetrahedral finite elements. Thus, at the level of shock absorber head it was applied the connection force variation mentioned in figure 4 in a polynomial form and the ankle prosthesis foot was considered as fixed one. According with the performed dynamic analysis, the computed sequence for virtual simulations was done for a time period of 2.68 (seconds) which corresponds for a complete gait in case of the analyzed healthy person. The obtained results after simulations can be seen in figure 6 and figure 7.

By analyzing the reported results from figure 6 and figure 7, the most significant ones are characterized by von Misses stress and displacements of the analyzed ankle prosthesis prototype. Thus, in Figure 7 it can be remarked a maximum value of von Misses stress equal with 57.8 (MPa), and this it was recorded in the area of cam mechanism. In particular, it can be remarked a smooth curve with large deflections during time period from 0 to 1 (second), which corresponds when the foot has lost ground contact and the same phenomena happens between time periods from 2 to 2.68 (seconds). Between time period of 1 to 2 (seconds) it can be remarked a smooth curve path and also a stress average of 15.378 (MPa), which is quite small.

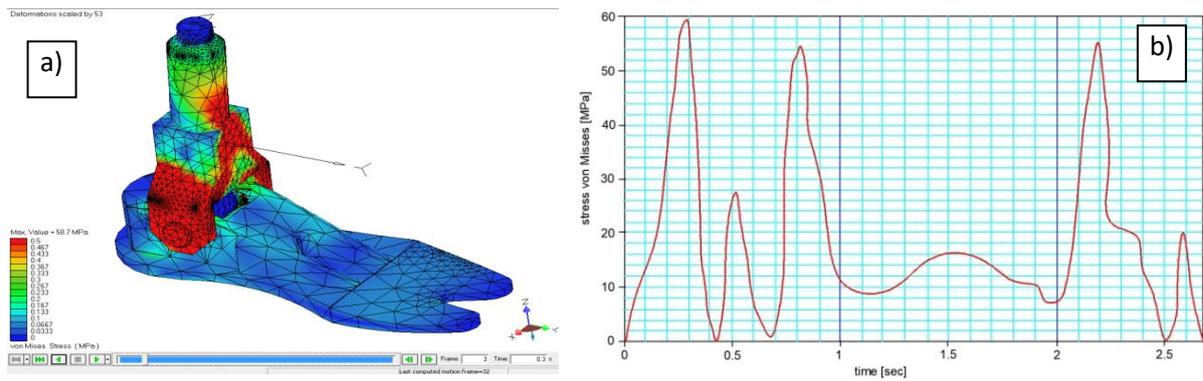


Figure 6. Ankle prosthesis Von Mises stress (MPa) vs. time (sec): a) stress map; b) graphic view.

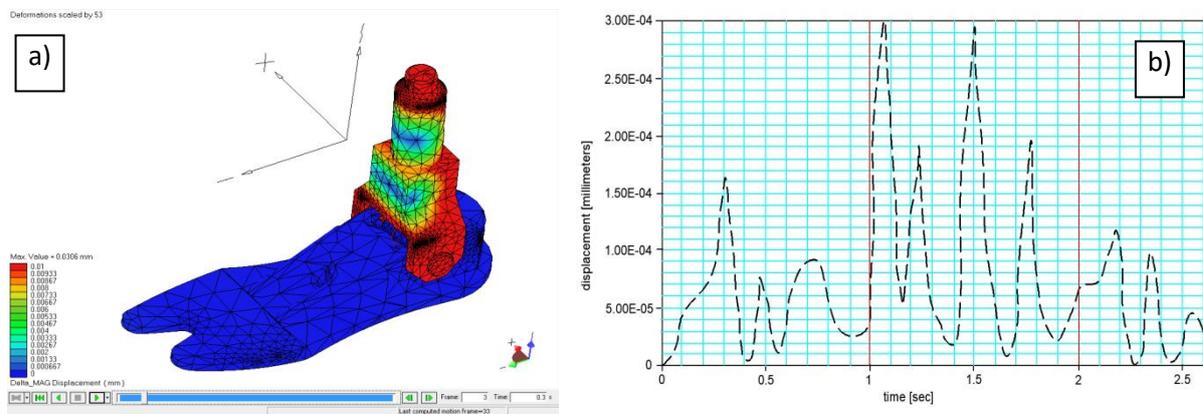


Figure 7. Ankle prosthesis Von Mises stress (MPa) vs. time (sec): a) displacement map; b) graphic view.

On the other hand, by considering the analyzed displacements it can be remarked a maximum value of 0.0306 (millimeters) which was obtained when the foot was left the ground contact and this value was obtained between time periods from 1 to 2 (seconds) according with the reported diagram from figure 7. In the other time periods like the one from 0 to 1 (second), the obtained displacements were not so high due to ankle prosthesis stiffness.

5. Ankle prosthesis prototype experimental analysis

By considering the design principles applied on the elaborated concept, a prototype was manufactured and it is shown in figure 8. This was created by modifying an old ankle prosthesis and the proposed shock absorber was acquired by FESTO Pneumatics and it is characterized by a maximum payload of 3500 (Newton). The elaborated prototype has 1.543 (kilograms) and this was resulted from FESTO shock absorber. According with the virtual simulations most of the ankle prosthesis components were manufactured from aluminum alloys. In order to validate the proposed ankle joint prosthesis prototype there were performed preliminary experimental tests with proper prosthesis adjustments and the amputee was let to wear this prototype for 10 days in order to accommodate with this. After 10 days, an experimental analysis was performed according with the presented protocol presented in previous section. This experimental analysis was done in his daily living activities accomplished by walking. Thus, a comparative experimental analysis was performed by having in sight the results reported in previous section, and this is shown in figure 9. By considering the obtained results reported in diagram from figure 9 it can be remarked the dotted curve which corresponds with the experimental tests of the amputee with ankle joint prosthesis prototype.



Figure 8. The new prosthesis used in human ankle disarticulations.

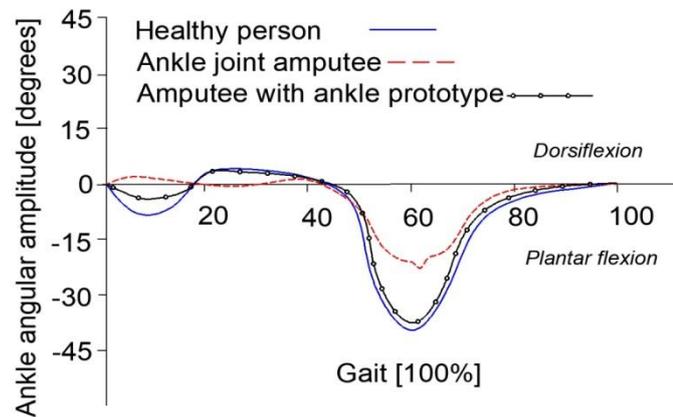


Figure 9. A comparative analysis after preliminary tests of the ankle prosthesis motion (deg.) vs. gait cycle (%).

It looks that this is very appropriate as pattern but also as values with the one of a healthy person during tests. Also at around 60% from a complete gait it can be seen that the obtained path is smooth. Thus, the maximum values were around 8.556 degrees for dorsiflexion and a minimum one of -32.223 (degrees) for plantar flexion. The maximum value in case of ankle angular amplitude during walking was around 40.7793 (degrees) and this curve was obtained in case of a complete gait in 3.16 (seconds).

6. Conclusions

A prototype of an ankle prosthesis was designed and elaborated. This will be used by persons with human lower limb amputation from above of ankle joints. Simulation results and numerical processing have outlined a good performance for suitable user-oriented walking specific operation and its design may require additional components in future developments. The concept is fairly simple wearable and lightweight and the novelty element is represented by the cam mechanism combined with a shock absorber. The obtained ankle prosthesis mechanism can be adapted for right or left human leg. This prosthesis can be personalized due to its parameterized form. In the future the mechanism principle will be extended for a human knee joint and also it will try to adapt this principle to children orthosis for knee and ankle joints.

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