Design and Numerical Characterization of a Human Ankle Prosthesis

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Abstract. This paper addresses a finite element analysis in dynamic conditions of a human ankle joint prosthesis based on a cam mechanism design. The proposed ankle joint prosthesis mechanism is a parameterized one and was designed in order to fulfil main human locomotion tasks namely walking during daily activities. A proper 3D CAD model has been developed and the proposed cam mechanism ankle prosthesis was modelled and simulated into MSC Visual Nastran environment. Results of simulations demonstrate the engineering feasibility of the design and validate the proposed parameterized prototype.

1. Introduction
Today there are many persons with locomotion deficiencies due to several dis-eases or accidents, from where these lost some human leg segments. For these persons different research centers develop human lower limb prosthesis which can improve or increase the human locomotion ability during daily living activities and moreover.

Significant existing prostheses are presented in [1, 2, 3, 4, 5] with different designs, especially dedicated to human ankle joint. In addition, a main common drawback can be considered the ankle joint angular limitation from where is no equivalent mechanism of this human joint, only a dumper. Kinematic analysis methods and techniques can be created to model the human natural walking, like in [1, 7, 8]. They can be also used as input points for dynamic analyses and to design human lower limb prosthesis equivalent to hip, knee and ankle joints. A similar model with the one proposed through this research was designed in [11, 12], and it was validated for an amputee namely a human male subject. Thus, our challenge is to adapt this to a human female subject, with different anthropometric data. In this case, we keep the same functionality and structure principle. This will be represented by a cam mechanism that will be evaluated from dynamic viewpoints, with finite element method for fulfilling human ankle joint mobility during walking. The proposed ankle joint prosthesis was designed with a low-cost concept and an equivalent DOFs to a natural human ankle joint. This design was characterized with results from simulations in a dynamic mode, of ankle prosthesis basic functionality.

2. Human walking experimental analysis
Nowadays there are different equipments and specific software which can be used to understand and to analyze human motions through walking experimental tests for biomechanics characterization. For this we use a motion analysis equipment called CONTEMPLAS and experimental analysis were carried out at Craiova University [9].
Our experimental research will be focused on the human ankle joint motion in order to acquire this in a polynomial form for using it in virtual simulations as input data for the parameterized ankle joint prosthesis. The experimental analysis principle is to place reflective markers on the desired joints, and with the aid of two cameras we track trajectories and angles in real time. A proper experimental analysis was performed in case of a female with 1.68m height, 65kg, age 28 by using a reflective marker on each human joint centre.

A snapshot during experimental analysis is provided in figure 1 and in figure 2 is shown the obtained result namely human ankle joint motion law developed by the analyzed female. A complete gait was performed in 1.4 seconds.

![Figure 1. A snapshot from experimental analysis](image)

![Figure 2. Ankle joint angle [degrees] vs. Gait [%]](image)

By having in sight the data literature reported in [10], it was obtained an ankle angular amplitude of 23 degrees during walking and this is a reasonable value situated between 20 to 30 degrees. The polynomial form of this motion law it has an accuracy of 95% from the represented curve reported in figure 2 and has the following form:

\[
\alpha(t) = -2.39812t^5 - 1.77398012t^4 - 0.0004t^3 - 0.00066t^2 - 0.389t + 0.9908t - 7.3084
\]  

(1)
3. Ankle prosthesis cam mechanism concept
The proposed ankle prosthesis has on its structure a cam mechanism which will actuate a shock absorber during gait, and also this will facilitate a proper support for the shank component. A structural scheme of the proposed mechanism is shown in figure 3.

![Figure 3. Ankle joint prosthesis structural scheme](image)

The cam mechanism will command and control the shock absorber and from figure 3 it can be identified the following components: 1- shock absorber connect-ed to tibia element; 2 – spring; 3 – cam follower connected with the shock absorb-er rod, 4 – the cam integrated on the human artificial foot; 5 – translational joint with a specific profile which respect human ankle motion law; 6 – artificial foot. This is a planar mechanism with a single DOF and details regarding of this mech-anism design can be remarked in [11, 12].

4. Ankle prosthesis cam mechanism design
Based on the cam mechanism model and by having in sight the anthropometrical data of the chosen human female subject from the experimental analysis, a parameterized ankle prosthesis was designed with the aid of CATIA 3D modelling software. This is shown in figure 4.

![Figure 4. Identifying the components of the designed ankle joint prosthesis virtual model](image)
From figure 4 it can be remarked the following components: 1 – tibia component – which in this case is represented by the shock absorber (it has the dumper adjusting possibility and it will attach to the artificial shank); 2 – shock absorber support; 3 – shock absorber rod; 4 – roller connected to the shock’s rod and it will slide on the cam profile described by the dumping displacement; 5 – bolt which will slide on a imposed profile by the human ankle joint motion law; 6 – Greissinger foot. A crosssection of the proposed cam mechanism human ankle joint prosthesis is shown in figure 5.

Figure 5. A detailed view of the ankle joint prosthesis virtual model with cam mechanism

5. Ankle prosthesis dynamic analysis
By having in sight the designed virtual model of the proposed ankle joint prosthesis mechanism, this was imported in MSC Visual Nastran environment.

For each component it was defined proper material characteristics, namely for rubber, steel and aluminium alloy. The entire model was meshed with tetrahedral finite elements and it was count a number of 44058 finite elements. As regarding the loads and initial conditions the foot component was fixed in space and at the shock absorber head it was applied a force variable in time obtained for a single gait from [1, 3]. By having in sight the literature overview, this force should be higher than initial force generated by the proper mass of the analyzed human female.

Thus in our case, by computing the mathematical models reported in [1, 3], this will have a values multiplied by 2, which was recorded in critical situations like stairs climbing or climbing on a angular surface.

The force variation $F(t)$ is presented in diagram from figure 6 and in figure 7 are shown the applied loads on the parameterized virtual model. Contact forces and friction forces were considered active ones during virtual simulations, according with the values presented in table 1. These values were applied in case of contact between cam profile and cam follower. For the sliding action in case of bolt no 5, friction will be neglected, due to the add of a bearing elements in case of the real prototype.

As regarding the time setup for virtual simulations in dynamic conditions, this was the same during experimental analysis evaluation for performing a single gait, namely 1.4 seconds.
**Figure 6.** Force variation $F(t)$ applied on shock absorbers head during time

**Figure 7.** Initial conditions and loadings applied on the ankle prosthesis

**Table 1.** Input parameters for dynamic simulation.

| Parameter          | Type/Value | Units | Parameter          | Type/Value | Units |
|--------------------|------------|-------|--------------------|------------|-------|
| Contact $\mu$      | 0.65       |       | Contact $\mu_d$   | 0.45       |       |
| Penetration depth  | 0.075 mm   |       | Force exponent     | 1.65       |       |
| Friction force     | Coulomb    | N     | Damping            | 34         | N·sec/mm |
According with the figure 6, the ankle joint motion law was applied as a polynomial form at the level of component no. 5 by having in sight the equation 1. The mentioned load was applied as a polynomial form, onto shock absorber body and this will have a sliding motion imposed by the link no 5 profile from figure 3. The force equation has the following form:

\[
F(t) = -1154.22967t^6 + 4238.6521t^5 - 9554.2369t^4 + \\
+615.33456t^3 - 1654.2367t^2 + 183.7746t + 0.5587325
\]  
(2)

Some snapshots acquired during simulations with the dynamic response represented through stress, are shown in figures 8 and 9. Thus, the dynamic response was characterized by stress, deformations and displacements depending on time through diagrams reported in figures 10, 11 and 12.

![Figure 8. Ankle joint prosthesis von Misses stress vs. time interval 0 to 0.5 [sec]](image-url)
By having in sight, the obtained results reported in figures 10, 11 and 12, it can be remarked that the paths from von Misses stress and strain have the same shape. The maximum stress value was recorded with a value of 46.9Mpa, as it can be seen in figure 10 and this was situated at the contact between cam follower and cam profile. Other high values were recorded in the area of component no.5 and the shock absorber support.
Similar values were recorded for total mechanical strain as a value of 0.01438%, which means that all the rigid components were have small deformations, as it can be remarked in figure 1.

In case of total displacements, there were recorded high values in the area of shock absorber segment and his support. The obtained value was 0.015123 millimeters according with the graph from figure 1. Thus, this dynamic behavior was related to friction forces between cam follower and cam profile, but also due to the bolt component no 5 during sliding motion on the foot component path.

The obtained results encourage to elaborate this prototype and to test it in real daily walking activities of a female amputee.

6. Ankle prosthesis prototype
According with the obtained results, which make this study feasible, the proposed ankle joint prosthesis has a good behaviour and a prototype was fabricated. This is presented in figures 13, 14 and 15.
Figure 14. Ankle joint prosthesis prototype – front view

Figure 15. Ankle joint prosthesis prototype assembled with a complete knee and ankle prosthesis

Only a part of components was fabricated from zero point, other were purchased, namely the shock absorber from FESTO Pneumatics and the foot was Greissinger Plus type provide from Otto-bock. In order to reduce friction, the designed prototype was equipped with ball bearings at the level of cam follower component and also at the level of component no 5 according with figure 4.

7. Conclusions
A new prototype of a human ankle joint prosthesis for human locomotion rehabilitation is proposed and equipped with a cam mechanism.
Simulation results have outlined suitable performance for suitable user-oriented operation in walking during daily living activities, although its design may require additional components in future developments.

The proposed design is fairly simple wearable and lightweight with adjustable structure and its operation is fulfilled with a shock absorber integrated in tibia segment.

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