Concept design and design optimization of the transfemoral prosthetic leg prototype

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Abstract. The biggest challenge with today’s lower leg prosthetic devices is to climb the stairs in a biologically inspired way. When climbing the stairs, due to the large moments in the knee joint, great forces in the knee occur. Because of the magnitude of these forces, which can be up to six times the weight of a person, it is necessary to use a hydraulic drive with an external power source in the knee and ankle joint. However, most commercially available above-knee prosthetic legs only have actuation in the form of damping in the knee joint. Hence, an amputee is forced to use a healthy leg to advance to each step first while amputated leg follows.

1. Introduction
The project of optimization of the transfemoral (above-knee) modified prosthesis RZ-0 includes the development and production of a new type of above-knee prosthesis RZ-W with double drive integrated in the lower leg, i.e., independent management of the knee and ankle joints together with separate drive units. By enabling a more natural gait and the ability to master activities such as getting up and climbing the stairs, this prosthesis aims to improve the quality of life of people with above-knee amputations. Section 1 contains a brief description of the history of the development of the RZ-0 (initial model) upper leg prosthesis project. There is an overview of the first four development phases and the tasks are listed, i.e., the goals of the current, fifth phase of work. Section 2 presents a series of activities undertaken to enable the first part of the fifth phase of the project. The following is section 3 with details of performing the activity, which is, assembling the components into a working prototype RZ-W. The conclusions are presented in Section 4.

2. Background
The activities related to this project have been going on for several years and consist of several phases. The project has been multidisciplinary from the very beginning. Social workers, orthopaedic doctors, and a group of engineers consisting of specialists in biomechanics, statics, hydraulics, mechanics, sensors, and robotics have been involved [1].

The first phase was to select the appropriate group of amputees and try to define all the parameters of the terms of reference that would be represent to the whole group. The second phase was to perform the necessary calculations related to the design of the structure.

The third phase was the optimization of the construction of the above-knee prosthesis, where based on the obtained data the most favourable position for the installation of a hydraulic linear actuator in the knee joint was obtained by synthesis, and then its stroke and other structural dimensions were defined.

In addition, it was necessary to solve the method of supplying the starter with oil, and select all the necessary hydraulic components to control and regulate the oil flow.

The fourth phase was the optimization of an artificial foot with an ankle joint. Experimental tests have shown that the time of movement of linear actuators, as well as the stroke of linear actuators in the knee
and ankle joint are not equal. Therefore, it was concluded that the management of these linear actuators should be separated [2,3,4,5].

This article describes the initial activities of the fifth phase of the project and has as a starting point the observations and conclusions collected during the implementation of the fourth phase. One of the important limitations for this project, in addition to reducing the volume of prosthesis aggregates as a whole, is the financial accessibility of prostheses to a wider population of users, which is reflected in the use of exclusively commercially available components [6].

The following points have been identified as primary objectives:

- Detailed analysis of the prototype of the above-knee prosthesis RZ-0 through an analytical model in CAD software. Special attention is paid to the verification of prosthesis kinematics using available, commercial actuators.
- Rapid construction of a load-bearing structure based on wood in order to build and verify the feasibility of a physical prototype. This approach allows the verification of the intended actuators and the design of the housings for the drive actuators in the lower leg.
- Translation of acquired observations into the design and production of 3D printed components of the entire structure.

3. Design and development of the new prosthesis leg concept

The commercial aspect of the project leads to limitations for prosthesis design, which is reflected in the use of exclusively commercially available components. The following figure shows the working prosthesis made at the end of the fourth phase of the project in which the actuators of the upper and lower part of the prosthesis are visible. These cylinders are made to order, for prototype testing purposes, and do not represent available components for the commercial development of a robust prosthesis model (Figure 1).

![Figure 1. Layout of the RZ-0 prototype prosthesis at the end of the fourth phase of the project of development of the upper leg prosthesis (left) and used aggregates (right)](image-url)

From the conclusions of the previous phases of the project, it was established that the hydraulic actuators of the company SNC, type CHNC20-25 and CHNC20-35, best meet the technical requirements of the imagined prosthetic actuators and are commercially available. Electric motors and hydraulic pumps from JUNG were selected for the unit, which with an individual total weight of 1.5 kg are currently the smallest and lightest versions available on the market. At the same time, these aggregates are half as light as those used in the previous prosthesis and with their smaller volume for the first time offer the possibility of integration into the lower leg part of the prosthesis.

As mentioned in the introductory chapter, the idea was for the very beginning to make a prosthesis construction out of wood to get a tangible working prototype as soon as possible for further design testing. The reason for this is that wood is easy to work with, and it is not expensive to fix something if it goes wrong or ultimately make a new prosthesis. Drawings according to which parts for a wooden prosthesis were made were drawn in the Solidworks program. The original idea was to make a lower leg and upper leg that would connect with each other. According to the literature, the following dimensions were taken [1]:

- Length of the lower leg (from the axis of the ankle joint to the axis of the knee joint) - 425 mm
- Length of the upper leg (from the axis of the knee joint to the end of the pelvis) - 575 mm.
The dimensions of the wooden bar are 60X40 mm. The lower leg would be connected to a metal foot that was already ready for use.

The following were used as input data for the kinematics of the prosthesis components:

- The foot should be maximally straightened at an angle of 90 degrees to the ground,
- In the lowered position, when the lower leg is at a 90 degree angle to the ground, the upper leg should be slightly less than 45 degrees to the ground.

These parameters were achieved with the help of Solidworks (Figure 2) to later make the physical wooden version of the prosthetic leg.

![Figure 2. 3D model of the RZ-W prosthesis concept in Solidworks](image)

The next step was the installation of cylinders that were selected based on the conclusions from the previous phases of the project. Two cylinders were procured from the US and SMC. The cylinders are from the CHN series (Figure 3). Some features of these cylinders are:

- relatively light weight
- Nominal pressure: 7 MPa
- Drill size (mm): 20.25, 32, 40
- Standard strokes (mm): 25 to 800
- 5 types of mounting

![Figure 3. Cylinder of the CHN series](image)

The design of the two cylinders available to the project is type C. The size of the drill is 20 mm. The shorter cylinder has a stroke (working path), i.e. 25 mm can be pulled out, and a longer cylinder 35 mm. On the SMC website, there is a possibility to download ready-made CAD models of these cylinders from the database, so they were downloaded for the Solidworks program. For both cylinders comes the equipment, i.e. two small holders named I0-2 (I-shaped single knuckle joint) that are wound on one side of the cylinder. They are like a CAD model, also taken from the SMC database (Figure 4).

When checking the dimensions of the CAD model on the basis of the physical models of the cylinders, a small mismatch of the drawings from the prospectus was noticed, i.e. actual dimensions and those in the CAD model, so they are aligned with the physical model. When this was done, the next step was to install a shorter cylinder (CHNC20-25) in the CAD model of the prosthesis. The idea was to install it in a prosthesis so that the cylinder is connected on one side to the hole in the foot provided for it. The upper side of the shorter cylinder would then be connected to the upper leg taking into account a maximum working distance of 25 mm. It was decided to connect it so that the centre is in the axis of the lower leg, i.e. in the middle. Therefore, it was necessary to make an opening in the wood where the
cylinder should fit and holes on the sides where the cylinder will be connected with a screw, which was done in the Solidworks program (Figure 4).

![Figure 4](image1.png)

**Figure 4.** Drawing of the opening for the shorter cylinder in the knee joint

The longer cylinder (CHNC20-35) should be tied to the lower leg on the underside and to the upper leg on the upper side. Since the longer cylinder should also be tied to the central axis of the lower leg, an opening in the shell should be made for it as well. On the basis of the kinematics and working paths of these cylinders, they come into a position very close to each other, it was necessary to make an opening along the entire lower leg as the most efficient solution. For the upper connection point of the longer cylinder, it was decided to make a metal part that would be fastened with bolts and to which the cylinder would be attached. The metal part is drawn in Solidworks and is made of aluminium in the local company.

When the wooden structure was fully modelled and the cylinders were virtually connected to the foot and the metal part for the upper leg, the resulting virtual RZ-W prototype looked like in Figure 5.

![Figure 5](image2.png)

**Figure 5.** Wooden prototype after installation of the cylinders and metal fixation

The next, and at the same time the biggest challenge, was the realization of the necessary kinematics of the prosthesis within the given limits of the cylinder. The movement of the lower leg was not a major challenge and the stroke of 25 mm of the lower cylinder was sufficient to achieve the desired movement of the lower leg. The challenge was to achieve sufficient thigh rotation. The lower leg has a given movement in the range of 95 degrees. In order to achieve this, it was necessary to adjust the position of the metal part to which the upper cylinder is connected. Mathematical calculation and displacement in the CAD model yielded a satisfactory solution which is shown in Figure 6. The effective operating lever of the cylinder is 24 mm in the obtained model.

With the successful completion of the design in CAD and the virtual verification of the kinematics, it is decided to move on to the development of a physical prototype of a wooden prosthesis with all the listed, available components.
4. Development and assembly of the physical prototype

By making parts of the structure from wood, cylinders were installed as shown in Figure 7.

With the successful completion of the physical prototype movement check, the next step was to install the units (pumps and electric motors) purchased from the German company JUNG-FLUIDTECHNIK GMBH. The prosthesis with all its parts was taken to the company HANSA-FLEX where all hydraulic components and lines are integrated in the prosthetic housing. The units (electric motors with pumps) are connected to small plates on the sides of the lower leg, and the oil tank is installed a little higher on the plate on the front side of the lower leg. The final first version of the prototype prosthesis with a wooden structure is shown in Figure 8. The electrical, drive control system is shown in the figure to the right.
5. Discussion and conclusion

The previous sections show a fast process of designing the components of the RZ-W prototype of the prosthesis based on the load-bearing parts of the wooden structure.

The following points are described in detail:

• Detailed analysis of the prototype of the upper leg prosthesis RZ-W through an analytical model in CAD software. Special attention was paid to the verification of prosthesis kinematics using available, commercial actuators. The observed deviations in the available CAD models of the cylinders were eliminated through the inspection of the physical models. The assembly of components into a virtual prosthesis is performed by complying with all given constraints.

• Rapid prototyping of a load-bearing structure based on wood in order to build and verify the feasibility of a physical prototype. The production itself was done relatively quickly, which confirmed the validity of the choice of wood as the primary material for the rapid and efficient production of a working prototype of the prosthesis. The flexibility of the wood and the possibility of subsequent constructions are thus recognized.

• The installation of available and commercially available (off-the-shelf) components (aggregates, rubber hoses, manifolds and oil tank) was also done relatively quickly and a verification, a functional, working prototype ready for further testing, took place.

The entire process was done in less than 30 days. Observations gained in this process are taken for the next step in the fifth phase of prosthesis development, which is the design and manufacture of 3D printed components of the entire structure for easier physical construction and more favourable integration of hydraulic and control system within the prosthesis.

Development of the model in which all the components are integrated brings us a step closer to the goal of creating a low-cost solution for transfemoral amputees.

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