



# Designing a Prosthesis for Animal Limbs

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**Abstract.** Currently, prosthetics of damaged limbs in Russia is available only to a limited number of pet owners. Despite the fact that additive technologies are becoming more and more available, their application in veterinary medicine is difficult and requires special knowledge. In this regard, the development of new approaches to the creation of affordable and functional prostheses for animals using modern IT technologies is an urgent task of great practical importance. The article presents a 3D model of a prosthesis for a golden retriever with the designation of the main structural elements necessary for the manufacture of a prototype, and provides a justification for the choice of materials for creating a prosthesis. Also, to substantiate the operability and reliability of the developed prosthesis design, a set of necessary strength, dynamic, thermal and other calculations was performed.

**Keywords:** Prosthesis · Trauma · Additive technology · 3D modelling · Amputation

## 1 Introduction

Nowadays there is an increase in amputations for animals by trauma, illnesses or congenital pathologies. Statistically, more than a million of amputation surgeries for domestic pets are conducted annually. Amputation drastically deteriorates quality of life and decreases his movement ability, which in turn afflicts its’ physical and mental condition. An effective way to restore movement ability is prosthesis – adjustment of an artificial limb. However, the existing technologies have a handful of shortages: high cost, complex engineering and manufacturing of a single prosthesis, biological compatibility of the prosthesis and the animal [1–3].

## 2 Significance

Accordingly, developing new ways to produce affordable and functional prostheses for animals using modern IT, is a relevant issue with big practical use. The developed prosthesis is designed for golden retriever. This dog breed has been chosen for its’ popularity among households. Besides, golden retrievers are very active, what imposes additional requirements for prosthesis functionality, that secures the restoration of retrievers’ physical activity [4–7].

## 2.1 Task Assignment

Based on the analysis of modern animal prosthetics technologies, we can conclude that a promising direction of development is the creation of bionic prostheses that maximally imitate the structure and functions of natural limbs.

In particular, for prosthetics of the hind limb of dogs, it is proposed to develop an innovative prosthetic design with the following features:

1. Modular design of the “foot” of the prosthesis with separate movable “fingers” connected by a hinge system. This will allow you to imitate the anatomy and kinematics of a dog’s paw, ensuring natural positioning of the limb when walking and running.
2. Use of high-strength and lightweight materials such as carbon fiber-based carbon fiber and titanium alloys. This will ensure sufficient load-bearing capacity with minimal weight of the prosthesis, reducing the load on the animal’s body.
3. The use of additive technologies (3D printing, 3D scanning) for the manufacture of an individual prosthesis based on a digital 3D model of a specific animal limb. This will allow the geometry of the prosthesis to be adapted as accurately as possible to the patient’s anatomy.
4. Equipping the prosthesis with a built-in system of sensors - mechanical, tactile, inertial. These sensors will be used in control algorithms to correct the movement of the prosthesis in real time.
5. Implementation of an electromechanical drive and control system based on artificial neural networks for recognizing motor commands from signals from the muscles of the stump. This will bring the control of the prosthesis closer to the natural neural control of the limb.

The implementation of these solutions based on advanced mechatronics technologies, 3D modeling, neural networks and microelectronic sensors will create a new generation of highly functional adaptive bionic prostheses for veterinary medicine.

Figure 1 shows an example of a prosthesis that satisfies all the requirements described above.

Thus, the model includes the following main components:

- Sleeve for fixation to the dog’s stump, repeating its individual shape. Stump geometry data were approximated based on typical dimensions.
- Adjustable frame element of the prosthesis with the ability to change the length and width to customize it for a specific patient. Serves as a load-bearing support.
- Modular foot design with individual movable toes that are hinged to the base. Allows you to imitate the natural movements of the paw during movement.
- Built-in system of tactile pressure sensors and mechano-tactile sensors for feedback to the nervous system to ensure coordination and balance during movement. Sensors are integrated into the inner surface of the prosthesis.
- Power drive in the area of the “knee” joint with hydraulic control to adjust the angle of flexion of the prosthesis during movement. The drive is controlled from an external unit via a wireless communication channel.



**Fig. 1.** Example of a prosthesis.

Considering anatomy features of golden retrievers and usage conditions, we have defined the following parameters of the designed construction:

- the base of a prosthesis is made of titanium alloy, which provides high durability of the construction while it has low unit weight. Length of the base varies from 25 to 35 cm, that fits the average size of a golden retriever hind leg. Such length allows the prosthesis to imitate natural proportions of a limb.
- the width of a prosthesis in foot area is 5–8 cm. Such width secures enough bearing surface area and stability, what is crucial for upholding balance while walking and running. The foot cover is made of hypoallergic and water-proof polymers, what makes it safe for animal skin and resistant to external factors.
- the width of a prosthesis where it is adjusted to a stump is 8–10 cm. This provides reliable fixation of the prosthesis and prevents its from being displaced while actively used. The binding is equipped with adjustable belts, what allows to adapt a prosthesis to the individual size of a stump of each dog.
- prosthesis maximum weight does not exceed 1 kg, what minimizes additional burden on an animal and makes it easy to move. Thanks to titanium alloy and polymetric materials we have managed to achieve optimal ratio of endurance and weight [8, 9].
- the construction supports width adjustment as well as mobility degree of the base. This allows to settle the prosthesis to fit dog's activity and the surface type it interacts with.

Other additional requirements for the prosthesis construction are:

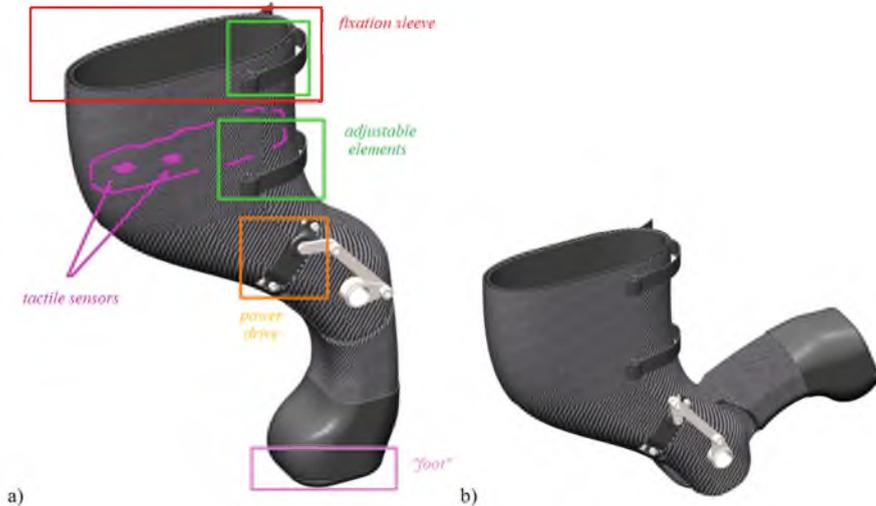
- touch sensors are built in the prosthesis base, they provide feedback about the surface interaction. These sensors enable a dog to orientate itself and provide additional security while moving.
- option to integrate with neuro-muscle control interface, due to relevant sockets and wire or wireless communication channels with external controller [10].

### 3 Theory

On the basis of the conducted analysis, we have developed a 3D model of a hind leg prosthesis using CAD/CAM SolidWorks. The model includes the following key components:

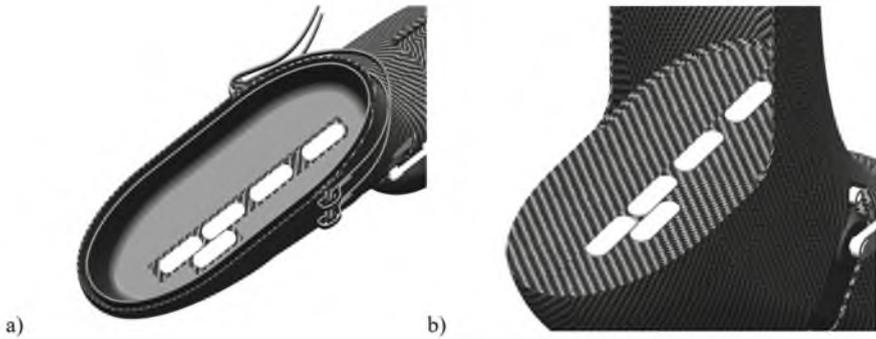
- fixation tube, adjustable to the dog's stump, replicates its' individual form. The stump's geometry has been modelled roughly by using average size.
- adaptive frame element, with adjustable length and width to fit any single dog. Works as support.
- the foot modular design with separate moving "dactyls", hingedly fixed at the base. Allows to imitate paw's natural movement.
- an inbuilt system of touch pressure sensors and mechanical touch sensors for feedback to the nervous system to provide coordination and balance while moving. The sensors are built in the inner part of a prosthesis.
- the hydraulic power unit in the "stifle" area to regulate yaw angle while moving. The unit is controlled with external block by wireless channel.

The appearance of a prosthesis 3D model with notation of main structural units (Figs. 2 and 3). This model has the fixation tube, the adaptive frame element, the foot modular system, the inbuilt system of pressure touch sensors, mechanical touch sensors and power unit in the "stifle" area. Let's examine the prosthesis main components in detail.



**Fig. 2.** (a) 3D model of the prosthesis in its original form; (b) 3D model of the prosthesis in a bent form.

The fixation tube is an upper part of the prosthesis, with locks it to the stump. This is a big cylindric element, which circles the upper part of the prosthesis and aims seize around and to hold the dog's stump. The adjustable frame elements is below the fixation tube and



**Fig. 3.** (a) Sensors (in white) on the inside of the prosthesis; (b) sensors (in white) sensors (in white) in another projection.

may be presented as a middle part of the prosthesis, with includes mechanisms to regulate length and width. This is a structural unit, with is fixed with other parts. The modular foot lies in the very bottom of the prosthesis and includes separate moving elements with can imitate animal's dactyls. These elements are hingedly fixed and theirs' purpose is to imitate movement. The in-built system of touch pressure sensors and mechanical touch sensors is designed for feedback to the nervous system (the sensors are not visible as they are inside the prosthesis). The power unit in the "stifle" area lies in the middle part of the prosthesis, which corresponds the stifle-joint. This is a device that contains hydraulic components to regulate yaw angle.

## 4 Practical Relevance

In order to prove efficiency and reliability of the developed construction we have made a complex of necessary strength dynamic thermal and other analyses.

We used finite-element analysis on a frame model, which included 51203 nodal points and 25620 end elements (second order tetrahedron) (Fig. 4). We have set the following limiting conditions for our calculations:

- Fixation of the frame's lower part, imitating fixation of the prosthesis to a dog's stump;
- Uniformly distributed load alongside axis Z, affects upper surfaces of a prosthesis model in foot area. The given pressure value is 0.15 MPa, what corresponds the quiescent load on a foot with size of 500 cm<sup>2</sup>.

The frame's material is titanium alloy Ti6A14V with elasticity modulus  $E = 113.8$  GPa and yield stress  $\sigma_{0.2} = 880$  MPa.

The result of the calculations were values of von Mises equivalent, presented on the picture below. Maximum stress value in the construction was 372 MPa, what is way less than the material's yield point.

The index of yield point:

$$\gamma = \frac{\sigma_{0.2}}{\sigma_{eq}} = \frac{880 \text{ MPa}}{372 \text{ MPa}} = 2.37 \quad (1)$$

Therefore, durability of the designed construction has safety margin of 2.37 times above the standard value set for this type of product.

When calculating rigidity and stability, the central beam of the prosthesis frame, made of titanium alloy BT20, has the greatest length (320 mm) and experiences maximum bending loads during operation. To ensure the functionality of the design, it is necessary to confirm that:

1. Beam deflections under given loads will not exceed permissible values;
2. The structure is sufficiently rigid and will not lose stability during operation.

Let's take as initial data:

- Beam material - titanium alloy BT20
- Elastic modulus  $E = 113.8$  GPa
- Section moment of inertia  $I = 1.92 \times 10^{-7}$  m (for section  $16 \times 3$  mm)
- Beam length  $l = 320$  mm
- Distributed lateral load  $q = 2$  kN
- Section width  $b = 16$  mm
- Section height  $h = 3$  mm.

The beam deflection  $\delta$  from the action of a uniformly distributed transverse load  $q$  is determined by the formula:

$$\delta = \frac{ql^4}{384EI} = \frac{2000 \cdot 320^4}{384 \cdot 113800 \cdot 1.92 \cdot 10^{-7}} \quad (2)$$

Thus, the maximum deflection of the central beam of the frame is 0.072 mm, which is significantly less than the permissible value (the maximum deflection is usually taken to be 1/200 of the length). Below is a graph of the beam deflection curve (Fig. 5).

Consequently, the rigidity of the beam is sufficient to ensure minimal deformation of the frame under given loads during operation of the prosthesis. This will avoid disruption of the structure.

Buckling force calculation shows that the center girder loses stability (extrusion from the flat level) when the critical load  $P_k$  is reached, which in its' turn is calculated with Euler formula:

$$P_{kr} = \frac{\pi^2 EI}{(kl)^2} \quad (3)$$

where  $k$  is an index for limiting conditions.

The balk is rigidly restrained with  $k$  equals 4. Setting the values, we receive the following result:

This value way exceeds the design load of 2 kN. You can see the graph for different values of  $k$ , 1 below (Fig. 6).

Therefore, the construction of the hull's center girder will not achieve critical condition and will be sturdy against buckling. To secure movement in the "stifle" zone of the prosthesis we have designed a hydraulic power unit. The unit must provide angulation from 0 to 50° to imitate joint's natural movement while walking. It is necessary to define correctly the spin moment of the power unit.

Distribution of equivalent stresses according to Mies in the prosthesis (by coordinates)

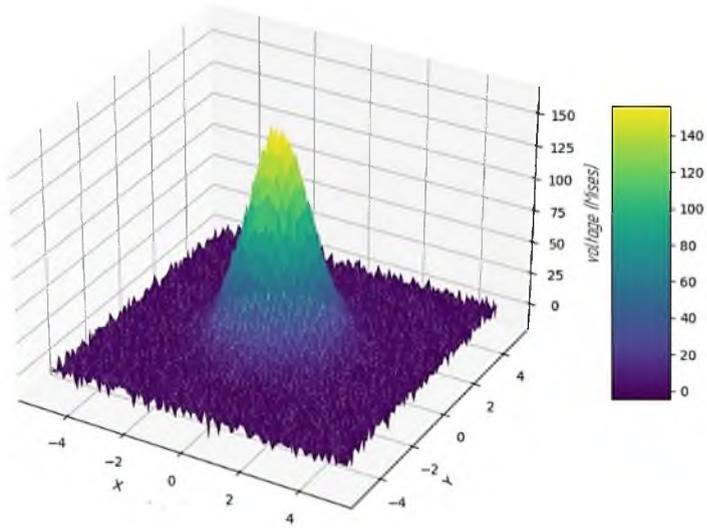


Fig. 4. Results of strength calculation of the prosthesis frame.

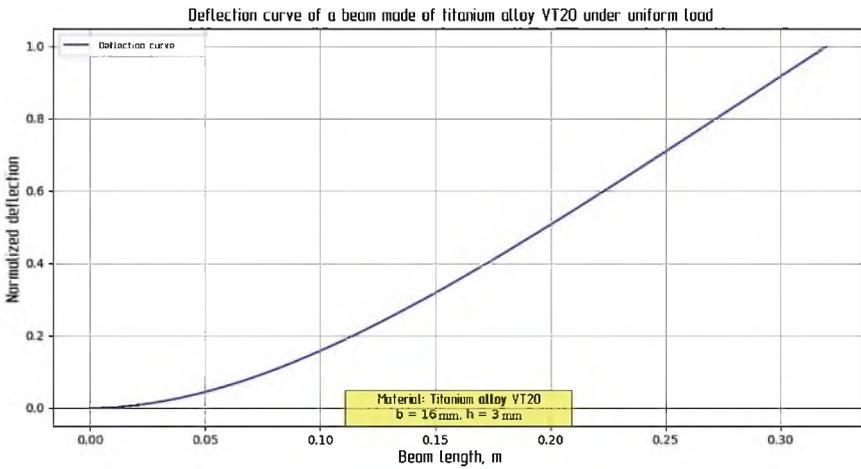
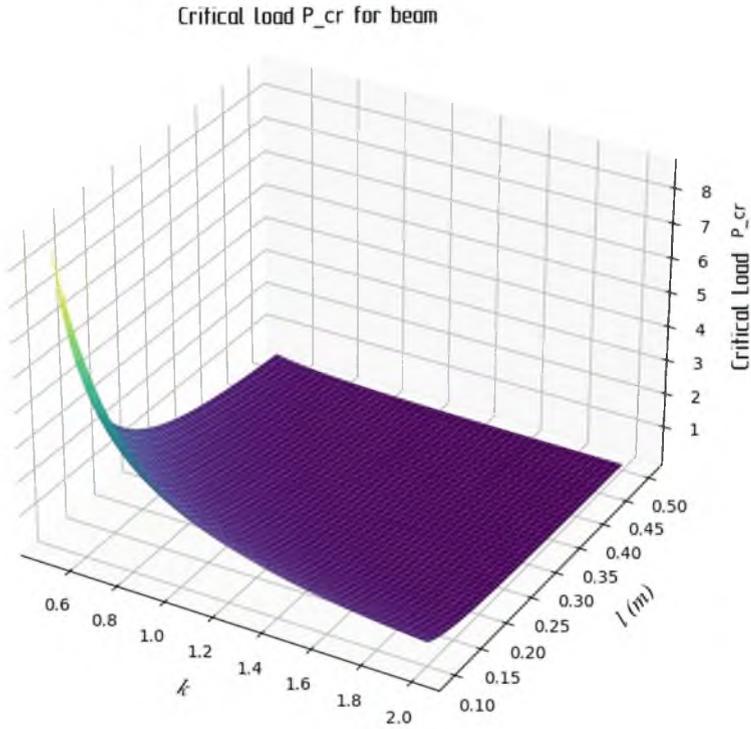


Fig. 5. Beam deflection curve graph.

Considering the weight of a hind limb (statistically a golden retriever’s hind leg weights 5 kilos) and application force (0.15 m) we have defined the necessary spin moment:

$$M = R \cdot F = 0.15 \cdot (5 \cdot 10) = 7.5 \text{ H m} \tag{4}$$



**Fig. 6.** Calculation of  $P_{cr}$  for different  $k, l$ .

Hence, considering the weight of a golden retriever's hind leg, the power unit must have spin moment at least 7.5 N m. Keeping the spin moment of 7.5 N m, in mind, and the given angulation between 0...50°, we have chosen the hydraulic power unit Parker series L90 with following features: maximum spin moment is 10 N m, angulation is between 0...270°, with a mobile control valve.

We have given a lot consideration to the choice of materials, while designing the prosthesis innovative construction. Each assembly required special approach considering its' functions, working conditions and interaction with biological tissues.

As framing is the basic supporting element of the whole prosthesis construction, other components are fixed to it, and framing is adjusted to the animal's stump, all these factors set high requirements to the material the framing is made of. Namely, we need high strength/weight ratio, low density, corrosion resistance, bio-compatibility, manufacturability. Feature analysis of different construction materials has shown that the titanium allow BT20 is the most promising option. This alloy has the following properties: tensile strength (1200–13000 MPa), with density (4.5 g/cm<sup>3</sup>), hardness (330...370 HB), elasticity modulus (110 GPa). As we can see, BT20 has very high strength/weight ration features, what is crucial for prostheses with mass limitations. At the same time, titanium alloys provide full bio torpidity and compatibility with tissues. The power unit in the "stifle" is based on a hydraulic cylinder, which forcer is moved by fluid pressure.

The cylinder barrel and unit's other parts' material define to a large extent durability and reliability of such a vital mechanism. Key requirements to the power unit's material are sufficient solidity and durability of acting surfaces, high workability to achieve necessary geometric precision of its' parts, rust prevention, and none ferromagnetic properties.

Based on these requirements, we have chosen the aluminum alloy 6082 in quenched condition (6082-T6). Due to heat processing (quenching and artificial aging) a high level of mechanical properties is achieved, which secure the reliable work of a cylinder and power unit's other parts. Thus, aluminum alloy (6082-T6) is an optimal choice for hydraulic power unit and its' elements.

Mechanical pressure and curve sensors are designed to record signals when the paw prosthesis interacts with surface and to feedback sensor information to the animal's nervous system (Fig. 7). The requirement to the material is sensor's sensitivity, properties' stability, low magnetic lag and signal's drift, microelectronic producibility.



**Fig. 7.** Appearance of the Parker L90.

Considering these requirements, we have chosen semiconductor silicon as material for sensor's sensitive parts. Advantages of single-crystal silicon are high piezo resistance (up to 200 units), linear signal in a wide pressure range, parameter stability and low magnetic lag, high reproducibility, cutting-edge silicon micro processing technologies. Using piezo resistant silicon sensors, it is possible to create high-precision feedback touch system to control effectively the movements of an animal prosthesis with computer AI [11–15].

## 5 Summary

We have designed a technical solution for manufacturing an innovative cutting-edge prosthesis of a dog's hind paw, while conducting this research. The designed construction has high functional capabilities, namely mechatronic controls, in-built pressure and

touch sensors, what provides extended adaptive features. The conducted construction calculations and modelling have confirmed the working efficiency of suggested technical solutions. While designing the prosthesis construction, we managed to solve the assignment and to create an innovative and functional prosthesis for dogs with extended features for automatic adaption to moving conditions due to “clever” mechatronics and control algorithms. The results obtained can be used at the following implementation of a prototype and its’ test.

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