Foot Prosthesis Design to Recover the Natural Biomechanical Position in *Ramphastos tucanus* Specimen

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***Abstract*—The proper performance of the biomechanics of the body has a key role in animal welfare. For this project, a foot prosthesis was designed for improving the quality of life of a *Ramphastos tucanus* specimen that presents an amputation at tarsometatarsus level. The main objective is recovering its statics biomechanics through the design and implementation of a prosthetic prototype based on a kinetic analysis. Using the incremental prototypes methodology, the biological system requirements were identified, the technical features were analysed, the prototype was designed by selecting one of three alternatives proposed and analysed by computational methods and then the device was constructed and implemented. Currently is being evaluated. Thanks to the application of an ethogram, it was identified *rest* as the static position to evaluate in the biomechanical analysis; the adjustment and implementation of a force sensor evidenced an overload on the pelvic limb with the amputation by supporting the 62,3% of the mass of the bird; the biometrics define the prototype size and showed an increase of musculoskeletal mass on the gripped limb; besides, the kinetics study exposed the difference of the force applied by the flexor tendon on surfaces. The design was created using CAD tools, and applying materials as PET-G, stainless steel, and aluminium. The finite element analysis was carried out before implementing the prototype. This process extends to an ongoing adaptation and evaluation protocol designed specifically for the bird, allowing to identify the impact of the prototype over the animal in the different aspects named previously.**

***Index Terms*—Animal welfare, biomechanics, prosthesis, *Ramphastos tucanus*, rehabilitation.**

I. INTRODUCTION

Wakatá Bio-park in Colombia, have accomplished the parameters that ensure the animal welfare into the institution. This means not just physical and mental health, but also the prevention of future illness too [1]. Between the animals they take care, there is a *Ramphastos tucanus* specimen with an amputation at tarsometatarsus level at the right pelvic limb. Although this bird does not present movement (displacement) problems, the biomechanical unbalance due to the adaptation of non-natural positions and the support of other structures on surfaces, generate a load redistribution on the pelvic limbs that could cause different health problems in the future affecting its quality of life. According to the welfare parameters and the physical health of the specimen, it was identified the importance to recover the natural biomechanical position through the design of a prosthesis prototype based on ethological results and kinetic biomechanical analysis, for its posterior implementation and evaluation.

Recently, there have seen developments of veterinary orthopaedic devices that have been created to solve generic or specific problems; however, although there are researching groups and companies dedicated to its production [2], under specific conditions associated with the user and its needs [3], most of these developments focus on companion animals. Many individuals or companies have generated empirical methodologies and protocols that are not documented or not publicly known. This is the common situation for prosthetics on wild animals, as a parrot that got a prosthetic foot at the University of Pennsylvania created by the School of Veterinary Medicine, this was made by 3D printing, but the materials used were not reported [4]. Another example was implemented in the Brazilian zoo, where a Flamingo got an artificial leg because his leg had to be amputated to prevent infection; this prosthetic device was made in carbon by a local prosthesis manufacturer [5]. In addition, there was a case in Cambodia where a young elephant received a prosthetic foot made by the Cambodian School of Prosthetics and Orthotics, the material was not mentioned in the notice, but they said that the prosthetic has to be constantly changed because the mammal grows fast [6].

This lack of information of the processes makes necessary deep research on the specimen and the biology of the species and its biomechanical features blending by this way the mechanical and medical knowledge to develop the proper device according to the needs of the animal and its living conditions.

To solve those situations that have been previously recognised, this project implements intrinsically the elements of the engineering model CDIO (Conceive, Design, Implement and Operate), by organising the paper as follows: Methodology, where methods and materials are described; Results, in which the biomechanical and design results are shown and finally the conclusions are presented.

II. METHODOLOGY

To carry out the prosthesis design, an incremental prototypes methodology was used. This included five phases described as follows. In Figure 1, the consecutive phases of the process are represented as well as the points were is necessary to evaluate and make decisions based on the answers.

In general, the development of the phases is linear, but there are three points during the methodology where the prototype design should be evaluated to identify if the process is working properly, or if it is necessary to improve it.

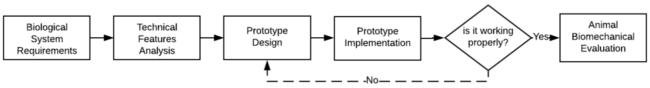

Fig. 1. Methodology diagram.

One of these points is located immediately after the implementation phase, where the performance of the device on the real context is evaluated, the initial impact for the animal by using the prototype is important and the proper movements and restrictions should work properly. If everything is working well, it is possible to continue with the evaluation phase, if not, it is necessary to review and improve the prototype design.

The five phases included in the methodology are described as follows, and there are two of them that have their own feedback:

Phase 1. Biological system requirements: An ethogram was used to carry out a behavioural study as a statistical tool to identify the needs, activities and behaviours of the animal [7].

Phase 2. Technical features analysis: Radiographs of the toucan were taken and a biometrics protocol [8] was adapted to identify the size and weight of the lost pelvic structures and also to recognise the technical characteristics that the prosthesis should have. Then, a sensor device was conditioned to identify the load distribution on the pelvic limbs upon flat and curved surfaces. And finally, a kinematic study was carried out to identify the forces implied in the biological system [9]. Additionally, a study of the environmental variables was made to identify the temperature and relative humidity which the device was going to be exposed and the average diameter of the branches to determine the device operating range.

Phase 3. Prototype design: Through the Quality Function Deployment (QFD) [10], the main features of the prototype that had to be solved were evidenced. Then, the prosthetic device was divided into three main components: the socket, the support and the dynamic mechanism. For each one of them, three solution alternatives were proposed and just one of them was selected through matrix-based variable prioritisation method; materials were selected by the same way, including main components, joint components and also the one situated between the prosthesis and the stump that should be hypoallergenic and comfortable. Then, the detailed design of the prototype was generated with CAD design tools. Finally, a mechanical analysis was carried out using CAE tools, simulating the real force conditions [11] and the selected materials according to the application and the habitat features [12].

As shown in Figure 2, this phase includes its own feedback and is located after the CAE analysis sub-phase. There, the results of the analysis will show if the prototype designed is going to work as is expected in the real application, if those results are positive, the next phase can be started, if not, the CAD model has to be checked, including the design and the materials.

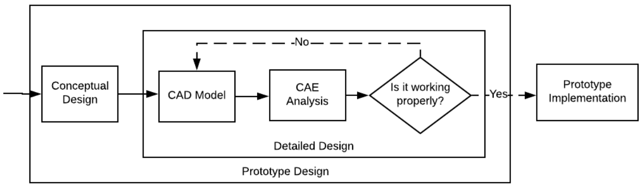

Fig. 2. Design feedback diagram.

Phase 4. Prototype implementation: The construction and assembly processes were carried out using 3D printing and mechanical tools. The implementation of the prosthesis device has been done thanks to an operant conditioning process with the animal [1], which helps to make the implementation easier and safe for the bird.

This phase includes another feedback that is located between the assembly sub-phase and the user implementation sub-phase as can be seen in Figure 3. There, it is important to realise that the device is working as well as the virtual model; if the prototype is working in the way it has to, the process continues with the user implementation sub-phase; but if the prototype has problems, it is necessary to review the construction and assembly sub-phase.

Phase 5. Evaluation of the prototype implementation: An adaptation and evaluation protocol was constructed to identify

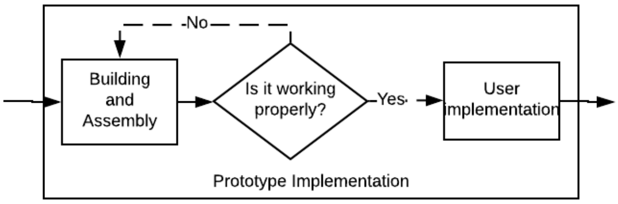

Fig. 3. Implementation feedback diagram.

the effect of the prototype implementation in the real context of the specimen. This protocol is still being applied to the animal.

III. RESULTS

For the biological system requirements, the behavioural analysis showed that the animal needed a device that could be adapted to different surfaces due to the animal forage in-floor. Also is important to conserve the biomechanical position in flat and curved surfaces. Thanks to the application of the ethogram, "rest" behaviour was identified as the most common, taking the position that characterises it to be evaluated in the biomechanical analysis.

For technical features analysis, later-lateral radiography showed the amputation located at 30.6 mm from the knee joint down with an angular form on the cross-section inclined 48.7^o towards the front. Also, the length of the transverse musculoskeletal tissue in the right and the left femur is 11.8 mm and 19.7 mm respectively and right and left tibiotarsus is 16.6 mm and 21.0 mm respectively. Biometrics made possible the reconstruction of the structures to get the position of the centre of mass showing it was displaced just 0.72 mm of the ideal position. Those measurements helped to identify that the device should have a support length of 12.57 mm and a maximum weight of 17.87 g. Additionally, the device should resist an average environmental temperature of 19.09^oC, had to be water-resistant along the time and should work on flat and curved surfaces (25.4 mm diameter). The toucan has a total mass of 584.5 g, and the load distribution identified with the force sensor was 62.3% (364.3 g) on the amputated limb and 37.7% (220.1 g) on the gripped limb. The force ejected by the flexor tendon of the left pelvic limb at tarsometatarsus level was 4.42 N with an angle of 28.9^o on flat surfaces and -7.43 N with an angle of -16.73^o on 25.4 mm diameter surfaces.

The selected designs for each component have their own advantages, those alternatives were built as 3D models in the detailed design phase in SolidWorks CAD software. The whole device was constructed as a dynamic prosthesis with one degree of freedom joint on the transverse axis and two support positions: flat and curve. PET-G was the selected material to construct the main parts using a 3D printer and stainless steel and aluminium for the union parts. Additionally, the liner was made of platinum silicone PlatSil Gel-00, shore OO30 rubber. Finite element analysis was carried out for the device, this guaranteed the necessary stiffness and mechanical support of the model for the required application, obtaining that the major strain was 0.05 and the major displacement was 0.34, both in the socket component.

The designed device tries to imitate the natural anatomical joint, in this way, this prototype satisfies the lateral restrictions and the restricted angular displacement with a 1^o of freedom joint on the transverse axis, as can be seen in the figure 4, with movement on the sagittal plane and specific range of movement that change according to the surfaces. This is a dynamic prosthesis that can adjust itself to flat and curved surfaces with mechanical activation through a pair of levers and a mass-spring system.

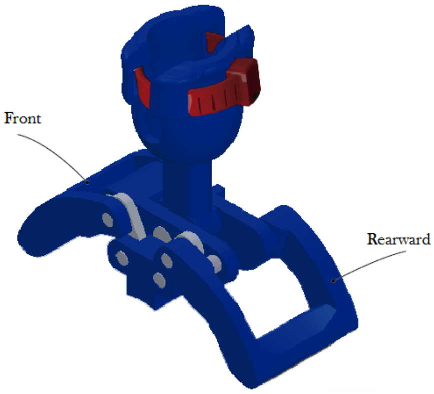

Fig. 4. Prototype CAD design.

The device has two support positions, which works according to the allowed movements and displacements like the real joint. When the device is in the open position, its arms, which simulate the digits, are open and the activator mechanism is blocked due to it is not in contact with any surface, and the lower face of the arms are supporting the normal force (N). In this position, the compression spring is in its natural position keeping the levers in their initial state; the joint has a range of movement of 90^o as can be seen in Figure 5, from the socket situated at 90^o perpendicular to the horizontal, to 180^o with the socket located parallel to the horizontal.

When the device is in the closed position, its arms, are closed until 25.4 mm diameter and the activator mechanism is active because it gets in touch with the curved surface, supporting there the normal force (N). This, makes the arms rotate on their axis due to the movement of the levers and the compression spring gets on a tension state; the joint has a range of movement of 110^o as can be seen in Figure 6, from the socket situated at 90^o perpendicular

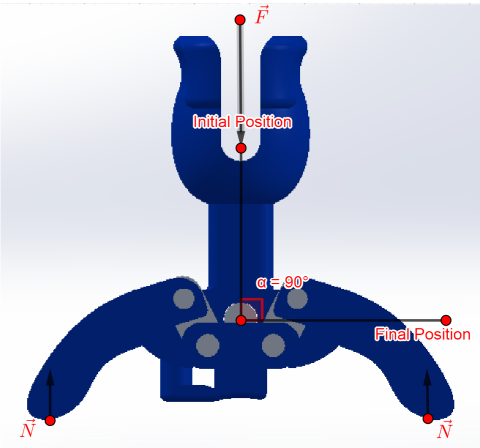

Fig. 5. Open support position of the prototype.

to the horizontal, to 200^o with the socket under the horizontal.

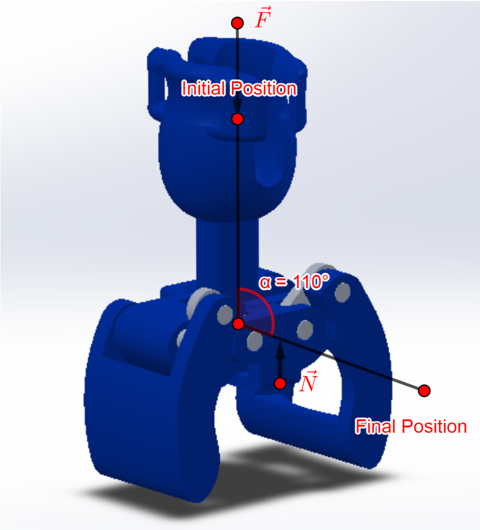

Fig. 6. Closed support position of the prototype.

For the implementation of the prosthesis, the operating conditioning protocol was used. It consists of four steps: positive association, follow up target, towel subjection and desensitisation. After completing them, was possible to place the liner on the stump and finally, the prosthesis as could be seen in the Fig.7. During the assembly and the implementation process was established that there were necessary changes to be made in the prototype design, so the redesign process was made, and also the liner material was changed to platinum silicone PlatSil Gel-10, shore A10 rubber.

IV. CONCLUSIONS AND FUTURE WORK

The results of the different processes in the biomechanical study showed the adaptation by the specimen to the amputation keeping the equilibrium and carrying out its activities without major problems.

(a) Final prototype.

(b) Toucan using the final prototype.

Fig. 7. Prosthesis device prototype

Prototype dynamic features tried to resemble the movements of the natural joint and grip mechanism, looking for allowing the toucan to carry out its activities with the greatest possible fluency and keeping the most of the time the natural biomechanical position, according to the habitat features too.

Methodologies taken from different fields of science and medicine were integrated to generate advances about the creation of veterinary orthopaedics assistance devices, been able to be implemented in pets and wild animals under human care because it takes into account all the context of the patient to generate the design of a product that is adapted to the patient needs.

Future work will evidence if the proposed prosthetic design generates positive changes in the animal biomechanics. It will be done by comparing the biomechanical data after the adaptation phase with the results of the biomechanical analysis applied previously.

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