# Design Modeling and Optimization of a Passive Lower-Limb Exoskeleton

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**Abstract**
The aim of this project is to design a belt that can be comfortably adjusted to the human body and that can support the loads that an already designed exoskeleton applies to this belt.
For this study, the contributions of the exoskeleton to the belt are introduced and studied, and FEM simulations are carried out in Ansys. With these results, the contact zone between the belt and the human body, and between the belt and the exoskeleton, are studied again.
With the new results, a new simulation is carried out, to which an optimisation process is applied using the Structural Optimization tool in Ansys, thus arriving at a final geometry that is well adjusted to the human body. With this final geometry, a new simulation is carried out with the PLA material, with which the prototype is going to be produced, and additionally, a simulation is carried out in Ansys ACP to study how the structure made with composite materials behaves.

**Keywords:** belt, exoskeleton, FEM, Ansys, Optimization, PLA, composite material

## 1. Introduction

Apart from diseases, there are additional significant dysfunctions such as spinal cord damage, degradation of musculature, osteoporosis, and other injuries which may require the patient to receive plenty of rehabilitation sessions in order to regain natural movement. In order to solve these problems, exoskeletons are present in the health sector.

Exoskeletons could be defined as wearable robotics mechanisms for providing mobility. In the previous six decades they have become popular due to an interest in enhancing physical performance. In addition, exoskeletons not only serve to improve the capacity of the wearer, but also to recover this motor capacity that has been lost or reduced, these are the rehabilitation exoskeletons.

Several classifications of exoskeleton categories can be performed, however, in this project the group formation criteria are depending on the part of the body the exoskeleton supports, main application of the exoskeleton, usage of power, and system containment [1]. In this case, and following in order the list of criteria previously mentioned, the focus of this project is a lower-limb, rehabilitation, passive, and autonomous exoskeleton.

Cognitive, sensory deficits or injuries due to falls or crashes, damage the nervous system and have as a consequence the loss of motion ability. It is well known that the nervous system cannot be recovered or restored, however, due to its plasticity, it is possible to find an alternative neuron path [1]. The main use of passive exoskeletons is to compensate for the effects of gravitational forces and inertia in the walking process without using motors [2].

Once defined the target exoskeleton, some requirements for its design must be fulfilled. These requirements are based on professional opinion of health professionals in the Aalborg University Hospital (AUH): human performance enhancement, low independence, natural interface, long life, comfortable, lightweight, reduced volume, proper safety, and aesthetic and easy of use.

## 2. Problem Analysis

Regarding mechanical design in the healthcare field, it should be borne in mind that the design is individual. Therefore, it should be noted that the design proposed in this project is only valid for a particular type of hip, and adjustable to similar types of hip.

Also, when defining the problem, it should be taken into account that the design of the belt is made for one of the phases of the entire gait cycle, considering mid-phase as the critical one. All the cycle is defined in Fig. 1.

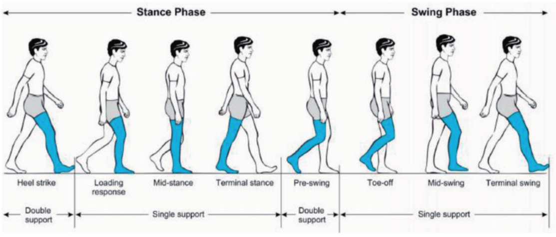


**Fig. 1** Phases of the gait cycle.

This project continues the work done in [2], where a lower-limb passive exoskeleton is manufactured. The objective of this project is to design a belt that can withstand the loads induced by the exoskeleton shown in Fig. 2.

Regarding the belt's design, information needs to be gathered. For this purpose the database of The Anthropometric Survey of US Army Personnel (ANSUR II) [3] is selected which consists of measurements of various variables of the human body, bending the hip of 6000 USA soldiers.

**Fig. 2** Lower-limb exoskeleton [2]

## 3. Problem Statement

In order to consider all the forces applied to the belt, all the contributions of the exoskeleton to the belt via the link between these two bodies must first be measured. As can be seen in Fig. 2, each of the joints is modelled as a pulley system, which means that the torque induced by each joint will be an impulse, i.e. it is a rather short signal with a large magnitude. These contributions are a torque of $15700Nmm$ as a contribution from the hip joint and $8833Nmm$ from the knee joint [2]. The weight of all elements of the exoskeleton is also considered in Eq. 1

$$F_{total} = (m_{knee} + m_{hip} + m_{attachment})\, g = 14.44N \tag{1}$$

In the case of loads, an adjustment pressure is also considered, which is the pressure applied by the body to the internal wall of the belt and has a value of $10N/m^2$ [4]. Forces of a maximum of $50N$ in each of the belt handle are introduced. Applying more than this force could have implications for the integrity of the patient, for example, subjecting oneself to a higher force for a prolonged period of time can cause ulcers [5].

The initial geometry is considered to be that corresponding to an ellipse shape Eq. 2, centred at the origin and with semi-axis $a$ the semi-major axis and $b$ the semi-minor axis, whose values are 158 and 113 mm respectively.

$$1 = \frac{(x - x_0)^2}{a^2} + \frac{(y - y_0)^2}{b^2} \tag{2}$$

Therefore, the initial geometry is shown in Fig. 3, and for the simulation is subjected to the above mentioned boundary conditions. Additionally, the contact between the hip and the belt is modelled as fixed support at two vertical surfaces close to the handles. The last boundary condition is to consider the attachment between the exoskeleton and the belt in a surface at the bottom of the belt.

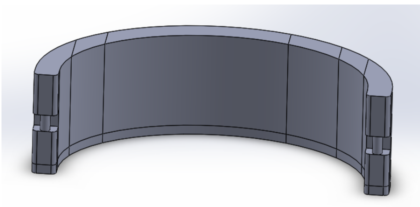

**Fig. 3** Initial geometry of one part of the belt

The results obtained from the simulation were lower tan expected. Thus, it is considered that both the way in which the contact between the body and the belt is modelled and the way in which the belt is connected to the exoskeleton need to be improved.

## 4. Composite Materials

Theory of composite materials is introduced as from this point. Decisions and assumptions are made considering the influence of this type of materials.

In the field of mechanical engineering and structural design, the use of metallic materials is very common. Its use is linked to the integrity it gives to the structure, its behaviour within the structure, the price and the availability of the material. However, increasingly it is common to see designs with composite materials such as carbon fibre. The reason for using composite materials in this type of structure is that the structure's integrity is less compromised while providing better performance, in other words, reducing the weight of the structure while increasing its strength. This is quite important in the case of exoskeletons as it may be necessary to transmit a large torque in the use of these structures for rehabilitation.

One of the most promising methods of manufacturing composite materials is 3D printing, which is an added substance producing technique for creating complex designs produced using composite materials. The strategy consists of printing layers on top of one another. The scope of materials utilized and created is really wide.

The theory on which the other composite theories are based is the Laminate Theory [6]. A lamina is a solitary layer, which can either be comprised of a homogeneous or a heterogeneous material. A few laminae can develop a composite plate or shell. With different overlay hypotheses, the thought is to display a cover comprising of a few laminae as one statically Equivalent Single Layer (ESL), in which all laminae are expected to be impeccably reinforced. A very important consideration for composite materials is that two coordinate systems must be declared, the global coordinate system of the structure with subscripts $\{xyz\}$, and the material's own coordinate system with subscripts $\{123\}$. In Eq. 3 the relation between stresses and strains in each coordinate system, being $T$ a rotation matrix, is shown.

$$\begin{gathered} \begin{Bmatrix} \sigma_1 \\ \sigma_2 \\ \tau_{12} \end{Bmatrix} = [T] \begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} \\ \begin{Bmatrix} \epsilon_1 \\ \epsilon_2 \\ \gamma_{12} \end{Bmatrix} = [T]^{-1} \begin{Bmatrix} \epsilon_x \\ \epsilon_y \\ \gamma_{xy} \end{Bmatrix} \end{gathered} \tag{3}$$

However, First-Order Shear Deformation (FSDT) theory is used. FSDT theory is opposite to Classical Laminate Theory (CLT) regarding kinematic assumptions, it is due to in FSDT the transverse normal forces are allowed to rotate. Also it is expected, that no longitudinal distortion is happening in the cross-over heading. Besides the relocations should be little contrasted with the plate thickness, hence the strains should be little contrasted with unity. The reason to use FSDT theory is that it is well-suited for designing the belt. CLT theory is applied in order to analyze thin plates, however, FSDT theory could be applied to shells, sandwich structures, and thin to moderate thick plates, which is the case of the exoskeleton belt.

Composite material design must not be done as if these were metallic structures because composite materials do not have an isotropic behaviour. A consequence of this is that the failures of these types of materials are varied and different from those of isotropic materials. The main failure modes are interlaminar failure due to failure of the matrix material in the layer, itralaminar failure when the fibres of the layer fail, and fracture interaction failure which is a combination of the previous two. Plenty of criteria are defined and used, in this project only one of them is considered [7].

### 4.1 Tsai-Wu Criterion

The generic formula of this criterion is as follows:

$$F_i\sigma_i + F_{ij}\sigma_i\sigma_j \leq 1 \quad i,j = 1,2,...,6 \tag{4}$$

Where each $F_i$ and $F_{ii}$ is a coefficient which depends on the strength of the material on each direction.

The reasons why this method is chosen for the analysis are that being a quadratic criterion it fits better to the experimental results, and because this criterion takes into account the interactions between plies [8]. The accuracy of this method lies in the $F_{12}$ coefficient, which is hard to measure experimentally as it belongs to a biaxial state of stress, therefore the reference value in Ansys is used [9].

The effects that differentiate composite materials from isotropic elements must be taken into account. One of the most important effects is the coupling between the stresses in the material and their associated deformations. By designing a symmetric laminate the bending-extension effect can be eliminated. In addition, applying this symmetry will also eliminate the bending-twisting effect.

Create a balanced laminate in order to avoid shear-extension coupling effect. For this reason it is necessary to put for each layer in the upper half of the laminate, the same layer in the same position in the lower half but with the opposite direction of the fibres.

## 5. Manufacturing

Two materials are available in order to manufacture the exoskeleton belt:

- Comfil polyethylene terephthalate modified (LPET) carbon reinforced.
- Polylactic acid (PLA).

### 5.1 LPET-Carbon Material

In the case of composite material, it is a material with carbon fibre reinforcement and a matrix of LPET, which is a PET plastic with modifications in some characteristics. The material is balanced and has a total thickness of 0.7 mm. The company COMFIL is in charge of supply. It is a balanced material, then the effect of extension-shear coupling is eliminated. However, the placement angles will be taken as ideal, as a small deviation can cause warpage in thin laminates, or the appearance of residual stresses in the thickness of the material.

The supplier provides the following properties of mechanical testing on a sheet following ISO 527-4 regulation:

**Tab. I** Properties of Carbon-LPET material

| | 0º direction | 90º direction |
|---|---|---|
| **Tensile Strength (MPa)** | 587 | - |
| **Tensile Modulus (MPa)** | 50 | 40 |
| **Tensile Strain (%)** | 1.25 | 1.25 |

COMFIL provides a standard procedure to manufacture a piece with its material. A brief outline is done in this paper, but the entire method is stated in [10].

- Prepare the plaster.
- Make the lay-up applying PET cover.
- Trim lines and grind.
- Preparation and consolidation, i.e. release film, apply silicone sheeting, put the piece into a high temperature vacuum bag, and consolidation in oven for 30-45 minutes at 218.33ºC.
- Cooling down

### 5.2 PLA Material

PLA is a thermoplastic biopolymer widely used for the manufacture of suture thread, implants, prostheses and packaging. The properties of this material can be altered by molecular weight modification and mixtures between isomers. One of the properties that give PLA a great potential for use in 3D printing is that this material deforms from 60-70ºC, and it is very ductile.

**Tab. II** Mechanical properties of PLA [11]

| | Values |
|---|---|
| **Tensile Strength (MPa)** | 59 |
| **Elongation at break (%)** | 7 |
| **Elastic modulus (MPa)** | 3500 |
| **Shear modulus (MPa)** | 1287 |
| **Poisson's ratio** | 0.36 |
| **Yield strength (MPa)** | 70 |
| **Flexural strength (MPa)** | 106 |
| **Ultimate tensile strength (MPa)** | 73 |
| **Percent of elongation (%)** | 11.3 |
| **Young's modulus (MPa)** | 1280 |

Its properties imply it is easy to print, as well as having a good finished printed product. Mechanically, this is significant, as it means no more stress concentrators. The method used to create a part with PLA is fused deposition modelling. This method is suitable for prototyping and small-scale production.

### 5.3 Resources study

Once the manufacturing processes have been defined for each of the materials, a study is made of the resources needed to create the part. When manufacturing the part with composite materials, the operator must be paid to make the mould, necessary to create the belt. Two solutions for the production of the mould are also studied, either in steel or in aluminium.

In Tab. III the resources needed for each method are shown. Therefore, as the price difference between manufacturing with composite material or with PLA is really huge, and the dimensions of the model are critical, it is decided to produce the belt with PLA, i.e. produce a prototype of the belt.

**Tab. III** Price of manufacturing processes.

| Method | Price (DKK) |
|---|---|
| **Comfil Method + Aluminum Mold** | 4260 |
| **Comfil Method + Aluminum Mold** | 5948.7 |
| **3D Printing (PLA)** | 400 |

## 6. Optimization

Optimization is the process of solving a problem in the most efficient way, i.e. using the minimum amount of resources necessary to obtain a solution. Optimization can also consist of finding the best solution by fixing the number of resources. In general, it is said that by applying optimization to a process, an optimal solution of this process or problem can be obtained [12].

Any optimization model must have three basic elements that make up the structure of each of these models. These elements are the variables, the objective function or functions, and the constraints of the model. A general problem could be presented as follows:

$$\begin{aligned} Find\,the\,optimum\,of\,:& \\ Objective\,function\,:\; z = f(x_1, x_2, ..., x_n)& \\ Subjected\,to\,the\,following\,constraints\,:& \\ g_1(x_1, x_2, ..., x_n) \leq b_1& \\ h_1(x_1, x_2, ..., x_n) = t_k& \\ Variables\,:\; x_1, x_2, ..., x_n \in \Re& \end{aligned} \tag{5}$$

In this project, it has been decided to apply optimisation tools to achieve the essential requirement for a passive exoskeleton to have the lowest possible weight. The weight is influenced by the number of layers, the more layers, the more weight. As well as by the orientation of the layers, since a good orientation of each layer means a reduction in the number of plates to be used. Finally, weight is influenced by the material and its mechanical properties, and by the geometry of the design.

Topological optimization is chosen for this project because of its speed. It is also a tool that is widely used in industry, which is both effective and fast, and which provides fairly good results. Although they must be re-interpreted with engineering judgement as it does not take into account various mechanical considerations, e.g. stress concentrators.

In order to apply topological optimization, several considerations must be taken [13]:

- Dissipative effects are not considered. All energetic considerations are within the linear theory of elasticity.
- The temperature does not affect the deformation.
- The process is quasi-static.
- It is considered mass conservation, and the volumetric forces are equal between the deformed and non-deformed body.

Additionally, considerations about mechanical behaviour [13]:

- Conditions of equilibrium

$$\sigma_{ij,j} + f^i = 0 \tag{6}$$

- Strain-displacement relations

$$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \tag{7}$$

- Constitutive relations

$$\sigma_{ij} = E_{ijkl}\varepsilon_{kl} \tag{8}$$

$$\varepsilon_{ij} = C_{ijkl}\sigma_{kl} \tag{9}$$

Where $\sigma_{ij}$ is the stress tensor, $f^i$ are volume forces, $\varepsilon_{ij}$ is the strain tensor, $u_i$ is the displacement vector, $E_{ijkl}$ is the elasticity tensor, and $C_{ijkl}$ the compliance tensor, which yields the inverse of elasticity tensor.

Once considerations taken in order to apply topological optimization are presented, they must be related to the finite element method. The main objective, when designing a structure mechanically, is to achieve maximum stiffness. This is the same as designing minimizing compliance. All of this is equivalent to changing the objective function for the total elastic energy, and thus minimizing it [13].

By discretizing the structure in N nodes and getting all the displacement of each of the degrees of freedom of each node, the following formula yields:

$$\prod = U - W \;= \frac{1}{2}d^T K d - r^T d \tag{10}$$

Where $K$ is the stiffness matrix, $d$ is the global displacement vector, and $r$ is the load vector. Then, the problem is to minimize the objective function $W(d)$ and the main restriction is $Kd = r$.

As mentioned, the use of the topological optimization tool has been chosen due to its speed and consistency in FEM (finite element method). Ansys Workbench is used as the program to perform topological optimization simulations with its Structural Optimization module.

There are four existing methods in Ansys for performing structural optimization: Density and Level Set based methods are used for topology optimization, Morphing method is a node-based optimization process, and Lattice Optimization method enables to create lighter parts using lattice structures with optimized graded density.

The most important consideration which must be accounted for is that all optimization methods result in a shape that respects the boundary conditions, that is, if a face or a surface has a boundary condition, the shape will not change there.

Among the three methods explained, the density-based method is selected, as moderate changes in the geometry of the result are expected. The Morphing method, although quite refined geometries with quite smooth edges are obtained as a result, does not practically change the initial shape. Both the density-based and the level-set based methods provide interesting results. In addition, when minimizing either compliance or mass, the density-based method is the one that provides reasonable continuum shapes. Level-set based method provides shapes with discontinuities.

### 7. Model Refinement

The aim of this project is to design a belt that is as optimised as possible in terms of mechanical and health-related design criteria, such as comfort and safety. The model is therefore being redefined in an attempt to bring it as close to reality as possible. This means that certain boundary conditions and geometries mentioned above will change.

The first consideration is the form of interaction between the belt and the exoskeleton. This is because the contact surface in the initial simulation was too small, meaning a high concentration of stresses, and there was also the possibility of the seal coming into contact with the human body underneath the belt, which would cause discomfort to the wearer. It is therefore defined that contact is made in the middle, both vertically and horizontally, of the outer face of the belt as shown in Fig. 4.

**Fig. 4** Position between the link and the belt.

The second consideration is motivated by the poor interaction between the human body and the belt designed for the first simulation. In Fig. 5 you can see how the depth of the hip does not really fit the model. This model, although fixed in this dimension, represents a realistic measurement in the population. Thus, a change in the reference geometry is made from a semi-major axis of $158mm.$ to $135mm.$

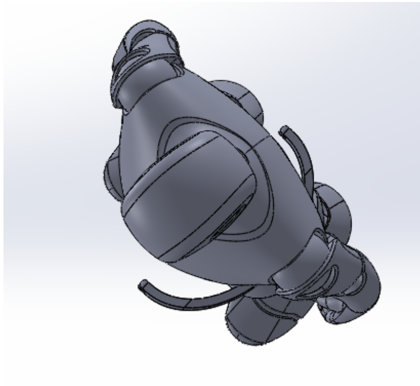

**Fig. 5** Interaction between belt and mannequin.

With these considerations in mind, the model is reformulated again. However, two new models are presented. Almost all the boundary conditions between these models are the same, however, the contact between body and belt is changed.

The first model is called the line contact model. It has a mass reduction of 43%. The material near the belt handles is significantly reduced, which leads to a high concentration of stress at these points. In general, the depth of the material does not change much along the entire belt curve, however, near the contact surface of the belt and exoskeleton, where the loads are applied, the depth is reduced, which leads to the appearance of stress concentrators.

The second model is called the surface contact model. It has a mass reduction of 40%. The material close to the belt handles is not so reduced and has a shape that makes it more robust. The depth reduction in the belt curve is fairly constant so in terms of manufacturing it is much easier to create. In addition, the optimised result looks quite symmetrical from a plane that splits the part horizontally in two, which makes it easier to study and manufacture.

Regarding the line contact model, it provides higher stresses than the surface contact model the affected area, in terms of stress, in the line contact model is larger. On its own, this last statement does not have much meaning as the real-life behaviour may still differ a lot, however, it can be said that a very localised stress zone, such as that of the surface contact model, is worse in terms of stress concentration.

On the other hand, as for the physical considerations of contact, if the movement of the belt at the hip due to the gait cycle is taken into account, it seems incorrect to reduce the contact to just one line. Similarly, having two surfaces above and below the area that is permanently in contact with the hip, and to which constant pressure is applied, seems more accurate in terms of physical modelling. As stated in previous chapters, one of the reasons for using the fixed support condition is to try to model the action of the frictional force between the hip and the belt. This prevents the belt from moving both horizontally and vertically. Furthermore, as also mentioned above, this friction force is constantly changing direction due to the motion of the human body.

Therefore, the boundary conditions of the model and the optimized shape that work with in the final design, are the ones corresponding to the surface contact model. The arguments from the physical point of view, with the friction force approximation discussed above, and the interpretation of the results produced by the optimization tool, lead to this model being chosen. Furthermore, one of the most important factors is that the optimized surface contact model results in a shape that is easier to fabricate.

## 8. Final Design

The results of the simulation called surface contact simulation, made with PLA as the base material of the part, are exported and used as input to the topological optimization module, leaving a shape like the view in Fig. 6.

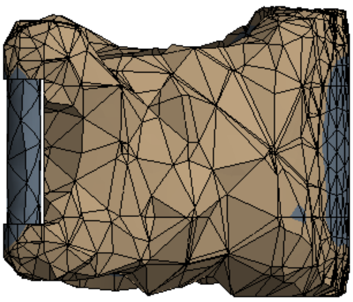

**Fig. 6** Lateral view optimized shape.

However, this figure is not suitable for manufacturing, and as mentioned above, the result of optimization should be reapplied certain design criteria to soften the shape. In this case it is designed taking into account a constant thickness of the part for easier manufacturing, the largest possible contact area between belt and exoskeleton, and the smallest reduction of material near the belt handles. The result is the final geometry shown in Fig. 7.

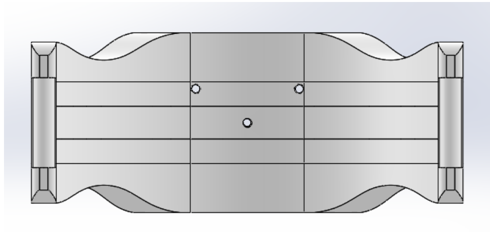

**Fig. 7** Front view of final geometry.

Once the final geometry is obtained, two simulations are carried out, each of them with one of the materials available for the design, although it will eventually be produced with PLA.

### 8.1 LPET-Carbon Final Simulation

This simulation is carried out using Ansys Mechanical Composite PrePost (Ansys ACP) module of Ansys Workbench. Several steps must be followed in order to define the composite material:

- Define what material is going to be used.
- Create the material with its depth. At this point it can already be called ply ($0.175mm$).
- Define the stackup following the plies, in this case 0/90/0/-90 as it is balanced (total thickness $0.7mm$).
- The rosettes to be used to declare the main directions of the material are defined.
- An oriented selection set is created based on the direction of the rosettes. The plies will be stacked in that direction.
- Up to this point it would be enough if you wanted to define a Shell element, however, for thick composite structures, the plane-stress assumption of Shell elements no longer holds true and it is needed to move solid elements for accurate representation [8]. Therefore, finally, the option of "solid model" is used, it indicates the direction in which you want to extrude and the type of extrusion, in this case Analysis Ply wise because you can analyze each of the plies.

When ACP Pre module is connected to a static structural analysis, failure criteria belonging to composite materials can be used. In this case the Tsai-Wu criterion is used. The results obtained are $0.008$ as average value and $0.43$ as maximum value of the inverse reserve factor. This means that if it does not reach 1, the zone is free of failure. In this case, the most compromised area is that of the main union between exoskeleton and belt.

### 8.2 PLA Final Simulation

This simulation has the same boundary conditions as the surface contact simulation, however, the contact between belt and exoskeleton is reduced instead of a surface, to the three holes of the belt as seen in Fig. 8.

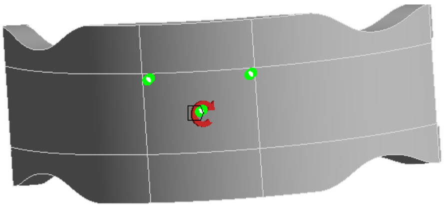

**Fig. 8** Model of the contact between belt and exoskeleton.

In this case, it is sufficient to use the static analysis module in Ansys as the plastic behaves like an isotropic material. Analyzing the maximum stress of this simulation, this occurs in the central drill, having a value of $10.874MPa$, which being less than $70MPa$ that is the yield strength of the PLA, ensures that there is no failure.

## 9. Results and Testing

Regarding the simulation with composite material, the stackup model of the fibres in ACP Pre seems to be correct, however, it must be considered that the manual placement of each of the layers is a job that must be quite precise. Similarly, the results provided in this simulation indicate that the structure does not fail, i.e. it has an Inverse Reserve Factor less than one. However, the final design of the belt with composite material is not fully taken into account, i.e. the simulation is performed with a geometry optimized for isotropic materials, therefore, it is considered that a large uncertainty must be taken into account in this model.

As for the simulation with PLA the maximum equivalent Von Mises stress occurs in the central hole of the joint with the exoskeleton, and its value is $11.847MPa$, the yield strength of the PLA is $70MPa$, so it is in a safe zone at all times, i.e. failure of the structure is not expected at any time.

However, due to the complexity of the load case due to the movement of the human body, and therefore the change in the direction of the loads, the model must be validated with a prototype belt.

In order to validate the model made for PLA simulation, the exoskeleton is mounted on the belts as indicated in Fig. 9. Once the mounting is done, testing with the belt and the exoskeleton is performed doing daily movements as sitting and walking as shown in Fig. 10 and Fig. 11.

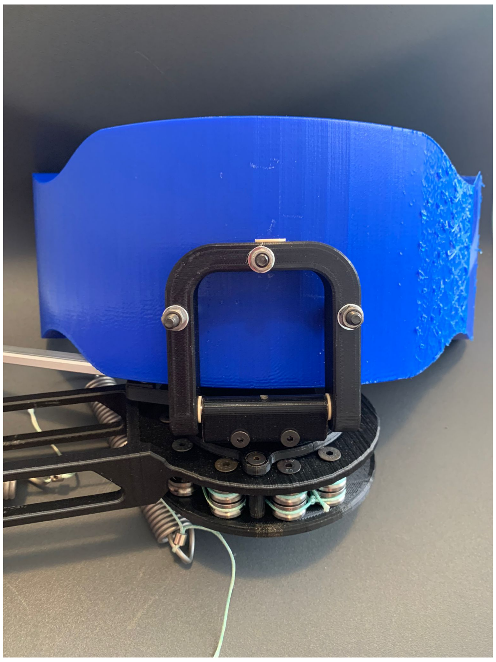

**Fig. 9** Attachment between belt and exoskeleton.

**Fig. 10** Test of sitting.


**Fig. 11** Test of walking.

As for the results of these tests, the belt not only did not fail but it did not move much during the experiment, i.e. it was well secured. The belt was not designed for the dimensions of the user who experienced it, however, it had a great performance.

A result of the experiment it is also extracted that the feeling between the belt and the human body is not uncomfortable. However, it could be improved by using some softer surface between hip and belt, so that it is in contact with a more spongy surface and also fills the possible gap between body and belt.

## 10. Conclusion

The use of exoskeletons in the medical field is widespread as the benefits that these mechanisms can bring to the rehabilitation process can be very good. Also, the use of passive exoskeletons with low weight, which can be portable, helps the patient's improvement process.

Several considerations have been taken into account in this project on the design of the composite belt, ending with a simulation in Ansys ACP which results in the belt not failing according to the Tsai-Wu criterion. However, due to the uncertainty of the dimensions of the belt, and the price of producing it in composite material, it was decided to make a prototype in PLA.

This prototype, apart from being cheap, is very light, thus fulfilling two of the initial requirements, namely cost and weight reduction. The functions of this prototype are twofold: to validate that the dimensions taken in the final geometry are correct, and to validate the simulation model made with PLA. This plastic simulation ensures that the belt does not break.

Once the belt has been produced, it is tested by being mounted next to the exoskeleton of the lower body. These tests conclude that the belt works well and that it is comfortable to a certain degree to wear while making basic movements such as walking and sitting.

The mathematical and physical models used in this project consider a static case, i.e. a static position of the user is assumed throughout the gait cycle. With a static model it is not possible to define the problem completely, i.e. a dynamic model is needed, simulating the whole gait cycle to ensure that the belt does not fail. Therefore, even if the belt does not fail in the simulations and tests considered in this work, more extreme scenarios such as jumps and falls that compromise the integrity of the exoskeleton must be considered in order to ensure that the belt does not fail.

In addition, a finer model of the contact between the human body and the belt is necessary in order to perfectly model the optimal shape of the belt. However, as the body moves, the contact moves, the frictional forces between the body and the belt change direction, and the case that was considered static changes completely. Therefore, the design that has been carried out in this project is very conservative to avoid failure due to these considerations. But again, it is necessary to analyze a dynamic model of the belt with the exoskeleton, interacting with the human body in each of its actions.

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