DEVELOPMENT OF A PNEUMATIC KNEE ORTHOSIS

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ABSTRACT

In this paper the design and the manufacture of a knee orthoses is presented. The orthoses is designed to help the elderly or disabled people to stand up and to sit down on a seat. The specifications of the orthoses’ design include the low weight, the small overall dimensions, and the possibility to be worn under the trousers. The orthoses uses two McKibben pneumatic muscle actuators as drivers. These actuators were modified inserting a spring to grow the traction force. The orthoses has been manufactured and some preliminary tests with a healthy person were carried out. The results are encouraging and suggest other work to optimize the device.

KEY WORDS

powered orthosis, design, pneumatic muscle, McKibben muscle

NOMENCLATURE

C : required torque at the knee level
a : length of the tibia in the sagittal plane
b : length of the femur in the sagittal plane
c : distance between the hip articulation and L3 in the sagittal plane
ΔL : shortening of the pneumatic muscle
θ : angle between the femur and the tibia in the sagittal plane

INTRODUCTION

For aged or disabled people often there is the need of a help for sitting down and standing up although they are able to maintain the gait for locomotion and to walk. Some authors proposed the use of armchairs with motorised folding seat able to hold up the body weight during the sitting down and standing up operations [1]. Although those devices work correctly, there is the need of a structured environment, with many of these devices, which is expensive to carry out. Moreover it is not possible to have many structured environments out of the domestic one. Another strategy is to use a motorised orthosis for the lower limb, which is able to assist the elderly people. In this case the orthosis has to respect some technical specifications such as low weight, low cost, high efficiency, and fast response; moreover has to be possible to hide the device under the trousers. To fit all these constraints the actuators that permit the movements play a major role in the developing of this orthosis. The Pneumatic Muscle actuator (PM) provides a good compliance and a high power-weight ratio. Furthermore, they are clean, have a low cost and are similar to the human muscles from the point of view of the traction force-shortness diagram. The first ideas of PM were...
patented in the 1950s. This PM, under the name of McKibben pneumatic muscle, was further developed in 1960s and following [2,3] for applications in artificial limb research. The McKibben PM consists of an internal bladder in rubber surrounded by a flexible sheathing formed from high strength fibres, which are attached at either end to fittings or to some tendon-like structures. Pressurising the internal bladder, the inner surface moves against the external shell, and tends to increase its volume. The PM shortens according to its volume increase, because of the high stiffness of the threads in the shell.

This paper explains the design of an orthosis for the knee articulation driven by PMs to assist elderly and disabled people during the standing up and the sitting down operations. In this paper the mechanical design, the manufacture of the prototype and the first experimental results are shown. The results are encouraging and push to work in this direction.

THE KNEE ORTHOSIS: DESIGN AND MANUFACTURE

The development of the knee orthosis follows these points: the design and the construction of the PMs, the validation tests of the PMs, the design and the construction of the orthosis and the first validation tests. The first point implies the modification of the design of the McKibben PM, by the insertion of a helicoidal spring to increase the traction force. Each head was modified to include a hole as connection with the end of the spring. The construction was made in our laboratory as for a standard McKibben PM [4]. The validation tests confirmed the design data. Two types of static tests were carried out: isometric (constant length) and isotonic (constant force).

The design of the orthosis was carried out following some assumptions:
- it shall be able to stand up a person of 75 kg;
- it can be worn under the trousers;
- it can be used both in a structured room and in open air;
- it doesn't interfere with ambulation (low weight, high efficiency, etc.).

These specifications give a chance to the design of an orthosis driven by PMs. In fact the PMs have some interesting characteristics that suggest their utilisation:
- high power-weight ratio;
- in open air the PMs can be fed by a little rechargeable tank having an autonomy of 5-6 operations;
- the diagram traction force-shortness of the PMs is very convenient for the desired traction force of the orthosis;
- their compliance agrees with applications in medical devices [6].

So the McKibben PMs were chosen as drivers of this device. In the following the design process will be described.

To calculate the driving torque that the orthosis have to supply, a simplified model of the human body was defined. The model uses rigid body dynamics and does not consider any biological muscle involvement. The unknown is the torque at the knee joint to stand up from a seat. This moment will be guaranteed by the orthosis. The human body model is a planar one, and is composed of three skeletal segments: the shank, the thigh and a part of the trunk. The classical assumptions were used for this model: all motion is in the sagittal plane, the segments are joined together by frictionless hinge joints, all the mass of the body, except that of the shank, is concentrated at the centre of the mass of the body. Moreover the observation of the strategy to stand up from a seat showed us that, for the equilibrium of the body, the skeletal segment of the shank maintains a quasi parallel position with the segment of the trunk. For this reason the assumption of the parallelism between these segments was assumed. The Fig. 1 shows the model of human body used, and the point of application of the load P, centre of the mass of the body. The angle \( \theta \) between the tibia and the femur changes from 70° (sitting position) to 175° (upright position). The length of the segments is assumed as follows: \( a = 418 \text{ mm} \), \( b = 428 \text{ mm} \), \( c = 214 \text{ mm} \).

![Figure 1. 3 segments model of the human body](image)

From the Fig. 1 these equations can be derived:

\[
\begin{align*}
    d & = \cos \alpha \\
    b \cdot \cos \beta - c \cdot \cos \alpha & = d \\
    \alpha + \beta & = \theta
\end{align*}
\]

and then a relation between the angle \( \theta \) and the distance \( d \):

\[
\theta = \arccos \left( \frac{d}{a} \right) + \arccos \left( \frac{d}{b} \left( 1 + \frac{c}{a} \right) \right)
\]

Finally the equation of the required torque \( C \) as a function of the angle \( \theta \) can be obtained:
The Fig. 2 shows the diagram of the required torque $C$ vs. the angle $\theta$ in our model.

\[
\phi = \text{inv} \cos \left( \frac{C}{P \cdot 4} \right) + \text{inv} \cos \left( \frac{C}{P \cdot b} \right) \left( 1 + \frac{C}{a} \right)
\]  

(3)

The Fig. 2 shows the diagram of the required torque $C$ vs. the angle $\theta$ in our model.

Considering that PMs are linear drivers, the relationships between the shortness $\Delta L$, the traction force $F$ and the arm of this force $f$ is calculated:

\[
\Delta L = l_{\text{max}} - 360 = \left( \frac{2 \cdot \pi \cdot f}{2 \cdot \pi} \right) \left( \frac{2 \cdot \pi \cdot f}{360} - \frac{2 \cdot \pi \cdot f}{360} \right)
\]

\[
\left[ \frac{F}{P} \cdot \frac{F}{P} \right] \left( \frac{F}{P} \cdot \frac{F}{P} \right) \left( \frac{F}{P} \cdot \frac{F}{P} \right)
\]

\[
\left[ \frac{F}{P} \cdot \frac{F}{P} \right] \left( \frac{F}{P} \cdot \frac{F}{P} \right) \left( \frac{F}{P} \cdot \frac{F}{P} \right)
\]

where $l_{\text{max}} = 82$ mm is the maximum shortness desired. This equation, showed as a diagram in the Fig. 3, has a trend similar to that of a PM. But for the purpose of a compact size of the orthosis both a big value of the force $F$ and a little value of the arm $f$ are required. So a modified version of the McKibben PM was designed and manufactured, as previously mentioned. To obtain greater values of the traction force of the PM and helicoidal spring was designed. It is linked to either end of the PM inside the camera. Both heads of the PM were modified to accept the spring. The main characteristics of the spring are:

- rest length = 122 mm
- working length = 221 mm
- stiffness = 2679 N/m

The PMs designed were manufactured and experimentally tested. The Fig. 3 shows the result of the tests for the spring and for the PM, with and without spring, compared with the desired diagram, equation 4. The Fig. 3 confirms the good agreement between the diagram of the PM with the spring and the required force diagram, equation 4.

The two PMs are fixed to the lower part of the orthosis, by one end of each muscle. The other end is linked to a cable, engaged on a pulley, which ends on the upper part just up the knee joint axes. The structural part is made by two lateral elements. Each lateral element is made essentially in 3 parts: a lower rod, an upper rod and the hinge joint. The rods are made by aluminium, while the hinge joint is made by steel. To permit the application to the lower limb, two shells in a thermosetting material are used to connect the two structural elements. The hinge joint is the most complex element of the orthosis for the geometry and the load condition. It was calculated by the Ansys code, a finite element (FE) program. In the Fig. 4 the deformation field of the lower part of the hinge joint is shown as output of the FE code.

The cable used to link the PMs to the upper element of the hinge joint is a steel-wire rope. It is made by a strand of a diameter of 1.7 mm and each yarn has a diameter of 0.3 mm. The pneumatic circuit is able to guarantee the knee torque during the stand up and the sit down operation. The different trend of the traction force is obtained by modifying the air pressure inside the PMs. The pneumatic circuit is reported in the Fig. 5. In this scheme both the
tank and the connection to the air supply are included. Anyway the tank is used only in open air, as air source, in absence of the compressed air line. A cylindrical tank having a volume of 2 dm³ gives autonomy for about 6 operations (air stored at 10 bar). It has approximately a diameter of 120 mm, a length of 300 mm and a mass of about 4 kg, with the air inside at 10 bar.

The manufacture of the components and the assembly of the prototype followed the design step and didn’t show any hard problem. A functional test was carried out to verify the behaviour of the orthosis with no patient. Finally some tests were conducted with a healthy person using the prototype on one of his leg, Fig. 6. These tests suggested some remarks:

- the traction force of the orthosis is big for an elderly person: his bones are brittle. So much attention has to be paid to the shape of the shells to spread the force on a wide area of the shank and of the thigh. Also the operative value of the knee torque that needs to stand up has to be evaluated, considering the residual capacity of the patient. The pressure in the circuit can be used easily to adjust the value of the torque;
- the prototype is too heavy to be a comfortable device to put on. It is necessary to design and manufacture the hinge joint in aluminium too. Anyhow a deeper study needs to reduce the total mass;
- the modality to supply power to the orthosis during the operation has to be studied with consideration. In fact the patient needs a soft power output, because of his precarious equilibrium.

CONCLUSIONS

This paper presents the development of a knee orthosis for elderly or disabled people. It is designed to help the standing up and the sitting down operations on a seat. The main characteristics of this design are the low weight and the small dimension, to permit a good ambulation and to be worn under the trousers. The orthoses uses the McKibben pneumatic muscle actuators as drivers. These actuators were modified inserting a spring to grow the traction force. The orthoses has been manufactured and some preliminary tests with a healthy person were carried out. The results are encouraging and suggest other work to optimize the device.

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