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Development of the production process of PPAM

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Abstract

This master thesis reports on the third generation of the Pleated Pneumatic Artificial Muscle (PPAM) which has been developed to simplify the production process of its former prototypes. This type of pneumatic actuator was conceived to overcome dry friction and material deformation which is present in the widely used McKibben type of pneumatic artificial muscle. The essence of the PPAM is its pleated structure which enables the muscle to work at low pressures and at large contractions. It is believed that PPAM is a valid alternative actuator for several applications, some that are still in a researching state and some others for which other PAM´s types have been already marketed. Its specific design presents interesting scientific aspects but entails a complex production process, which has been considered as its major disadvantage. Due to the long production time, it was impossible to respond to demands of other researchers to build muscles for them at a reasonable price.

During the development of the third generation the production process has been drastically simplified and the building time has been reduced to 2 hours, which represent a reduction of 75 % in regard to the previous one. Another interesting advantage of the new production process is its flexibility. As complex pleating gadgets are not needed, it is possible to build muscles with different characteristics in the same set-up. This new step was possible due to the use of Fused Deposition Modeling (FDM) rapid prototyping technology.

Contents

List of Figures

List of Tables

Chapter 1

1 Introduction

This master thesis is a study of the development of the new manufacturing process of Pleated Pneumatic Artificial Muscle. Due to the changes introduced in the production, the final design of the actuator has been also modified and it is considered the Third generation of this pneumatic actuator. The Pleated Pneumatic Artificial Muscle has been developed by the Multibody Mechanics Research Group of the Vrije Universiteit Brussel for a decade. It belongs to the class of Pneumatic Artificial Muscle (PAM). It was introduced by Daerden [1999] [1] to overcome some shortcomings of existing muscle models as the McKibben PAM, which is considered the leader of this type of actuator. PAMs are alternative pneumatic actuators, which have a better power to weight ratio than the cylinders. They are extremely lightweight because their core element is a membrane and they can transfer the same amount of energy as cylinders operating at the same conditions. As all the pneumatic devices, PAMs have an inherent compliant behaviour. The force developed by a pneumatic cylinder is only dependent on pressure while PAM´s force is also dependent on their state of contraction/inflation, which can be controlled by the gauge pressure. This is an important feature for a safe interaction between machine and human and, also it is needed when the machine has to operate delicately in order to handling of fragile objects [2].

During the conception of the Pleated PAM, the membrane layout was arranged into radially laid out folds that can unfurl free of radial stress when inflated. The lack of radial stress of the Pleated PAM avoids hysteresis and increases the actuator´s performance. Furthermore, this novel actuator has a maximal contraction range and enormous force output, which are its outstanding characteristics with regard to the other pneumatic artificial muscle types.

Due to these interesting charateristics, it is believed that PPAM is a valid alternative actuator for several applications, some that are still in a research state and some others for which other PAM´s types have been already marketed. The Multibody Mechanics Research Group of the VUB has been applying its own actuator in its research studies for the last years. It has been applied in a bipedal walking robot; in a robotic arm for direct human assistance; in rehabilitation, in order to design suitable protheses and orthoses; and in architecture, in adaptable tensile membrane structures. Figure 1.1 shows photographs of some PPAM´s aplications.

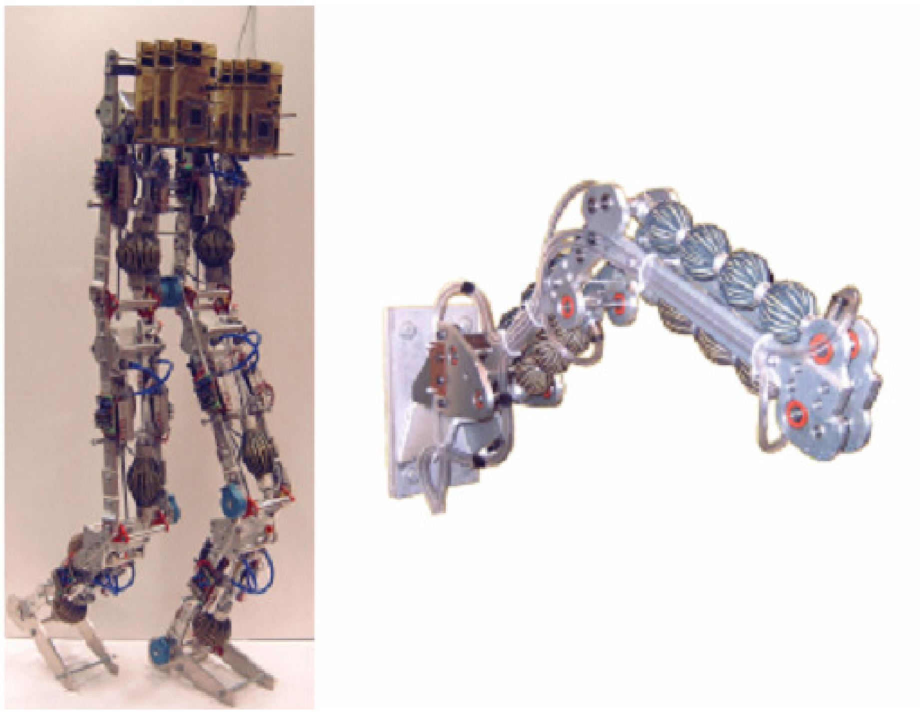

Figure 1.1: Photographs of Lucy (bipedal walking robot) and Soft Arm (robotic arm for direct human assistance) [3]

Although the first generation of PPAM, which was developed by Daerden, presents interesting scientific aspects, as maximal forces, its prototype needed a very complex manufacturing process that entails a insufficient lifespan. Considering this actuator for a bipedal walking robot (Lucy), the second generation of PPAM was introduced by Verrelst [2005] [4]. The muscle´s membrane was adapted in order to extend its lifespan and to simplify the construction of the muscles. The good results obtained by the second generation (PPAM 2.0) validate its especific membrane design, in which the membrane can be devided into two main parts: the pleated airtight fabric and the high tensile fibres. Its fabrication process was changed completely. It was based on separated high tensile fibres instead of a flat woven high tensile fabric. However, it was still too much complex causing failure muscles and slowing the research down.

The third generation of PPAM (PPAM 3.0) has been developed in order to simplify the manufacturing process and to avoid failure muscles. This new step was partialy promoted by the accesibility of a Fused Deposition Modeling (FDM) rapid prototyping machine, which can be used to make complex and lightweight parts at a reasonable price. Due to it, the end fittings can be drastically improved making possible the fabrication of slenderer muscles. These more complex end closures can also be used at the production process of the muscle. During the development of PPAM 3.0 the mathematical model of the previous generation has been assumed, therefore, the theoretical composition of the muscle´s membrane has been maintained.

In order to validate the new generation, some tension tests are performed to compare the prototypes performance with the mathematical model of developed force equation. Muscles made with different number of pleats are tested on different trajectories at isobaric conditions.

Chapter 2

2 Pneumatic Artificial Muscles

This chapter gives a general study of Pneumatic Artificial Muscles based on the work of Daerden [1]. It serves as a theoretical introduction to their properties, which are completely applicable to the specific PAM type studied in this thesis, the Pleated PAM.

2.1 Definition, concept and operation.

A Pneumatic Artificial Muscle (PAM) is a contractile device wich is operated by pressurized gas. The actuator´s core element is a reinforced closed membrane attached at both ends to fittings. When it is inflated with pressurized gas, usually air, it expands radially and contracts axially generating a uni-directional pulling force along the longitudinal axis.

A PAM is powered by the pressure difference between the inside gas and the surroundings. PAMs have a limited pressure difference across the shell due to the limited material strength. These typical values range at about 500 to 800 kPa. The gas is forced into it or extracted out of it changing the inside pressure and/or the volume and actuator lenght according to the adecuated pulling force which has to be generated to get the equilibrium.

For a better understanding it is made a diferential study of the process. During a time interval dt, an infinitesimal mass dm of gas is forced into the muscle, which is at a relative pressure of $p = P - P_0$. Therefore, the membrane´s volume increases dV and an amount of work (dW_m) is fed into the muscle

$$dW_m = pdV \qquad \text{Eq 2.1}$$

During the same dt, the lenght of the muscle changes by dl displacing a load F over the same diferential distance requering an amount of work

$$dW_l = -pdl \qquad \text{Eq 2.2}$$

Neglecting the membrane´s material deformation and the low inertial muscle properties, the amount of work fed to the muscle (dW_m) and the one which is requiered to displace the load (dW_l) are equal. Due to it, the generated pulling force is expressed as [Chou and Hannaford, 1996; Daerden, 1999]:

$$F = -p\frac{dV}{dl} \qquad \text{Eq 2.3}$$

By a basic analysis of this expression it is possible to get some important ideas of PAM´s operation: 1..The generated force is directly proportonial to the relative pressure inside the muscle. 2..The generated force also depends on the variation of volume with regard to lenght. If the PAM operates at an overpressure (p>0), the volume of the actuator increases with decreasing lenght (and viceversa) (dV/dl<0) until a maximum volume is reached.

Comparing the PAM´s force-lenght expression (Eq.2.3) to that of standard pneumatic cylinders, it is possible to name ($-dV/dl$) as the actuator "effective area" [Paynter, 1988]. A cylinder develops a force which depends only on the pressure and the piston surface area so that at a constant pressure, it will be constant regardless of the displacement. The main difference between PAM´s and standard pneumatic cylinders is that the effective area and the generated force change a function of contraction at constant pressure. Therefore, for each pair of pressure and load a PAM has an equilibrium contraction, which corresponds with the equilibrium effective area. Figure 2.1 gives the working principle of a PAM of an arbitrary type and shape kept at constant pressure. The PAM´s effective area decreases with the contraction increase until the minimum muscle´s lenght, when actuator´s volume is maximum. Therefore, at maximum contraction forces become zero and at a low contraction these forces can be very high. Theoreticaly, some kinds of PAMs can have infinite forces at zero contraction.

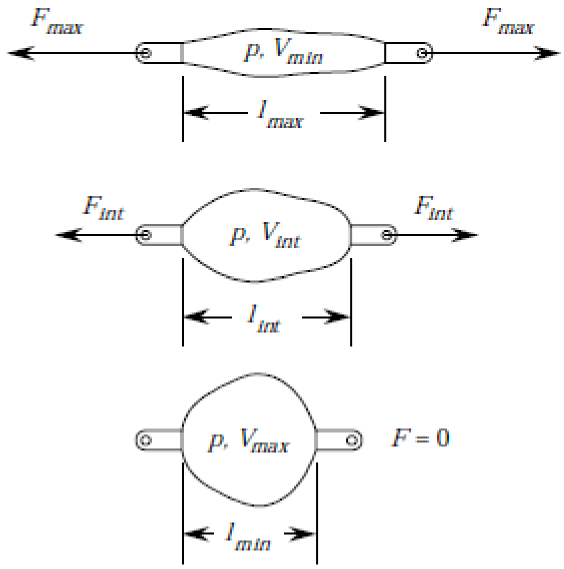

Figure 2.1: Arbitrary PAM. [Daerden]

2.2 Compliance and stiffness of PAM´s actuators

2.2.1 Single PAM

Considering PAMs in the abstract it is possible to understand their opertaion by comparing them with a elastic body. A PAM deforms under stress (e.g. external forces), but returns to its original shape when the stress is removed. A basic property of an elastic body is the resistance to deformation by an applied force, which is named Stiffness, K. In the International System of Units, it is typically measured in newtons per metre. Another important concept about elastic bodies is Compliance, C, which is defined as the inverse of stiffness, and represents the elastic body´s capacity of complying with a request, and physicaly it is the displacement of a loaded structure per unit load. The PAM stiffness and compliance can be deduced from the basic PAM tension ecuation, Eq. 2.3:

$$K = C^{-1} = \frac{dF}{dl} = -\frac{dp}{dV}\left(\frac{dV}{dp}\right)^2 - p\frac{d^2V}{dl^2} \qquad \text{Eq 2.4}$$

The first term is due to gas compressibility, as every pneumatic actuator, and the second term is due to the PAM´s variable effective area, $-dV/dl$. If the actuator is closed, the first term can be directly related to gas compressibility, which is a quite high value compared to that of liquids as water or mineral oil. Due to this high compressibility, an air actuator has higher compliance than its liquid counterpart. The second term expresses muscle stiffness at isobaric conditions, it only depends on the variation of the effective area ($-dV/dl$). If the pressure regulation of the muscle is fast enough, only this term will determine compliance. A muscle´s compliance can be adapted by a pressure control. An increase in the PAM´s pressure, increases its stiffness and diminishes its compliance.

2.2.2 Antagonistic Set-up

As their natural counterparts, PAMs are only able to act on a contraction way. Therefore, two of them are nedded to generate a bidirectional motion: while one muscle is moving the load, the other one is acting as a brake to stop the load at its desired position by balancing the generated forces. To move the load in the opposite direction the muscles change function. This opposite connection of the muscles to the load, which is known as an antagonistic set-up, is able to operate either linear or rotational motion.

With a complete knowledge of the used PAMs, it is possible to notate the effective area of each muscle as function of its lenght: $(dV_i / dl_i) = f_i(l_i)$. Therefore, Eq 2.3 can be rewritten for each muscle as:

$$F_1 = -p_1 f_1(l_{10} - x) \qquad F_2 = -p_2 f_2(l_{20} + x) \qquad \text{Eq 2.5}$$

Introducing the balance of the forces and the initial lenght of each muscle l_{i0}, the position of the load is completely determined by the gauge pressure ratio, (p_1 / p_2). Figure 2.2 shows a linear antagonistic set-up and a graph in which the position of the load is calculated for different gauge pressure ratios

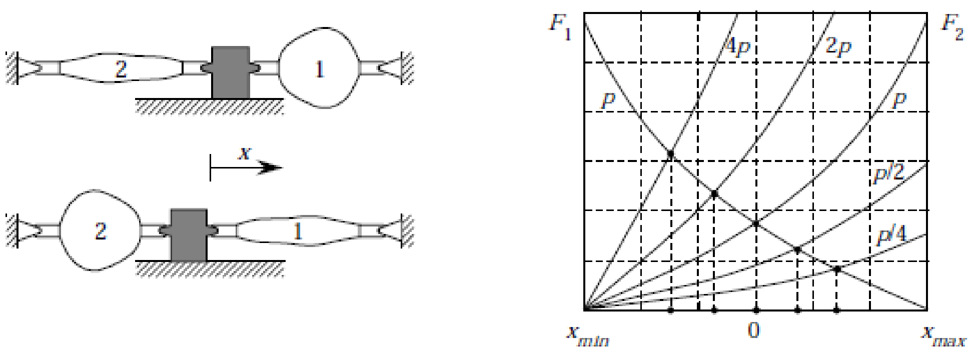

Figure 2.2: Antagonistic set-up [1]

As in a lonely PAM, stiffness and compliance are two interesting properties of an antagonistic set-up, where both muscles operate as an integrated whole. To simplify the mathematical development, refering both contractions to the load displacement, it is assume that both muscles are identical. The force that moves the load is

$$F = F_1 - F_2 = -p_1 \frac{dV_1}{dl_1} + p_2 \frac{dV_2}{dl_2} = p_1 \frac{dV_1}{dx} + p_2 \frac{dV_2}{dx} \qquad \text{Eq 2.6}$$

And stiffness can be expressed as

$$K = -\frac{dF}{dx} = -\frac{dp_1}{dV_1}\left(\frac{dV_1}{dx}\right)^2 - \frac{dp_2}{dV_2}\left(\frac{dV_2}{dx}\right)^2 - p_1 \frac{d^2V_1}{dx^2} - p_2 \frac{d^2V_2}{dx^2} \qquad \text{Eq 2.7}$$

Eq 2.7 shows that stiffness and commpliance of a antagonistic set-up depends on the sum of the pressures, independently of load position. If the sum of the pressures increases, the actuator stiffness will increase.

2.3 Skeletal muscle resemblance

Most of the PAM´s applications are based on skeletal muscles resemblance, either replacing them (robot legged locomotion) or interacting with them (rehabilitation). Therefore, it is beyond the scope of this work to give a basic description of skeletal muscle, which is based on Daerden´s study.

Skeletal muscle is a form of voluntary striated muscle which drive mamals´ limbs, eye, tongue and chest linked to bones by tendons. Due to it, the muscle contraction force is transferred to the skeleton as a torque acting about a joint. It is one of three major muscles found in biology, the others are: cardiac muscle, which powers the heart; and smooth muscle, which controls intestines and veins. Skeletal muscles transform chemical energy into mechanical power and their microscopic structure is extremely complex. A sarcomere is the basic functional unit of the skeletal muscle and responsible for its contraction and its striated appearance. The tension generated by a sarcomere varies depending on its state of contraction. [5] [6]

Although every characteristic of skeletal muscles is due to its complex microscopical structure, the study of their similarity with PAMs takes into account their macroscopic behaviour. Both are linear contractile engines, which are able to generate pulling forces according to a decreasing load-contraction relation, which depends on the activation level (gauge pressure on PAMs). Hogan [1984] explained the skeletal muscle stiffness modulation in a mechanical way. It is comparable to the reasoning followed in the previous section with neural activation level replacing PAM´s gauge pressure. Position is controlled by the ratio of activation levels, while stiffness is determined by the sum of these. Without any stiffness or with stiffness too low, the skeleton would collapse or start oscillating due to gravitational destabilization of the whole skeletal system. On the other hand, without any compliance the system would not be able to absorb mechanical shocks or perform tasks that need delicate handling.

The energy sources of skeletal muscles and PAM´s are not comparable, PAM´s are powered by pressurized air while the skeletal muscles transform chemical energy into mechanical one. Due to it they have several differences: skeletal muscles do not change volume during contraction; and they have energy stored in them and running through them.

The relationships between tension, length, velocity, and activation are major characteristics of PAM which vary greatly from type to type. Human skeletal muscle also has its own particular characteristics: for example, the convex shape active tension-length relationship (Gordon et al. 1966) and the non-linear passive tension-length relationship, which can be seem in Figure 2.3. Each of these properties is also a function of activation level (McMahon 1984, Winters 1990, Zahalak 1990).

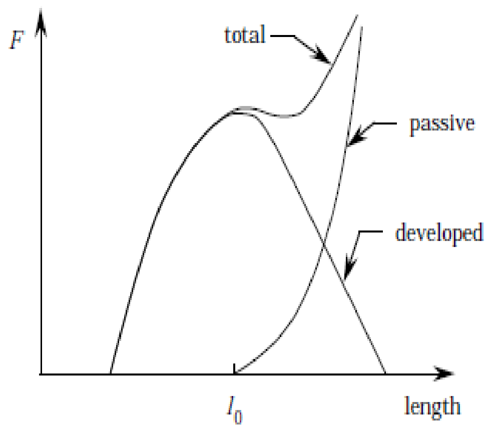

Figure 2.3: Skeletal muscle tension-lenght relationship [1]

As was done by Daerden, some of the typical performance data of skeletal muscle are given below (Hunter and Lafontaine, 1992; Hollerberg et al., 1991; McMahon, 1984; Chou and Hannaford, 1996):

• contraction range: within −50% to 50% of rest length, typically −12% to 36%;

• contraction rate: $2s^{-1}$ to $20\ s^{-1}$;

• stress: 350kPa peak value, 100kPa sustained;

• power to weight ratio: 200W/kg peak value, 50 W/kg sustained;

• efficiency: 25% to over 45%.

2.4 PAM´s classification

Several kinds of PAM have been developed since their first conceiving in 1930, S. Garasiev. Following Daerden´s classification, they can be distinguished according to the kind of operation, the geometry and type of the membrane:

- **Overpressure or underpressure operation**. PAM´s which operate at underpressure have several disadvantages compared with overpressure opertation. In underpressure operation the gas is sucked out of the membrane and contraction stops when the membrane sides touch. Therefore, these actuators have to be designed quite thick in order to obtain reasonable values for maximum contraction. Contractions of 20% for muscles of a maximum diameter of 50mm and length of 100mm are mentioned. Forces vary between 20N and 140 N, but it is not mentioned at what underpressure. With ambient pressure at about 100 kPa, PAM´s can convey much more energy by overpressure than by underpressure. Therefore they are usually designed to operate at an overpressure.

- **Streching or rearranging membrane**. It refers to the manner in which the membrane inflates: to be able to expand radially, either the membrane material has to stretch radially or the radial section has to change by rearranging the membrane's surface. In case of pure rearranging, the total membrane surface is constant regardless of contraction and volume. This allows for a greater tension to be developed as no energy is put into stretching membrane material.

- **Braided/netted or embedded membrane.** It refers to the tension carrying element of the muscle: a structure either embedded in the membrane or embracing the membrane.

Some examples of **embedded muscles** are Morin muscles [Morin, 1953], Baldwin muscle [Baldwin, 1969], Paynter knitted muscle and Paynter Hyperboloid muscle [Paynter, 1988]. Baldwin type muscle consists of an elastomeric membrane, a very thin surgical rubber, embedded by glass filaments in the axial direction.

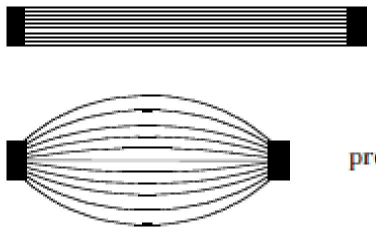

Figure 2.4: Balwin type muscle. [Daerden]

The difference between braided and netted muscles is the density of the network surrounding the membrane, a net being a mesh with relatively large holes and a braid being tightly woven. Because of this, if the membrane is of the stretching kind, **netted muscles** will only withstand low pressures. Therefore, netted membrane PAM´s will usually have a diaphragm of the rearranging kind. Some examples of netted membrane PAM´s are the Yarlott Muscle [Yarlott, 1972], the Romac muscle [Immega, 1987], which can be seen in figure 2.5; the Kukolj muscle [Kukolj, 1988] and the Pleated PAM [Daerden, 1999], which is deeply studied in Chapter 3.

Braided muscles are composed of a gas-tight elastic tube or bladder surrounded by a braided sleeving. When pressurized the tube presses laterally against the sleeve. The general behavior of these muscles with regard to shape, contraction and tension when inflated will depend on the geometry of the inner elastic part and of the braid at rest, and on the materials used. Usually, braided muscles have a cylindrical shape because of the cylindrical bladder shape. Although the braid is always connected to fittings at both ends, the inner tube can be attached [McKibben] or unattached [Winters, 1995] to them.

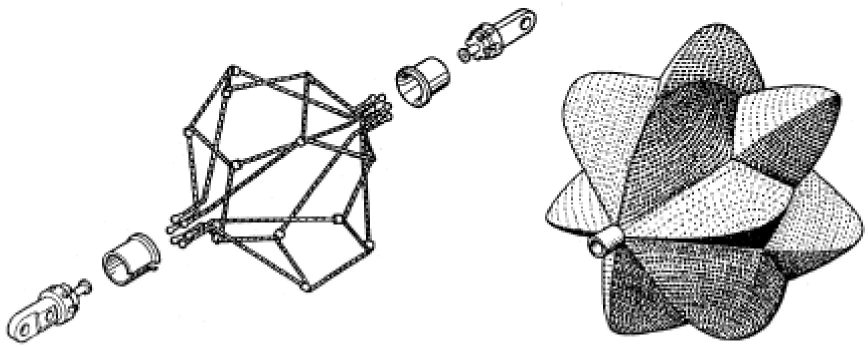

Figure 2.5: Romac, standard version [Immega, 1996]

2.5 McKibben Muscle

The McKibben muscle is the best known and most frequently used and published about PAM´s type. This muscle was introduced by McKibben for orthotic applications in the fifties. Due to the similarity in lenght-load curves between this artificial muscle and skeletal muscle, it seemed an ideal choice for this purpose [Schulte, 1961].

Since the late 1980´s, when it was reintroduced by Bridgestone Co. [Inoue, 1987], several forms of this type of muscle have been comercialized by different companies such as the Shadow Robot Company [Shadow Robot Company, 2003], Merlin Systems Coorporation [Merlin Systems Coorporation, 2003] and Festo [Festo, 2004]. Since then, several groups all over the world have been using McKibben like muscles to power robots, mainly of anthropomorphic design, and prostheses and orthotics [Raparelli et al., 2000; Eskiizmiler et al., 2001; Klute et al., 2002; Berns et al., 2001; Davis et al., 2003; Kingsley et al., 2003; Pomiers, 2003; Kawashima et al., 2004; Wisse, 2004].

In figure 2.4 the concept of the McKibben muscle is given. It consists of an inner tube surrounded by a braided sleeving. McKibben muscle has both its tube and its sleeving connected at both ends to fittings that transfer fiber tension and serve as gas closure. Typical materials used are latex and silicone rubber and Nylon fibers.

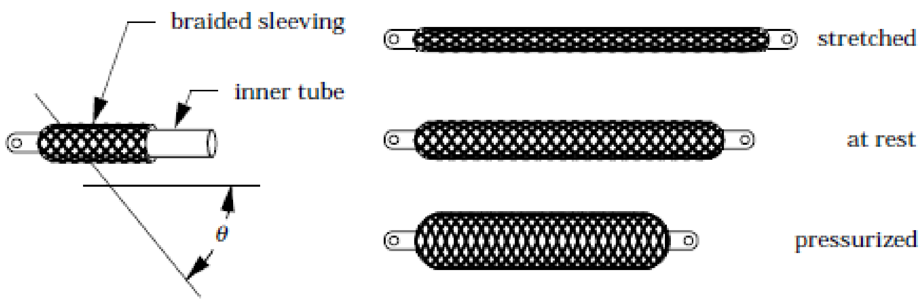

Figure 2.6: McKibben type muscle [Daerden]

When the internal bladder is pressurized, the high pressure gas pushes against its inner surface and against the external shell, and tends to increase its volume. Due to the non-extensibility (or very high longitudinal stiffness) of the threads in the braided mesh shell, the actuator shortens according to its volume increase and/or produces tension if it is coupled to a mechanical load.

Inherent to this design are dry friction (between sleeving strands and tube and between the strands themselves), non-elastic deformation of the diaphragm and elastic lateral deformation. Dry friction and non-elastic deformation of the diaphragm will show up as hysteresis and threshold pressure, while elastic lateral deformation will lower tension.

Due to this PAM type is the most frequently encountered, some static and dynamic length-tension testing results are given below. Chou and Hannaford (1996) [7] published a paper which reports mechanical testing and modeling results for the McKibben artificial muscle pneumatic actuator. It reports ranges of contraction-extension of 0.75-1.1 of initial length for Nylon fiber McKibben Muscles and 0.86-1.14 for fiberglass McKibben Muscles. They also report a threshold pressure of 90 kPa, hysteresis width of 0.2–0.5 cm and height of 5–10 N for a Nylon braid muscle of 14 cm rest length and 1.1 cm rest diameter and more or less double these figures for an approximately equal sized fiberglass braid muscle, as can be seen in figure 2.5.

Caldwell et al. (1993b) report forces attaining only 53% of their values predicted by Eq. 2.3. As for power to weight ratios of McKibben Muscles, values cited by Caldwell et al. (1993b) range from 1.5 kW/kg at 200kPa and 3 kW/kg at 400 kPa. Hannaford et al. (1995) cite a value of 5 kW/kg and Hannaford and Winters (1990) even 10 kW/kg. To determine these values, no auxiliary elements such as valves, were taken into consideration. The weight of McKibben Muscles is typically about 50 g (Tondu et al. (1995), l0 = 34cm, D0 = 1.4 cm), but can be as low as 5.5 g (Caldwell et al. (1993a), l0 = 9cm, D0 = 1cm). And their typical operating gauge pressure range is 100-500 kPa.

The main reason for McKibben muscles success seems to be its simple design, ease of assembly and low cost. On the other hand life expectancy of this muscle, of which no written reports were found, seems not very high. Users complain about early braid fiber failure at the point of clamping. Anyway, the major disadvantage of the McKibben Muscle is its inherent dry friction and threshold pressure.

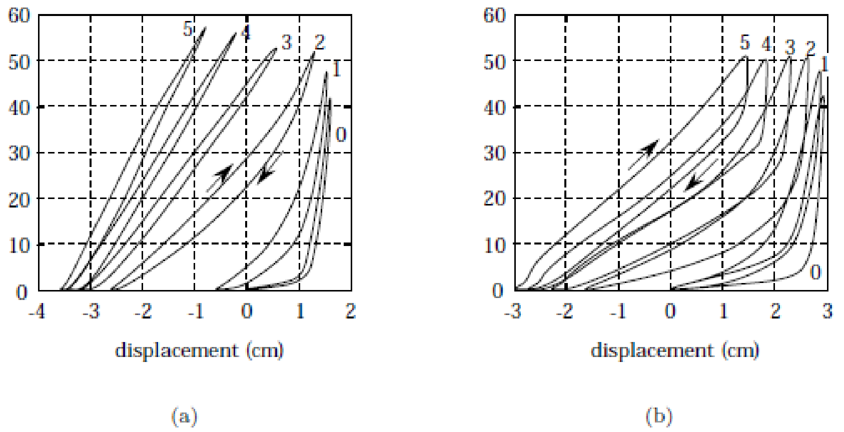

Figure 2.7: Mckibben Muscle tension (N) and hysteresis at isobaric conditions (0, 1, 2, 3, 4 and 5 bar), (a) Nylon braid, (b) fiberglass braid. [7]

Chapter 3

3 Pleated Pneumatic Artificial Muscles

3.1 Background

The Pleated Pneumatic Artificial Muscle (PPAM) is a novel actuator which has been developed by the Multibody Mechanics Research Group of the Vrije Universiteit Brussel for a decade. This section provides a small review about the development of the first [1] and second generation [4] of PPAM. Studing their skills and weaknesses it is possible to understand the main reasons which have caused the changes from the first design until the third generation. It is possible to identify a continuous problem in order to reconcile the development of the actuator performance (mechanic and energetic characteristics) and the manufacturing process (production time and low cost).

3.1.1 First generation of PPAM

PPAM was firstly designed by Daerden [1999] to overcome some shortcomings of existing muscle models as the McKibben PAM, which is considered the leader of this type of pneumatic actuator. Daerden designed the Pleated PAM focussed on improving the muscle performance. The major disadvantages of the McKibben Muscle are its inherent dry friction and the elastic and non-elastic deformation that will show up as hysteresis, threshold pressure and a decrease in the generated tension. It is therefore difficult to control and its lifespan is reduced by the friction.

The Pleated PAM membrane layout is arranged into radially laid out folds that can unfurl free of radial stress when inflated avoiding friction and material deformation. This leads to a strong reduction in energy losses with regard to the classical types. The folded membrane is positioned into two end fittings closing the muscle volume and providing tubing to inflate and deflate the enclosed volume. Figure 3.1 sketches the Pleated PAM concept.

Daerden´s design is named “First generation of PPAM”. It uses a high stiffness membrane that is initially folded together and unfurled upon inflation. The membrane is a fabric made of an aromatic polyamide such as Kevlar to which a thin liner is attached in order to make the membrane airtight. The high tensile longitudinal fibres of the membrane transfer tension, while the folded structure allows the muscle to expand radially. The end fittings are constructed with a circular inner structure to position and align each fold of the membrane, while an outer aluminium ring prevents the membrane of expanding at the end fittings. An epoxi resin fixes the membrane to the end fittings.

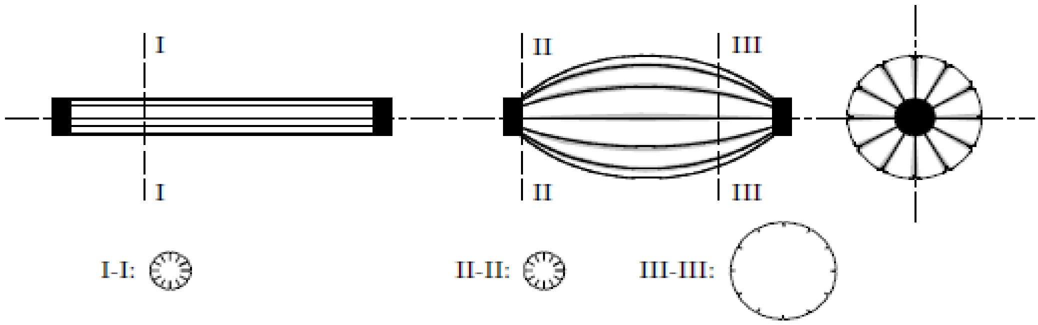

Figure 3.1: Pleated PAM [Daerden, 1999]

Due to its specific design, the PPAM generates higher forces than other designs, has a larger stroke and is not bothered by friction related hysteresis. It has a weight of about 100 gr while it can generate forces up to 5 kN. The PPAM contraction can be more than 40 %, depending on its original slenderness (theoretically 54% for a infinitely thin muscle). The muscle prototype built by Daerden [1999] can easily work at pressures as low as 20mbar with a maximum working pressure of 4 bar.

Daerden established a rigorous mathematical model for the PPAM performance based on zero parallel stress pressurized axisymetric membranes that was proved to be very accurate with regard to the real PPAM.

The surface of this membrane is generated by a meridian curve that is revolved about the axis of symmetry, the x -axis. From a static force equilibrium analysis of the membrane, a relation between the shape of the generating curve, the membrane meridional tensile stress σ , the applied gauge pressure p and the developed force F can be established, see Daerden [1999].

PPAM´s characteristics, such as equatorial diameter (D), volume (V), developed tension (F_t), stress (σ_1) and material strain (ε_1) were subsequently derived and these were found to be proportional to contraction, slenderness and material compliance.

If a high tensile stiffness membrane material is used, the influence of elasticity is not very significant at contractions of more than 5%. Therefore, an inelastic solution was derived and discussed. This led to geometric similarity laws, which are represented in ecuations: 3.1, 3.2, 3.3 and 3.4 [Daerden], relating the characteristics of scaled membranes by using dimensionless functions (d, v, f_t, ς) that only depend on slenderness and contraction. At this case, the inelastic behavior can be used as an approximation to compare membranes of different values of slenderness.

$$D = l_0 d\left(\in, \frac{l_0}{R}\right) \qquad \text{Eq 3.1}$$

$$V = l_0^{\,3} v\left(\in, \frac{l_0}{R}\right) \qquad \text{Eq 3.2}$$

$$F_t = p l_0^{\,2} f_t\left(\in, \frac{l_0}{R}\right) \qquad \text{Eq 3.3}$$

$$\sigma_1 = \frac{p l_0^{\,2}}{A} \varsigma\left(\in, \frac{l_0}{R}\right) \qquad \text{Eq 3.4}$$

Although the first generation of PPAM presents interesting scientific aspects, as generate maximal forces, it has some drawbacks in order to be economically lucrative. The first prototype of PPAM needed a very complex manufacturing process that entails a insufficient lifespan. The membrane of the prototype was folded while starting from a flat woven fabric, and to create a circular shape, some folds were glued together with an overlap. This overlap and the tiny length of the pleats were the main causes of the leakages that appeared during the imperfect bulging process of the pleated membrane, which is shown in figure 3.2. Due to these utility inefficiencies a second generation of PPAM was developed.

Figure 3.2: Photograph of three inflated states of the first generation PPAM

3.1.2 Second generation of PPAM

The second generation of PPAM was introduced by Verrelst [2005] while considering this actuator for a bipedal walking robot. The main objectives of this adapted design were to extend the muscle lifespan and to simplify the construction of the muscles.

During the development of the PPAM 2.0, the membrane composition was changed, as is depicted by figure 3.3. Instead of the Kevlar fabric, another more flexible material is used to create the folded membrane while the generated tension is transferred by individual high tensile stiffness fibres that are only positioned at the bottom of each crease. The pleated flexible membrane is composed of a woven polyester cloth that is made airtight by a polymer liner. This change make possible to build an airtight cylindrical fabric in which the folds are created afterwards. During the pleating process, separate fibres are positioned in every fold. This new membrane production process avoids the folded overlap, which caused several failures.

Due to the high cost of the CNC machining, the toothed inner metal tube of the end fittings of the original prototype was replaced by a straightforward aluminium basin where the membrane was fixed. Therefore the folds and their respective fibres were not deliberated aligned.

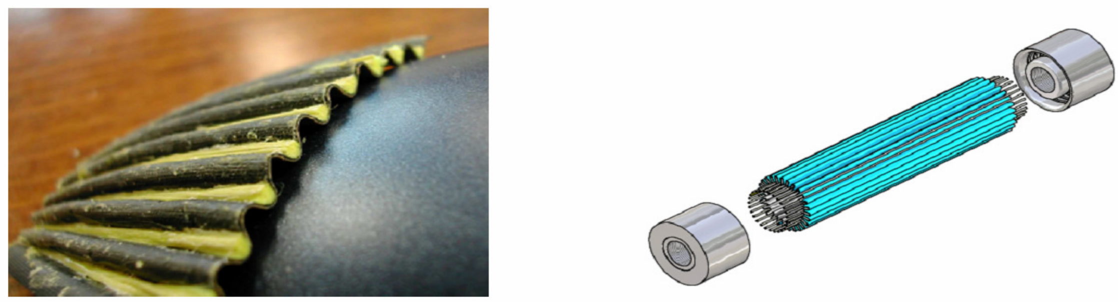

Figure 3.3: Photograph of a membrane section and Composition of PPAM 2.0 prototype [Verrelst, 2005]

Due to the new design, the original mathematical model was adapted, as can be seen in Verrelst [2005]. The original model assumed a continuous axisymetrical circular membrane, while in the new model is assumed that longitudinal tension is only transferred by the finite number of tensile fibres neglecting any influence of the pleated airtight polyester membrane.

The differences in the initial assumptions imply some changes in the resulting mathematical expressions of the muscle´s characteristics, however, the resulting analytical solution is almost identical. The new expressions of the generated tension and fibre stress depend on the number of pleats (n).

$$F_t = p\frac{n}{2\pi}\sin\left(\frac{2\pi}{n}\right)l_0^{\,2} f\left(\in,\frac{l_0}{R}\right) \qquad \text{Eq 3.5}$$

$$\sigma = \frac{1}{ns}\varsigma\left(\in,\frac{l_0}{R}\right) \qquad \text{Eq 3.6}$$

While the fibres stress is inversely proportional to the number of fibres and to the fibres section, the expression of the generated traction has integrated the term $\frac{n}{2\pi}\sin\left(\frac{2\pi}{n}\right)$, that lower the value when the number of fibres is decreased. As the number of fibres increase to infinity, the new term converges fast to 1. If the number of fibres is greater than 15, the difference between the developed tension of the second and the first generation is theoreticaly less than 3%.

Verrelst built some muscle prototypes made with 40 pleats, an initial lenght of 110 mm and a radius for the fibres position of 11,5 mm. Using tese dimensions in equations 3.1, 3.2, 3.5 and 3.6, results in themuscle characteristics depicted in figure 3.4.

The development of the second generation represented a great improvement because the tension generated by its prototype, which were built with 40 pleats, had been reduced only by 1% in regard to the older PPAM, and its lifespan had been improved drastically. A muscle moved up and down a load of 130 kg by a slow varying gauge pressure between 1 and 3 bar during more than 400.000 cycles. Figure 3.5 shows how the membrane unfolded in a more uniform way.

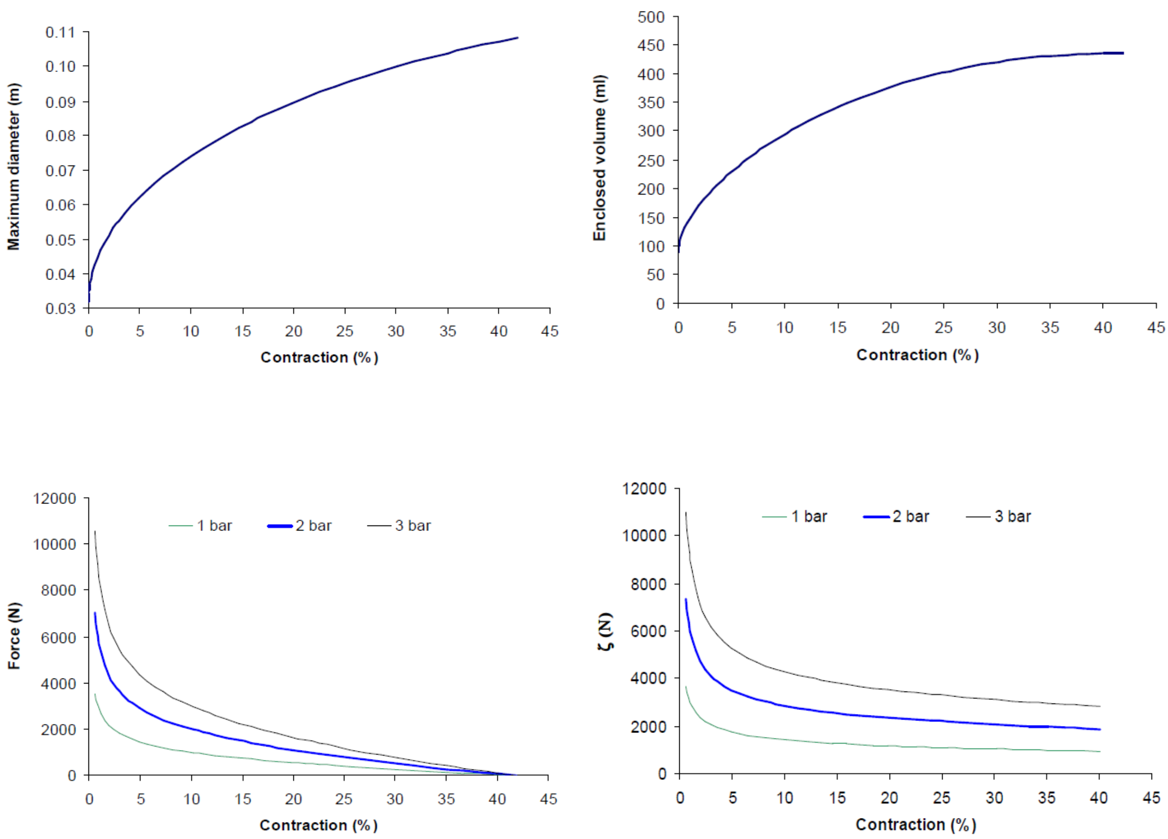

Figure 3.4: Therotical characteristics of PPAM 2.0 [Verrelst, 2205]

Figure 3.5: Photograph of three inflated states of the second generation PPAM

The improved lifespan of the muscle made PPAM 2.0 useful for several applications. The Multibody Mechanics Research Group of the VUB has been using it in their researches until 2008. But, although the fabrication process had been changed completely, it was still too much complex causing failure muscles and slowing the research down. The production process of the PPAM 2.0 can be seen in figure 3.6. It started making the three main parts of the muscle: airtight flexible cylinder, fibres and end fittings. A standard muscle was confectioned with 40 fibres that had to be built and positioned in their pleats individualy. For making one fibre, some thinner ones were extracted manually from a Kevlar woven cloth and joined with latex in order to make them stronger and to protect them from the epoxy used during the gluing, as can be seen in Figure 3.7. These operations were one of the main causes of the long production time, about 90 minutes were needed to confection 40 fibres

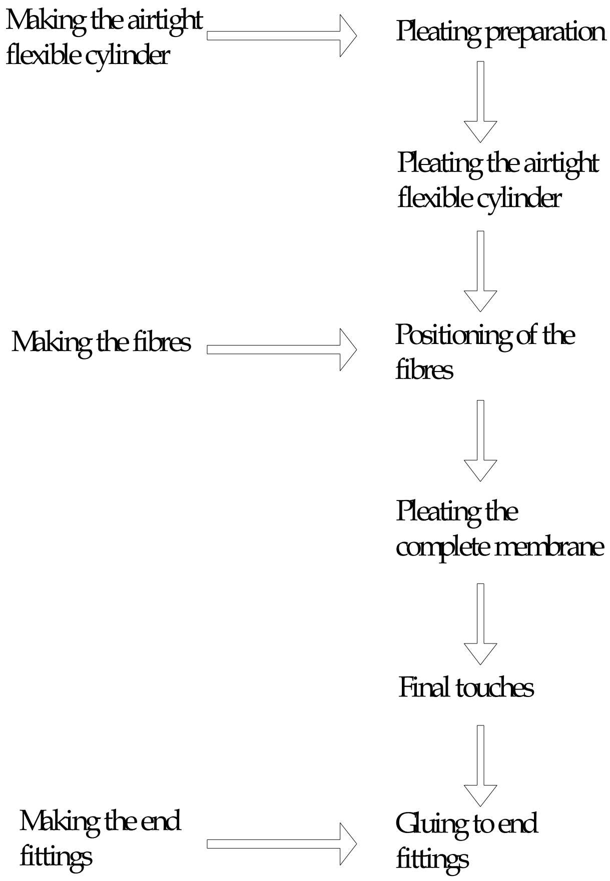

Figure 3.6: Diagram of the production process of the second generation of PPAM

Figure 3.7: Photographs of the production of the fibres [PPAM 2.0]

The other main reason was the complex pleating, see Figure 3.8, in wich there were needed several gadgets: 40 ropes, 2 cylinders (each one was made of 80 small metal plates), 40 thin rods, a ballon, some bridels and some elastics. All these gadgets caused lots of problems and some times the fabric was damaged invalidating all the previous work. At the middle of the pleating, some of these gadgets were removed and the fibres were positioned for the second part of the process. When the membrane was built it was needed a final colocation of the fibers to position them at the same distances for the gluing. However, there still was a problem: the possible relative movement between the fibres and the pleated fabric.

Figure 3.9 shows a photograph of the most important failure point of the second generation of PPAM. A few Kevlar fibres were broken somewhere at the border with the aluminium end fittings. It is believed that this problem was caused by two main reasons: 1). The epoxy which were used to fix the membrane and the fibres to the end fittings came into the fibres causing that they break more easily after some cycles. 2). Placing the individual fibres in the pleats at the correct distances was difficult because they were positioned individualy and they were not completely fixed during the gluing process with the end fittings

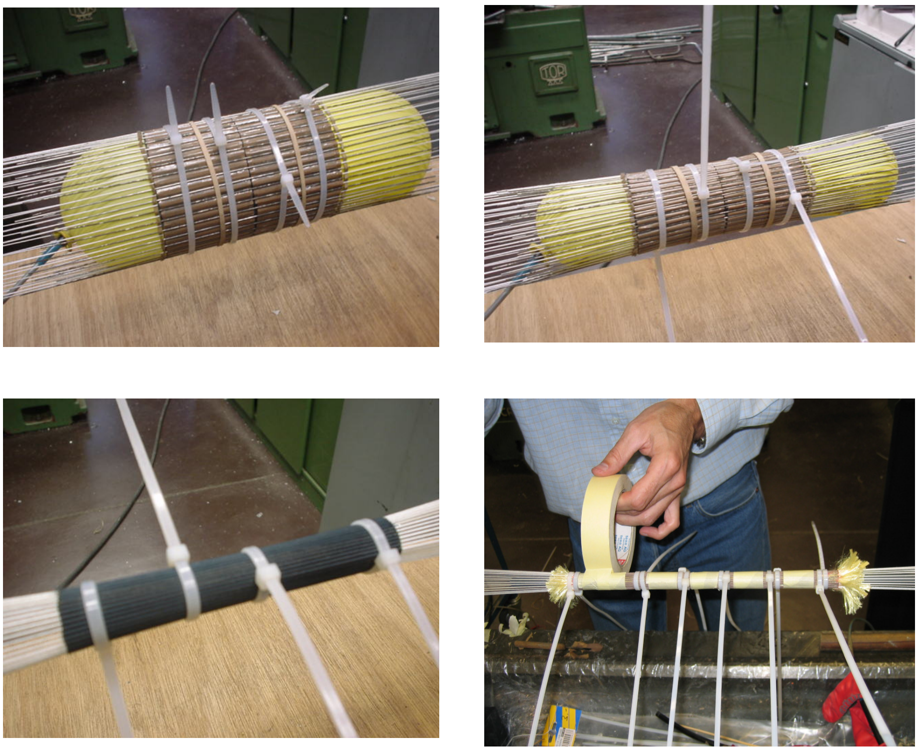

Figure 3.8: Photograph of the pleating process [PPAM 2.0]

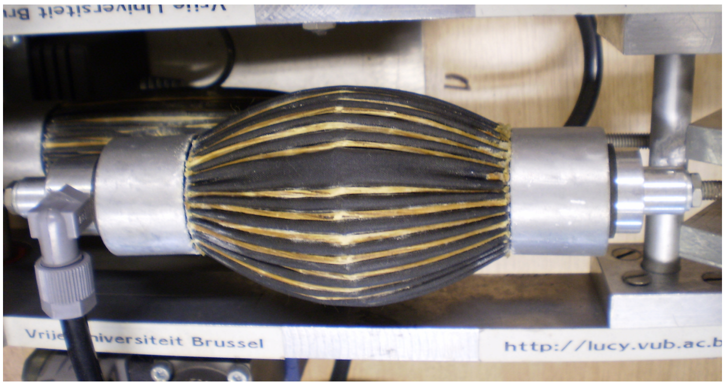

Figure 3.9: Photograph of a PPAM 2.0 with a broken fibre.

3.2 Conception of the Third generation of PPAM

The main disadvantage of the PPAM 2.0 is the complexity of its production process which caused several failure muscles and a long production time. A experimented builder required about 8 hours to build one muscle. To simplify the manufacturing process and to avoid failure muscles, focusing in a possible comercial production, the third generation of PPAM has been developed. As any redisign of an existing product, PPAM 3.0 is based in older designs, experience and new technologies. This new step was partialy promoted by the accesibility of a Fused Deposition Modeling (FDM) rapid prototyping machine, which can be used to make complex and lightweight parts.

The good results of PPAM 2.0 validate its especific membrane design, in which the membrane can be devided into two main parts: the pleated airtight fabric and the high tensile fibres. Therefore, during the development of the PPAM 3.0, the mathematical model of the second generation has been assumed, therefore its membrane composition has been basicaly maintained.

In order to improve the production time, the new manufacturing mixes some operations of the previous production process: pleat the membrane, position the fibres and close the muscle with the end fittings. The new rapid prototyping machine is used to create more complex end closures composed of more than one part. Using one of these ABS parts, which has teeth towards the outside, togehter with a continuous high tensile fibre, it is possible to fold the membrane at the same time that it is fixed to the end fittings. During this process, the continuous fibre is arranged over the internal teeth and the pleated fabric. The fabric takes the same shape that the toothed part and the fibre is positioned at the bottom of every pleat. The production process is drastically simplified: the use of several pleating gadgets is avoided as well as the repetitive operations of making the fibres. Furthermore, fixing an external toothed part to each side of the muscle, the pleated membrane is deliberately aligned.

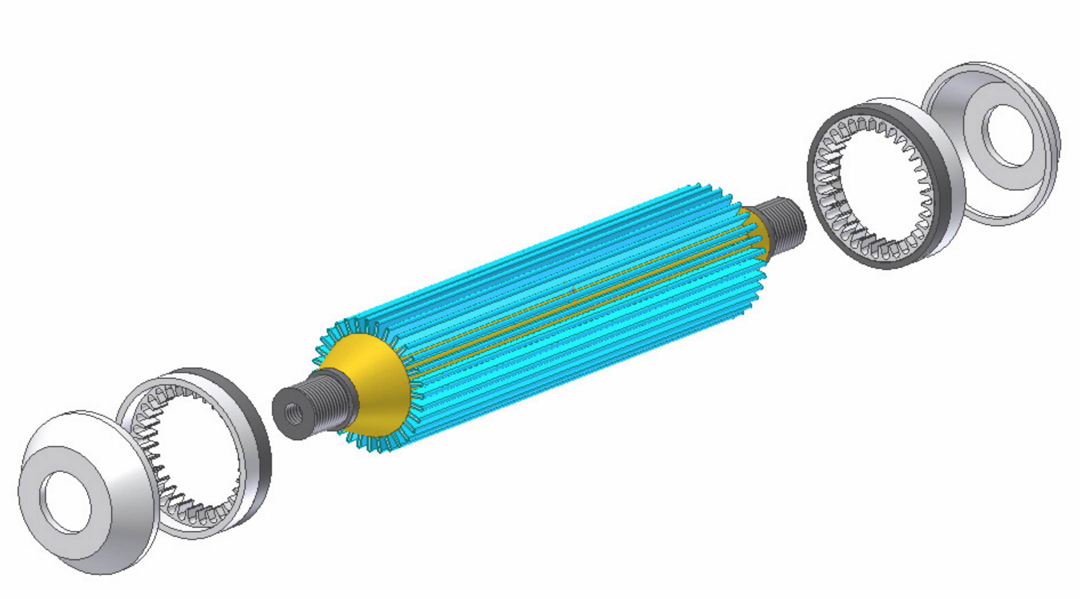

Figure 3.10: Composition of the new muscle prototype

3.3 PPAM 3.0 design and materials selection

3.3.1 Pleated airtight fabric

The pleated airtight fabric is the most important part of a Pleated PAM. It is responsible of keeping the pressuriced air inside the muscle being able to unfurl free of radial stress when inflated keeping the fibres in meridional planes. Besides this, it transfers high forces from the pressuriced air to the high tensile fibre, which is theoreticaly done without dry friction. Due to these objectives the fabric must be airtight, flexible, inelastic and lightweight.

The membrane of the previous generation had been validated by experience, therefore, PPAM 3.0 mantain the membrane concept. The folding starts from an airtight cylindrical fabric, which is made of a simple woven polyester cloth and a internal polymer liner, in which the folds are created afterwards, see fig 3.11. The diameter of the cylindrical fabric must be at least the same than the maximum diameter of the bulged muscle. This maximum diameter is calculated by the mathematical model as function of the muscle slenderness and intial lenght.

The previous generation membrane presented some few air bubbles between the liner and polyester layers. These bubbles complicated the pleating process and weakened the membrane. This problem has been solved by introducing some changes in the membrane materials and in its production process, see section 3.4. The new polymer liner is a little bit stronger than the old one and, due to the limited material resources according to the supplier posibilities, the new polyester cloth has a fine coating, which has to be cleaned in order to get a good gluing with the polymer liner.

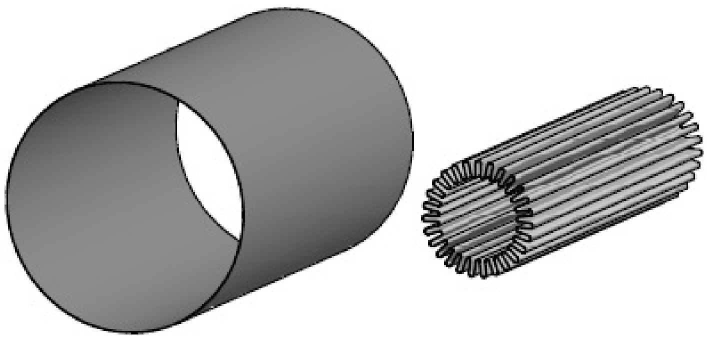

Figure 3.11: Membrane folding [Verrelst, 2005]

During the development of the PPAM 3.0 another material, which combines flexibility and airtight behaviour, has been considered. The Archictecture department of the VUB is currently researching about pneumatic structures made of inflatable parts. They are made from a plastic cloth which is turned into a closed volume by a high temperature sealing. A muscle prototype is built and tested with this membrane material, see fig 3.12.

The tested fabric is firstly pleated from a flat woven fabric and the circular shape is created afterwards by sealing a thin longitudinal line in the top of a fold. It is too much thick to get a right pleating and the sealing is not homogeneous enough. During the test, in which the muscle is inflated and deflated from 1 to 3 bar carrying a load of 130 kg, some leakages appear in the sealing and its surroundings after few cycles.

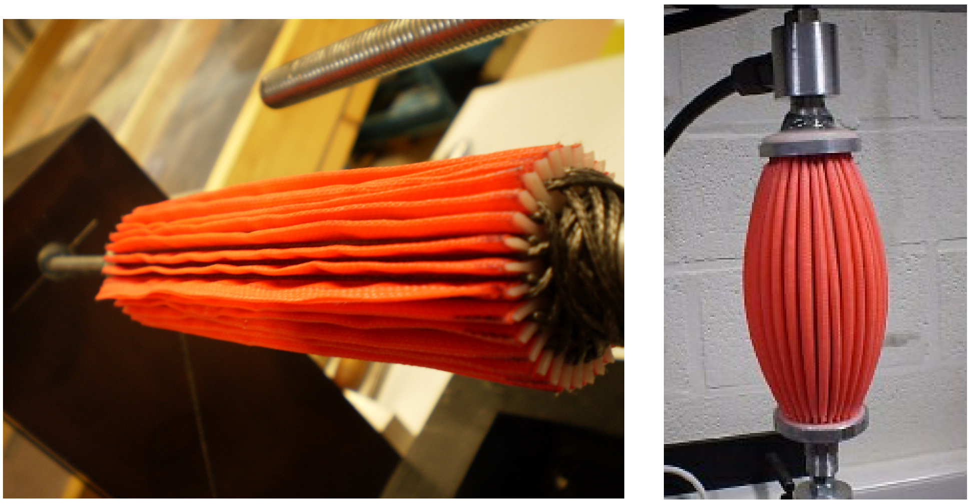

Figure 3.12: Photographs of the muscle prototype built with the plastic fabric

3.3.2 High tensile fibre

As was mentioned in previous sections, the main difference between PPAM 3.0 and its older generations is that the new design use a continuous high tensile fibre instead of several separated ones. It is the tension carrying element of the muscle, a fibres structure embracing the flexible pleated fabric.

The fibres must be lightweight and have really high tensile strength and Young´s modulus. Besides this, due to the especific design, fibres must have higher strength and elasticity modulus in the fibre axis direction compared to the radial one. A complete study about fibres material choice can be found in Daerden [1999] which concludes choosing a organic fibre, Kevlar. It is an aromatic polyamide which is fabricated by E. I. Du Pont de Nemours & Company.

The first generation used a Kevlar woven cloth as membrane and the second generation used Kevlar fibres which were extracted manually from the same Kevlar woven cloth. Due to the high tension developed by the muscle, few fibres were joined with latex in order to make stronger ones.

As a continuous fibre is needed in PPAM 3.0, it can not be extracted from a woven cloth. Therefore other products, as fibre reels, have been considered. During the first stage of the choosing process, the possiblities are reduced to two fibre types: Dyneema and the already used Kevlar. Dyneema is the registered trademark of a polyethylene fibre developed recently by DSM. It is made from ultra-high molecular weight polyethylene (UHMWPE).

According to the information consulted by the autor: [8], [9], [10], [11] and[12], Dyneema seemed to be another suitable election with several advantages but some weaknesses. Table 3.1 shows mechanical and physical properties of the studied materials.

	Quantity	Value				Unit
		Kevlar 29	Kevlar 49	Kevlar 149	Dyneema	
Mechanical properies	Young´s modulus	70,3	112	179	55-172	GPa
	Tensile streght	2920	3000	3450	1400-3090	MPa
	Elongation at break	3,6	2,4		2,7-4,5	%
Physical properties	Density	1440	1440	1470	960	Kg/m3
	Water absorption	7	3,5			%

Table 3.1: Properties of Kevlar and Dyneema

Dyneema advantages. Dyneema has excellent strength to weight and modulus properties similar to those of aramids as Kevlar. The density of polyethylene is lower than that for the aramids so the weight specific properties of PE are superior and almost match those of high modulus carbon fibres. It offers the same level of cut-protection as Kevlar but offers greater abrasion resistance and its coefficient of friction is comparable to that of Teflon. It has low moisture absorption and excellent flex fatigue resistance. Therefore it is almost insensitive to chemicals and solvents and benefits from remarkable longevity.

Dyneema weaknesses. Dyneema has lower melting point (c.a. 150 degrees C vs 400 for Kevlar) and exhibits CREEP. It is presented as non-recoverable elongation when constant load is applied for long time. It is more severe in materials that are subjected to heat for long periods, and near the melting point. But for late models and thicker ropes the CREEP is almost non-existent effect.

Due to the theoretical similarity between the tensile strenght and Young´s modulus of the two studied materials, Kevlar and Dyneema, some traction tests have been performed in order to compare both material samples. During the practical comparison fibres of 1 mm in diameter are tested. Although these tests should have determined the fibre´s material, they have not been successful. The used fixing tools can not transfer so high tensions to the fibres and they therefore slip through the connectors invalidating the tests. Dyneema samples slip at loads about 450 N while forces up to 1000 N are regristed with Kevlar fibre.

As the fibre material selection could not be based on the realiced traction tests, and due to the limited material resources according to the supplier posibilities, it was decided to use Dyneema as material for the high tension fibre during the rest of the development of PPAM 3.0. It is possible to obtain Dyneema fibres of different thicknesses with diameters of 1, 1.5, 2, 3, 4 and 5 mm with maximal tensions of 1300, 1950, 3800, 9000, 12500 and 20000 N respectively.

3.3.3 End closures or fittings

The end fittings of the former generations serve basically to close off the membrane ends and to keep the folds in place. In PPAM 3.0 they are also useful to pleat the membrane together with the continuous high tensile fibre. Due to this critical role during the production process, their design has become more important.

As was mentioned in previous sections, the new end fittings design is composed of some few parts which have different functions. Using the Fused Deposition Modeling (FDM) rapid prototyping technology it is possible to obtain complex lightweight small parts but they can not transfer the high tension generated by the muscle (forces over 5 kN have been reached). Therefore the end fittings have to be built using ABS parts togheter with other metal ones. Figure 3.13 shows the five parts of the end fittings final design made for a muscle with 32 pleats.

The end fittings are composed by different parts: some are internal (the membrane is possitioned around them) and some others are external (they are possitioned around the membrane). The internal parts are used during the building process in which the membrane is pleated arranging the continuous fibre around it. The aluminum body provides the pipe for the pressurized air and transfers the developed tension to the connectors by the thread while the internal teeth serve to give the correct folded shape to the membrane, which characterize the whole muscle performance.

On the other hand, the external ones are used after the building process to fix definately the whole muscle. The external teeth are used during the gluing process keeping the fibre and the membrane in place while the aluminum ring prevents the membrane of expanding at the end fittings during the inflation. In order to get a more aesthetic muscle and to position the muscle connectors at both sides of it, the cap covers the whole fixing structure.

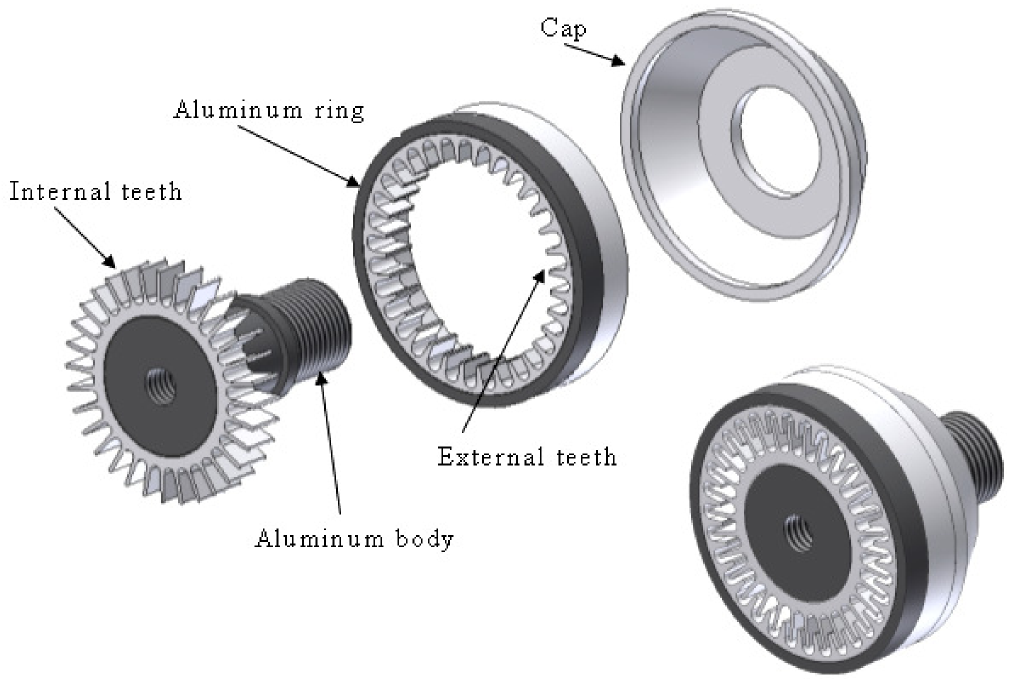

Figure 3.13: New end fittings

As was the case of the PPAM 2.0, this muscle prototype does not incorporate neither air connector nor pressure sensor connector. The aluminum body has a thread where additional muscle connectors can be screwed. In this way, a broken muscle can be replace easily, keeping the connectors in the specific application frame. Figure 3.14 shows the two different connectors to be fixed at each side of the muscle. These two connectors incorporate the same three functions as those of the second generation of PPAM: 1..Guiding the pressurized air in and out the enclosed volume; 2..Creating the interface for the connection to the specific apllication frame; and 3..Providing an attachement for a internal pressure sensor.

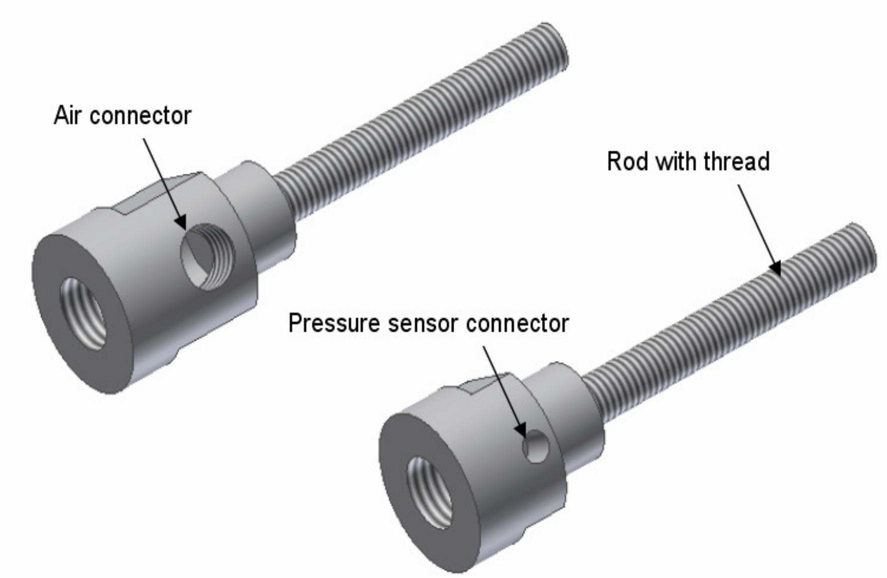

Figure3.14: Drawing of the two muscle end connectors

The internal teeth are designed according to the number of pleats (n), the radius for the position of the fibres (R), the diameter and thickness of the original cylindrical fabric ($D_{cylinder}$ and T), the fibre diameter (D_{fibre}) and the diameter of the end of the teeth (D_{ABS}), as can be seen in Figure 3.15. Introducing these muscle characteristics in ecuations 3.7 and 3.8 it is possible to determine completely the teeth shape.

$$\frac{\pi D_{cylinder}}{2n} = \left[\pi\left(D_{ABS} + T\right)\frac{(90-\beta)}{360}\right] + P + \left[\pi\left(D_{fibre} + T\right)\frac{\left(90 - \frac{180}{n} - \beta\right)}{360}\right] \qquad \text{Eq 3.7}$$

$$\left[\frac{\left(D_{ABS} + T\right) + \left(D_{fibre} + T\right)}{2}\right]\cos(\beta) + P\sin(\beta) = R\sin\left(\frac{180}{n}\right) \qquad \text{Eq 3.8}$$

The main weakness of PPAM in regard to other PAM types is its high broadness. Although the muscle lenght do not represent a problem, its minimum radius is delimited in order to be practically produced. This high radius entails a large dead volume, which decreases the muscle performance. In order to get a great slenderness, which increases the muscle maximum contraction and diminishes its performance, the main objective for the designer is to get the minimum R for each muscle lenght. It can be obtained using the fabric and fibre as thin as possible (complying with mechanical requests); with minimum β (β = 0); and minimum diameter of the end of the teeth, which is determined by the maximum accuracy of the rapid prototyping machine.

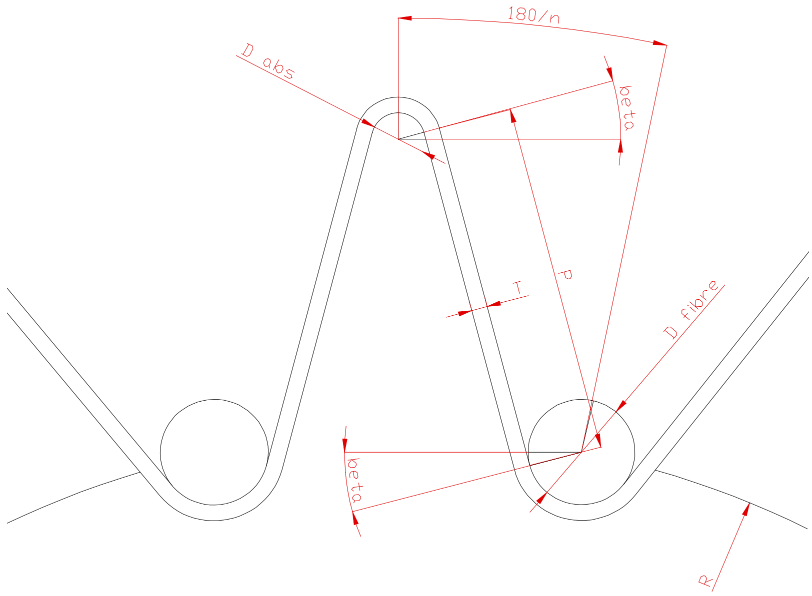

Figure 3.15: CAD drawing of the teeth design

Another way of getting the minimum radius of the position of the fibres is to reduce the number of pleats. With β = 0, the reduction of n is proportional to the reduction of R but, it is also proportional to the increase of the teeth depth (P). It can be a problem because the pleats have to be as shallow as possible in order to avoid parallel stress components in the membrane. Figure 3.16 shows two end fittings designs, with the same R but 32 and 16 pleats respectively. It can be seen that the teeth depth of the 16 pleats design almost doubles that for the other design.

Although the radius of the muscle can be reduced, the dead volume is not avoided. Due to it, other ideas have been developed at the same time that the third generation of PPAM. The basic concept is to position some closed parts inside the muscle membrane that diminish the pressurized air volume. The new rapid prototyping machine can be used to make some lightweight for this purpose. Two different concepts have been developed.

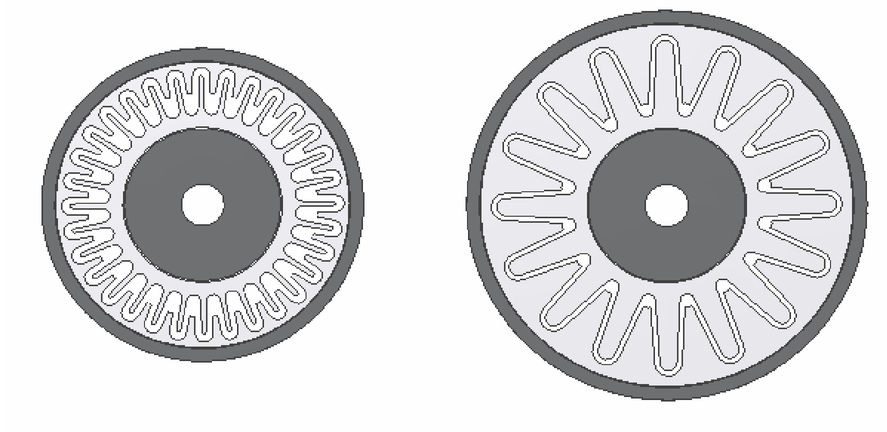

Figure 3.16: Comparative of two endings designs

The first concept is to create a solid volume attached to the end fitting that do not have the air connection. It could to be used to position the gauge pressure sensor and could serve as mechanical stop. The second concept is to create a contractile cylinder attached to both end fittings where other specific connectors are needed in order to canalize the pressurized air to the membrane. This contractile cylinder can be used to position the gauge pressure sensor and to hold a return spring. During the contractile cylinder material selection it is important to take into account two facts: 1.. It introduces some spring-like behaviour to the muscle and 2.. The air inside the contractile cylinder is pressuriced according to its volume variation. Figure 3.17 shows how these two concepts can be implemented.

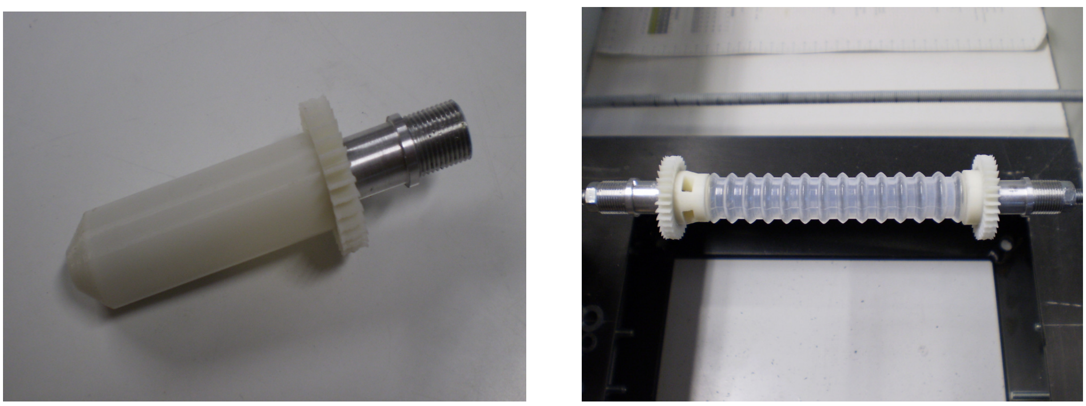

Figure 3.17: Photographs of two differents implementations to reduce the dead volume

3.4 PPAM 3.0 production process

The third generation of PPAM has been developed according to two main objectives: to simplify the manufacturing process and to avoid failure muscles. As is mentioned in previous sections, during the development of PPAM 3.0, the production process has been much simplified and production time has been drastically improved, focusing in a possible comercial production. The production process of the PPAM 3.0 can be seen in figure 3.18. This new step has been possible due to the use of Fused Deposition Modelling (FDM) rapid prototyping technology and a continuous high tensile fibre.

The airtight flexible cylinder is made with a new polymer liner which is a little bit stronger than that for the previous generation. Therefore, the metal cylinder which is used to made the fabric cylinder around, has been modified. The new one has a longitudinal gap that make possible the extraction of the fabric cylinder. In order to make the building of the muscle easier the fabric cylinder is mainly prepleated by using a simple metal part. During this process, the external and internal pleats are marked. Figure 3.19 shows photographs of these two operations.

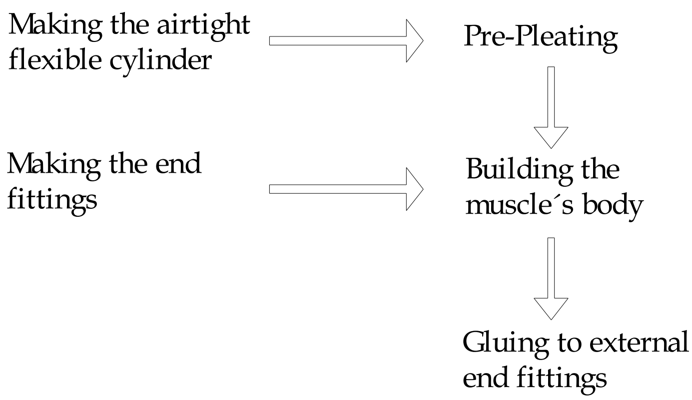

Figure 3.18: Diagram of the production process of the third generation of PPAM

The airtight flexible cylinder is made with a new polymer liner which is a little bit stronger than that for the previous generation. Therefore, the metal cylinder which is used to made the fabric cylinder around, has been modified. The new one has a longitudinal gap that make possible the extraction of the fabric cylinder. In order to make the building of the muscle easier the fabric cylinder is mainly prepleated by using a simple metal part. During this process, the external and internal pleats are marked. Figure 3.19 shows photographs of these two operations.

Figure 3.19: Photographs of the building and prepleating of the fabric cylinder

The construction of the muscle body is the main part of the muscle production. The internal parts of the end fittings, which include the aluminum body and the internal teeth, are positioned at the correct distance on a threaded rod. The pre-pleated airtight flexible cylinder is colocated around the rod, which is fixed to a specific set up built for this purpose. Then, the continuous high tensile fibre is arranged over the internal teeth and the pre-pleaated fabric. The continuous fibre is colocated at the bottom of each crease in a consecutive way. It goes from one side of the muscle to the other as many times as the number of pleats. Figure 3.20 shows some photographs of this operation. At the end of the building process, the fabric has taken the same shape that the toothed part and the fibre has been positioned in meridional planes at the bottom of every pleat.

When the fibre is completely arranged, the external teeth are fixed at both sides of the muscle at the same distances that their internal counterparts. During this process, a high viscousity glue is used in order to fix definately the whole structure without impregnate the fibre. After the extraction of the threaded rod, the caps are colocated. They are positioned covering the whole fixing structure in order to get a more aesthetic muscle and to position the muscle connectors at both sides of it.

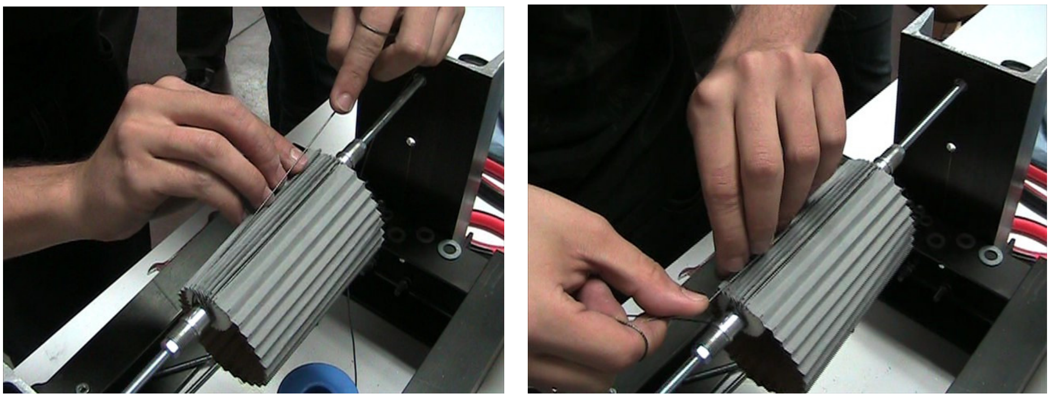

Figure 3.20: Photographs of the muscle body building process

Finally, figure 3.21 shows photographs of the new muscle prototype made with 32 pleats at different states of inflation. Note the regular unfolding of the airtight flexible membrane while the Dyneema fibre is positioned at equal distances. Some lifespan tests have been performing, at which the muscles inflate and deflate slowly from a gauge pressure of 1 bar to 3 bar carrying a load of 130 kg. At the moment, these incomplete tests have reached about 35000 cycles, and it has observed a perfect behaviour of the muscles.

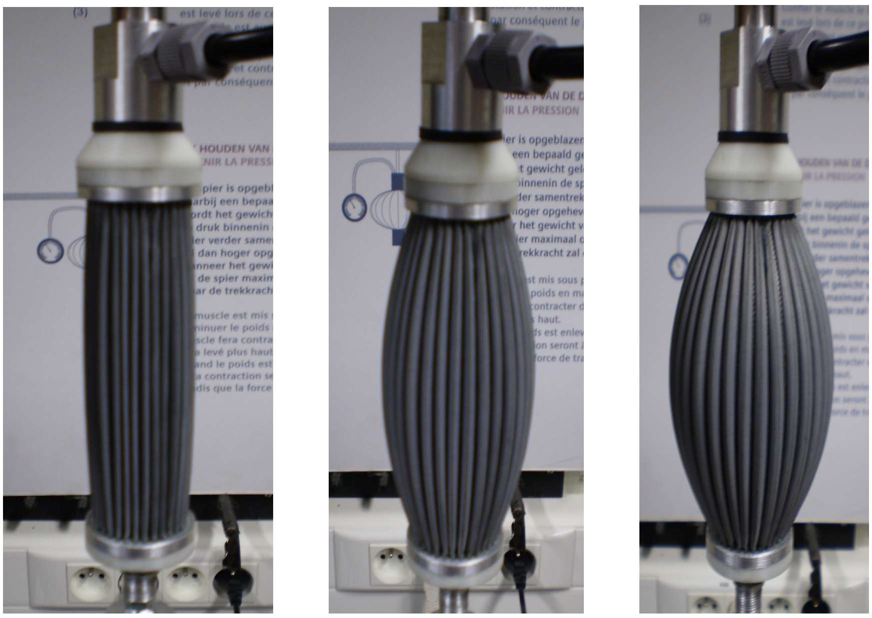

Figure 3.21: Photographs of the muscle prototypes at different states of inflation

3.5 Static load tests

As was done by Daerden [1999] and Verrelst [2005], static load tests are carried out to compare the prototypes performance with the mathematical model of developed force equation (ec. 3.5). Five different muscles are tested on different trajectories between 150 N and 3 kN with a test bench at isobaric conditions, while applying three different gauge pressures: 1, 2 and 3 bar. The tested muscles have a physical membrane length l_0 = 110 mm and an unpressurized radius R = 11,5 mm for the position of the Dyneema fibres. Four of the muscles are made with 32 pleats and a radius of 15,6 mm at the top of the polyester fabric pleats while the other one is made with 16 pleats and an external radius of 20,2 mm. Testing these two different designs it is possible to analyse the influence of the number of pleats and their shape in a practical way.

One side of the muscle is fixed to the load cell while the other side is attached to a movable frame. The tests are performed by controling the displacement of this frame. During each test, frame position, muscle force and applied gauge pressure are recorded. The forces are recorded with a load cell of 10 kN and the pressure inside the muscle is regulated by a Kolvenbach pressure servo-valve, KPS 3/6. [13]. In order to increase accuracy, the pressure inside the muscle is measured by a gauge pressure sensor, BSDX5000G2R. [14] Figure 3.22 shows photographs of the two different muscle designs during the tests.

Figure 3.22: Photographs of the two different muscles during the tests

At the begining of each test, the voltage controlling the servo-valve is set to regulate the pressure inside the muscle for a constant level: 1, 2 or 3 bar; and the moving part of the test bench is positioned according to the initial muscle force asigned for each run.

Figure 3.23 gives the results of the tests by depicting force as a function of contraction for each of the four muscles with 32 pleats at the three different gauge pressures. The repeatability seems succesful but, as in the tested carried on the second generation prototypes, an important hysteresis effect is noticed. It is observed that the muscles present more hysteresis at 1 bar than at bigger gauge pressures. Figure 3.24 gives a detailed view of the hysteresis for the case of 1 bar gauge pressure. It is seen that the four muscles present a comparable hysteresis width.

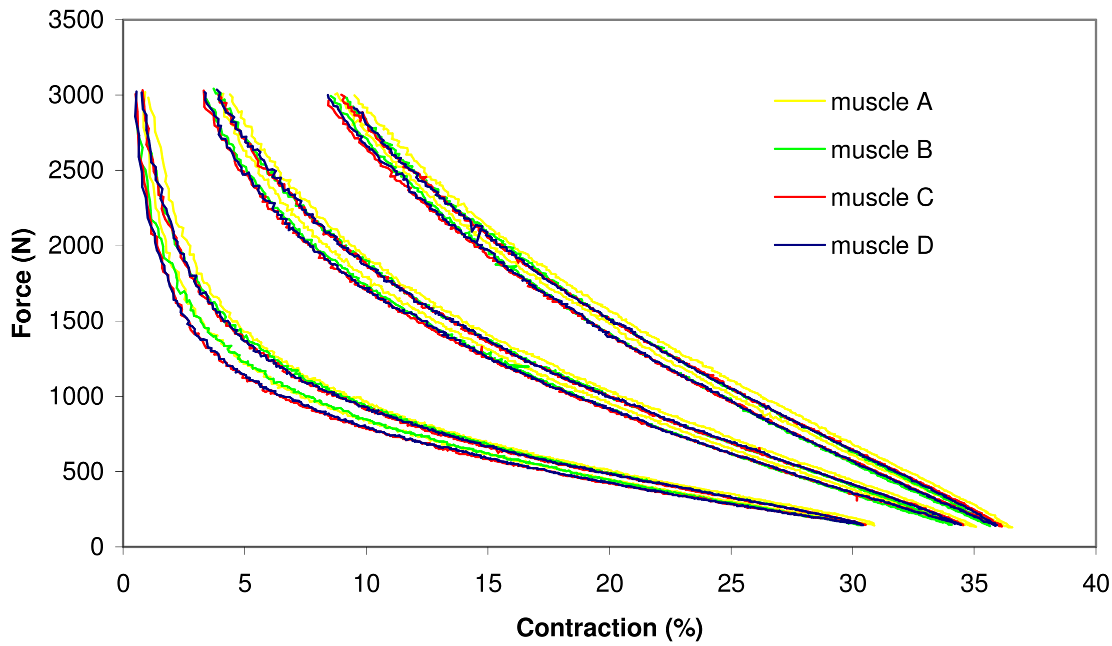

Figure 3.23: Measured forces as a function of contraction for the four muscles made with 32 pleats at pressure levels 1, 2 and 3 bar

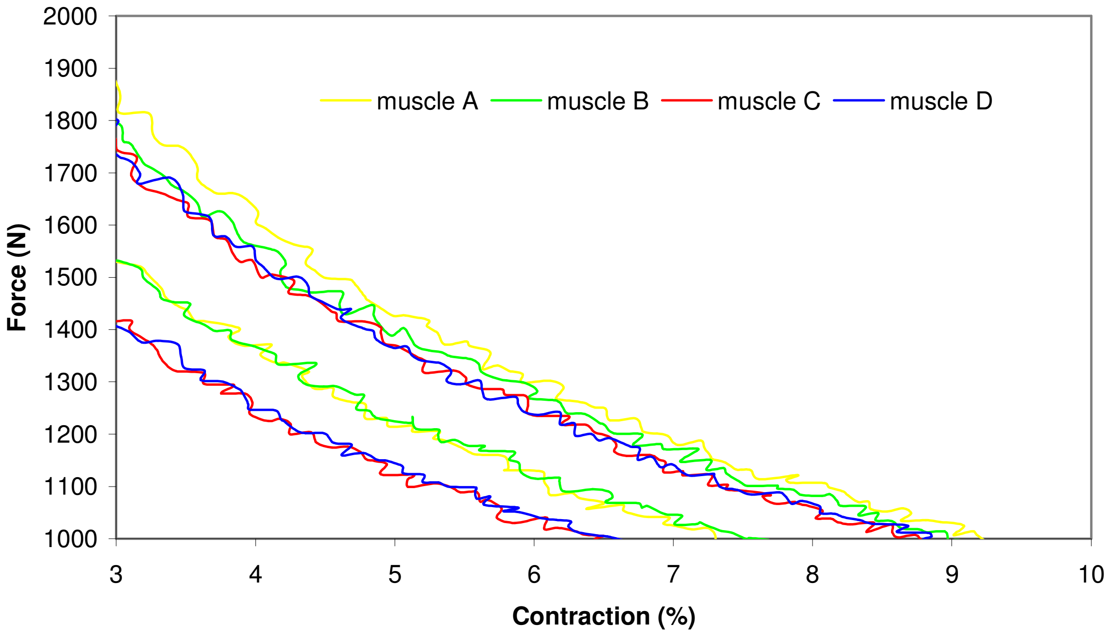

Figure 3.24: Detailed view of measured forces as a function of contraction for the four muscles made with 32 pleats at pressure level 1 bar

In order to analyse the influence of the hysteresis in a complex trajectory, some other tests are performed. At each gauge pressure, the muscles are tested during three different cycles in a continuous way (the muscle starts the second cycle at the same state that fhinishes the first one). During the first cycle, which is called Complete cycle, the muscle is inflated and deflated being limited by the maximum and minimum forces of the tests: 3 kN and 150 N. The muscle reaches the maximum contraction at the minimum force. Then, during the second cycle the muscle goes from 3 kN to 2/3 of the maximum contraction, and at the third cycle it goes from 3 kN to 1/3 of the maximum contraction. Figure 3.25 shows the force measurements of one muscle obtained during the three cycles. It is seen that the hysteresis introduced by the complete cycle affects to the other two. The initial contraction of these shorter cycles is bigger than that of the complete one. However, the second cycle seems to return to its initial position, which is therefore the same that the initial position of the third cycle. As this is an un-modelled behaviour, the following analysis is based only in the results of the complete cycle.

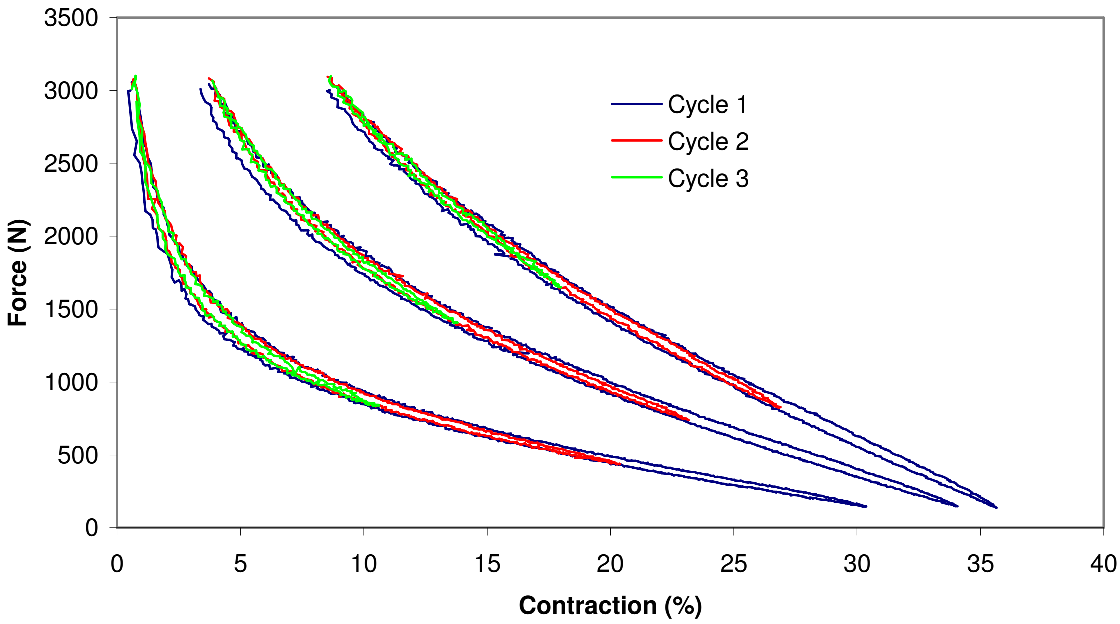

Figure 3.25: Measured forces during three cycles as a function of contraction for one of the muscles made with 32 pleats at pressure levels 1, 2 and 3 bar

Figure 3.26 gives the results of the complete cycle of the muscles made with 32 pleats together with those for the muscle made with 16 pleats (muscle E). According to the mathematical model, the developed forces should be proportional because both designs have the same theoretical slenderness. Furthermore, as they have the same dimenssions, the theoretical proportion should be only dependent of the different number of pleats according to the ecuation 3.5. $\frac{F_t(16\ pleats\ )}{F_t(32\ pleats\ )} = \frac{0.9745}{0.9936} = 0.9808$

It is seen that the results are not exactly proportional. The difference between the curves of both designs increase with contraction and gauge pressure. Furthermore, the muscle E is not able to reach the same contractions that the others. In order to compare the muscles behaviour at different gauge pressures with the theoretical model, the measured forces have been devided by the measured pressures. Figure 3.27 gives all the pressure scaled measuraments. It is noticed again the similarity between the results of the two designs.

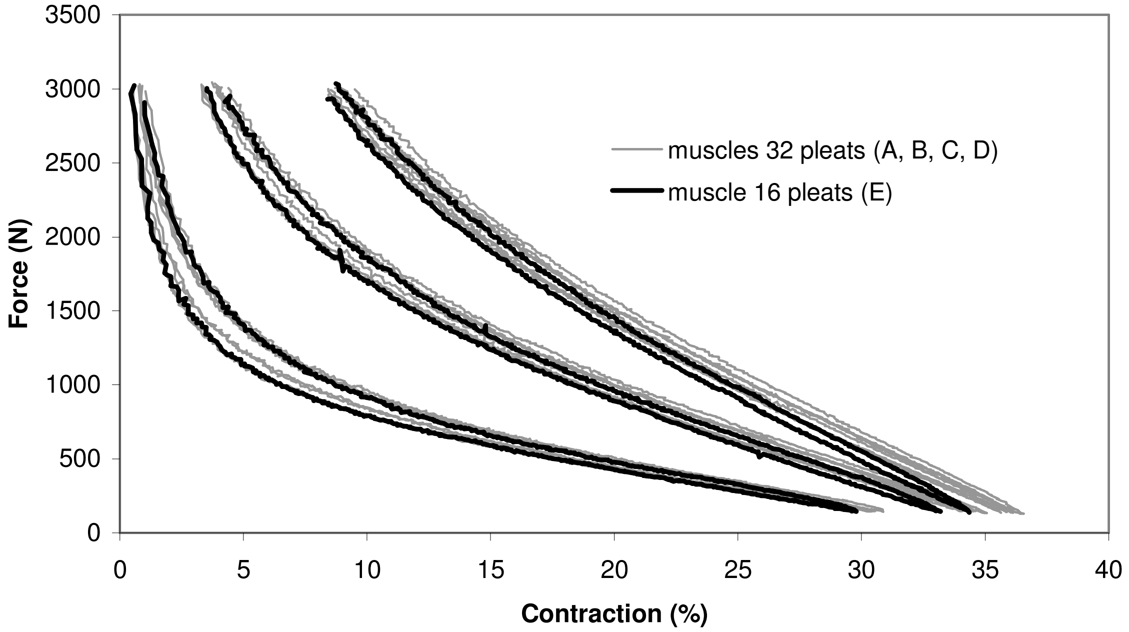

Figure 3.26: Measured forces as a function of contraction for five muscles at pressure levels 1, 2 and 3 bar

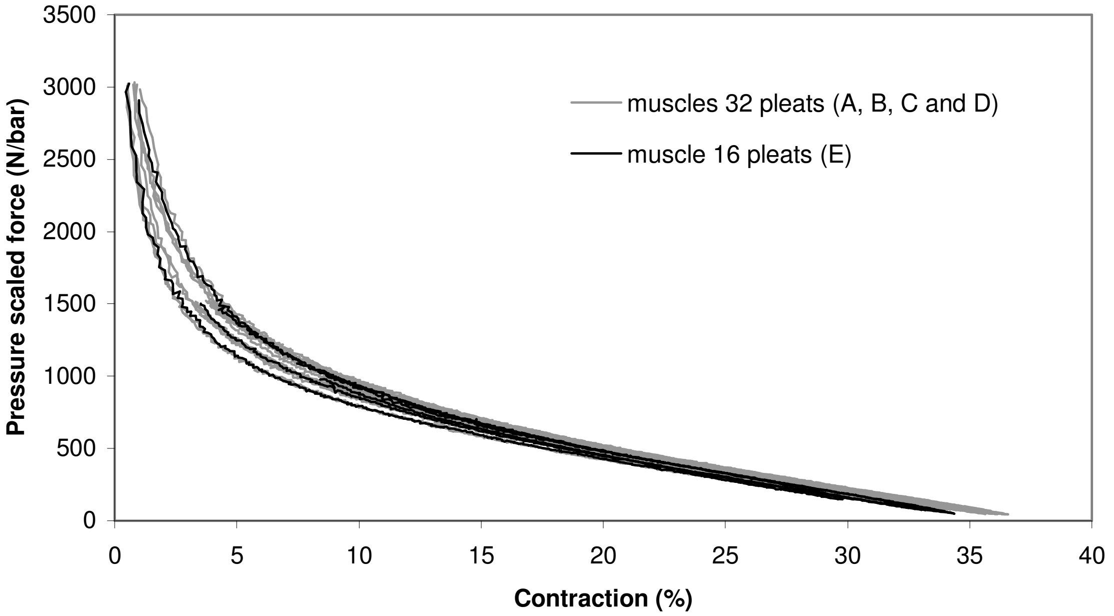

Figure 3.27: Pressure scaled forces as a function of contraction for five muscles

As was done by Verrelst, the pressure scaled measuraments are compared with theoretical graphs calculated with different radius. Figure 3.28 and figure 3.29 show this comparison for the muscles made with 32 and 16 pleats respectively. In these figures are included theoretical graphs for the actual radius at which the fibres are positioned in the prototypes, R = 11,5, and for some other bigger radius. It is observed that the theoretical model with R = 11.5 mm fit the measured data for contraction down to 20 % in both cases: 32 and 16 pleats. But, for larger contractions, the measured forces are smaller than those of the theoretical model. It is believed that this difference at large contraction is due to the radial stress in the polyester membrane. And this stress is caused by the finite number of pleats. Therefore, the membrane of the muscle with 16 pleats suffers more stress than its counterparts of the muscles made with 32 pleats.

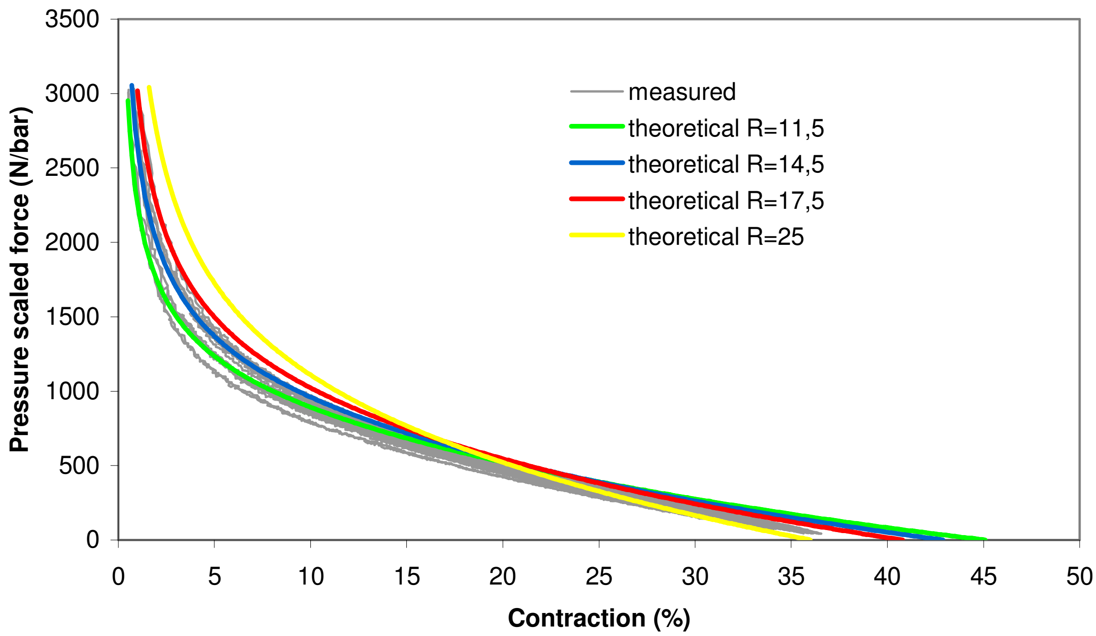

Figure 3.28: Pressure scaled measured forces as a function of contraction for 4 muscles made with 32 pleats comparedwith theoretical model

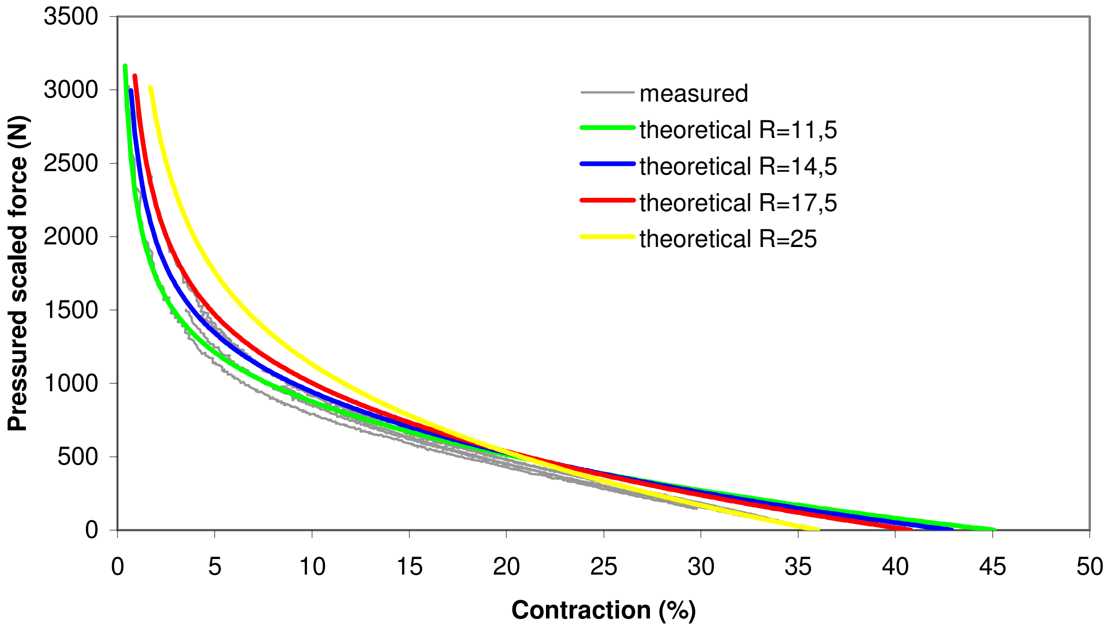

Figure 3.29: Pressure scaled measured forces as a function of contraction for 1 muscles made with 32 pleats comparedwith theoretical model

In both designs, the approximation of the real force with the mathematical model is suitable enough for dimensioning purposes. But, for control purposes, an accurate estimation of the force function is required. In order to achieve a better force estimation, a 6^{th} order polynominal function fit on the pressure scaled forces of the muscles with 32 pleats is performed. Due to only one muscle with 16 pleats has been tested only, its force function is not estimated. The polynominal fit of the force function can be expressed as:

$$F_t = pl_0^{\,2} f(\in) = pl_0^{\,2}\left(f_6 \in^6 + f_5 \in^5 + f_4 \in^4 + f_3 \in^3 + f_2 \in^2 + f_1 \in + f_0\right) \qquad \text{Eq 3.9}$$

and the coefficients of the fitting process for the force function are given in table 3.2. These values are valid when the generated force F_t is expressed in N, the initial muscle length l_0 in m, the pressure expressed in bar and the contraction expressed in %. This polynomial fit of the dimensionless force function can be use for any muscle with the same slenderness that the studied ones: $l_0 / R = 110/11.5 = 9.56$

f_6	f_5	f_4	f_3	f_2	f_1	f_0
0.001127	-0.164187	9.578031	-285.5242	4614.184	-41674.62	232860.9

Table 3.2: Coefficients of the polynomial force function approximation

Figure 3.30 shows the force estimation compared to the pressure scaled force measurements of one muscle at contractions between 5 and 30 %. And figure 3.31 depicts the relative error between measurement and estimation. It is seen that a substantial error is present due to hysteresis. It represents an increase on the hysteresis width in regard to the former generation. The forces generated by the new prototypes present a relative error of ±10 % in regard to a polynomial fit function while that of the previous generation was ±5 %.

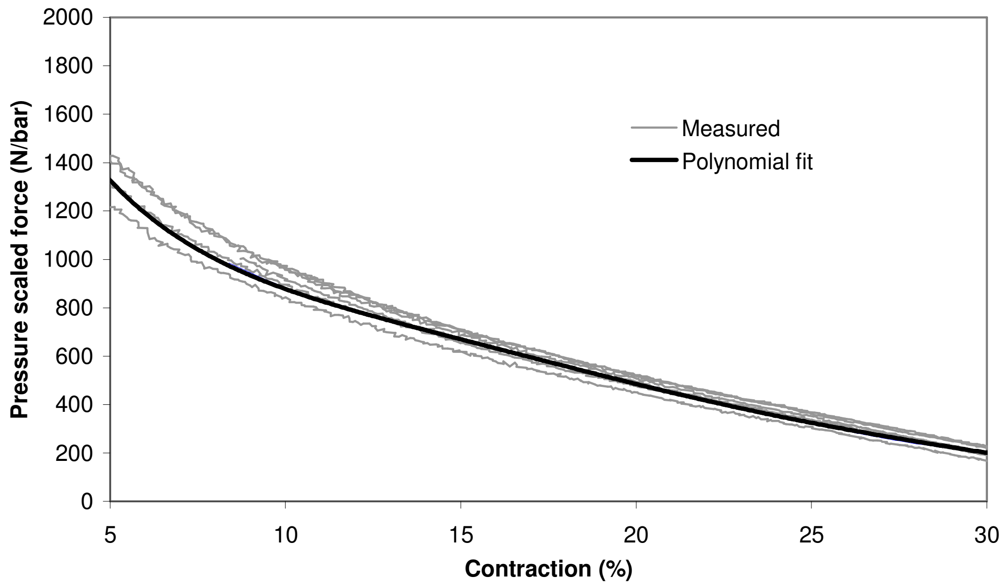

Figure 3.30: Pressure scaled measured forces as a function of contraction compared with polynomial fitted estimation for 1 muscle made with 32 pleats.

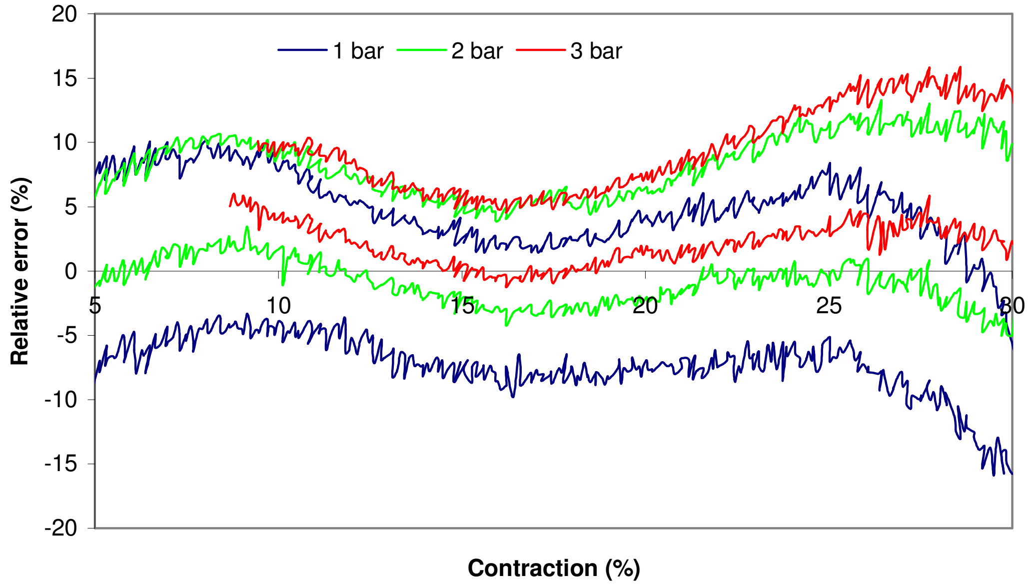

Figure 3.31: Relative error between the polinomial fitted estimation and the pressure scaled measured forces as a function of contraction for 1 muscle made with 32 pleats

Chapter 4

4 General conclusions

This thesis reports on the development of the manufacturing process of Pleated Pneumatic Artificial Muscle. This novel actuator was conceived to improve the performance of other types of Pneumatic Artificial Muscle (PAM), as McKibben PAM. Its specific design presents interesting scientific aspects, as maximal forces and large contractions, but entails a complex production process which has been considered as its major disadvantage since its first design [Daerden, 1999]. In order to extend its lifespan and to simplify the construction of the muscles the Second generation of PPAM was introduced by Verrelst [2005]. The good results obtained validate the adapted membrane design of the Second generation but, its production time was too much long (to build one muscle about 8 hours was required).

During the development of the third generation of PPAM the production process has been drastically simplified and the building time has been reduced to 2 hours, which represent a reduction of 75 % in regard to the previous one. The new manufacturing mixes some operations of the previous production process. It is possible due to the use of Fused Deposition Modeling rapid prototyping technology and a continuous high tensile fibre (Dyneema). The rapid prototyping machine is used to increase the complexity of the end fittings of the muscle. The new end closures have a toothed structure which is used during the building process. Arranging the continuous fibre over the internal teeth it is possible to build the membrane at the same time that it is fixed to the end fittings. This operation is done in a specific set-up which was built for this purpose instead of in a vice, where the prototypes of the previous generation were built.

Another important aspect of a muscle according to comercial perspectives is its material cost. The use of the rapid prototyping machine diminishes the cost of the end fittings. During their production (for a muscle with n = 32 pleats, R = 11,5 mm and l_0 = 110 mm) about 18 cm^3 of fusing material are needed, which represent a total cost of about 7,2 euro. The six ABS parts needed for a muscle are built at the same time at the machine in 90 min while the 4 aluminum parts can be done in about 2 hours. Besides, each new end fittings only weight 16,3 g. They are much more lightweight than the former ones which reduces the weight of the prototype to 48 g.

The new production process avoids the use several complex pleating gadgets, as a balloon, elastics or several thin rods which introduced instability in the previous process. Some times the fabric was damaged invalidating all the previous work. Another interesting advantage of the new production process is its flexibility. As complex pleating gadgets are not needed, it is possible to build muscles with different designs in the same set-up. It is possible to change the number of pleats, the radius of the fibre´s position and the shape of the pleats.

In the previous production process a high quantity of pleats were needed in order to keep the pleated shape of the membrane during the gluing while in the new manufacturing: the less pleats, the easier and faster the production is. It facilitates the fabrication of muscles with smaller radius of the fibre´s position. This radius, which is very similar to the internal radius of the membrane, determine the dead volume. Therefore it is an interesting objective for future research studies as well as the different implementations for avoiding the dead volume that have been introduced in this work.

During the static load tests, which were carried out to validate the new generation, muscles with different number of pleats (32 and 16) were tested. Analysing the results it was noticed an increase on the hysteresis width in regard to the former generation. The forces generated by the new prototypes present a relative error of ±10 % in regard to a polynomial fit function while that of the previous generation was ±5 %. It is also observed that the forces generated by the new prototypes at low contractions, down to 20 %, are more suitable to the mathematical model than the former ones. During this contraction range the prototype built with 16 pleats developed forces highly comparable to those with 32 pleats. However, at contractions up to 20 % the measured forces are smaller than those calculated by the mathematical model. This difference becomes bigger with the contraction and with the gauge pressure. It is caused by the radial stress in the polyester membrane, which increases with smaller number of pleats. Therefore, according to the theoretical model resemblance, the difference between the number of pleats of the tested muscles can be neglegted for low contractions but it becomes more important for larger contractions. In the near future some more tests will be realized to complete this analysis and determine the influence of the number and shape of pleats.

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