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A Novel Bio-Inspired Fluidic Actuator for Robotic Applications

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Abstract

Biological research on the spider leg mechanism has inspired the development of a novel hinge joint actuator with an antagonistic fluid system. Current bio-inspired robot systems with fluidic muscles can provide a higher power density than conventional piston-cylinder assemblies with the same working pressure and diameter. But like conventional robot arms, current fluidic systems work with the same structural concept: stability is provided by a framework of beams and links while the actuators are placed upon it. A more efficient, lightweight principle can be found in spider legs. An exoskeletal architecture of stiff, tube-like limbs and flexible joint membranes comprise the primary structure, which is filled with hemolymph and muscles. The two most important joints of biological spider legs are extended hydraulically by an increase in fluidic pressure, whereas flexion is performed by the muscles. Recent data from biological studies show that this counterplay of hydraulic extension and muscular flexion is the source of spiders' incomparably lightweight and powerful legs. Furthermore, the exoskeleton protects the sensitive acting parts and ensures functionality even in harsh conditions or environments. The presented fluidic joint actuator exemplifies the technical application of this unique system. A stiff exoskeleton, with an inflatable joint membrane is constantly filled with fluid pressure, which creates the default extension of the joints. In addition, a fluidic muscle, with a higher pressure, is integrated into this "low pressure domain" and connected to the limb. The muscle is filled to generate flexion. So the counterplay of passive "high cross-section–low pressure" extension and actively controlled "low cross-section–high differential pressure" flexion makes a novel, dynamic rotary actuation system possible. Moreover, balancing the two pressure levels allows individual, case-based adjustments and increases the energy efficiency of the system.

1. INTRODUCTION

Conventional industrial and mobile robotic systems are mostly operated with electrical motors. By placing the motors at the joints, the moving robot arm has a large mass. In contrast, a fluidic robot has the advantage of generating the actuation force in the center of the robot, which is less mobile, and then transmitting the actuation force to the moving arm or leg. This movement is more energy efficient due to the lower inertia in the moving parts. However, existing hydraulic robots mostly work with conventional piston cylinder assemblies which are actually designed for heavy duty machinery. Characteristic for these

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systems is that the limbs of the construction have to bear the loads and the fluidic actuation system is placed on top of the limbs, which causes additional load. Furthermore, the piston-cylinder assemblies are often made from steel, thus the parts themselves become quite heavy. Another non-trivial point is that there is always an energy loss due to the friction between the moving rigid parts and the seals.

To minimize or eliminate these disadvantages of fluidic actuation systems, more and more research in the field of fluidic propulsion systems has been conducted. Several universities and companies are currently developing new kinds of pneumatic and hydraulic actuators. By replacing the heavy, metallic piston-cylinder assemblies with inflatable and elastic elements, more lightweight and energy efficient moving systems are possible. Currently, most developments are found in the field of robotics and medical technologies.

2. STATE OF BIOLOGICAL SCIENCE

As already mentioned, the use of fluidic propulsion in the field of robotics is a big issue, because lightweight design is essential for increasing energy efficiency and improving dynamic behavior. Biology supplies us with a perfect example of fluidic propulsion: the spider leg is an ideal showpiece, which demonstrates how lightweight design and fluidic actuation can go hand in hand.

2.1. The mechanism of the spider leg

Spider legs consist of seven tubular, exoskeletal segments, which are coherently connected to the prosoma. Besides tissue, nerves and arteries, the legs are almost completely filled with muscles. Most of the joints between the linked limbs are extended and flexed by muscles [1], [2]. The exceptions are the two most important leg joints, the femur-patella-joint and the tibia-metatarsus-joint. These joints are extended only by fluidic pressure. They can be considered as hinge joints with the pivot axis on the top (distal) side and a flexible joint membrane on the lower (dorsal) side [3]. After Ellis [4] determined an association between the hemolymph pressure in the legs and the joint extension, Parry and Brown [5] proved the association with empirical experiments. In Figure 1 a cross-section of a tibial limb is shown to illustrate this construction. Arteries and nerves are located centrally (grey areas section A- D) inside the protective exoskeletal tube, surrounded by muscles that fill a large area of the cross-section, shown as black in the lower half of Figure 1.

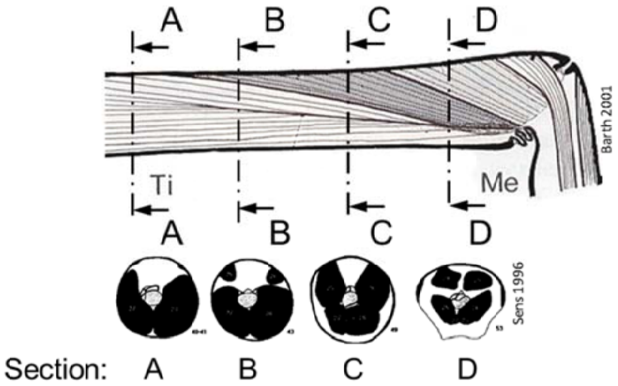

Figure 1. Cross section sketch of a tibial segment of a spider leg according to findings from [6]and [7]

Due to the fact that spiders have an open blood circulatory system, all of the intermediate space - shown as white areas in Figure 1 - between the muscles and the tube-like cuticle is filled with hemolymph, the spider's bloodlike fluid. Furthermore, the leg tubes are connected to the prosoma, which can be considered as a central reservoir for hemolymph and muscular contraction of the prosoma displaces fluid from the central body into the extremities. Therefore, the intermediate spaces between the muscles, called lacunae, can be viewed as channels that enable a quick shift of fluidic volume. Consequently, the pressure in the legs increases and the flexible joint membranes are forced to expand. [8]

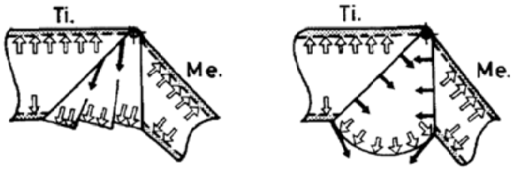

Figure 2. Mechanical design of the joint membrane of the tibia-metatarsus joint [1]

According to BLICKHAN et al., the expansion of the joint membrane can be attributed to inflating the flexible cuticle rather than stretching it. This fact is illustrated in Figure 2. If the membrane consisted of an isotropic material and had a consistent thickness, a bladder-like expansion would cause tensile stress in the material. This stress develops tensile forces which cause torque to counterforce the extension. A more energy-efficient principle is an expansion by inflation of the membrane. Most tension occurs radially and only minimal tangential tensile forces are developed in the membrane, so counteracting torque can be avoided. But therefore, the membrane also has to be folded when the joint is flexed. [1]

As shown in Figure 1, there are a lot of muscles to counteract the movement. On the one end, these muscles are fixed at the cuticle of their surrounding dorsal limb, on the other end there is a connection to the subsequent limb. When the leg joints are extended, the muscles are relaxed and have their maximum length. Contraction leads to a pulling movement and an active flexion of the leg segment. SIEBERT and WEIHMANN have investigated this movement and determined some relationships between muscle force and length for the metatarsal flexors of a *cupiennius salei* spider. First of all, the hydraulic joint extension principle is space-saving because there is no need for extension muscles. [9]

Furthermore, in comparison to endoskeleton muscular joints, where the pivot point is at the center and muscles are located beside the joint [10], the pivot of an exoskeletal hinge is located eccentrically on the distal side of the limbs. This has two biomechanical advantages, the leg limbs can almost entirely be filled with flexors and the distal pivot, in comparison to the dorsal muscle endpoint connection on the subsequent limb, that lead to the largest possible lever ratio. This is the recipe for the uniquely slender and powerful legs.

2.2. Biological control mechanisms of the fluidic spider legs

However, another aspect to be considered is the control mechanism of the legs. As mentioned above, the prosoma is the central reservoir of the fluid and all legs are connected to it. So, the first thought is that all of the C-shaped flexed legs of a sitting position should extend simultaneously by displacing hemolymph from the prosoma into the legs. But in fact, this is not the case; the spider has to be able to control each joint individually to achieve a walking, running or jumping movement.

STEWART and MARTIN have investigated that already before the spider starts walking, the required pressure in the legs is provided from the prosoma. Parallel to the pressure, the leg muscle activity is increasing in order to prevent a premature extension. Furthermore, the global pressure level remains increased during an entire walk. [11]

This clearly supports the assumption that the fluidic extension of the spider leg has a passive role while the muscular flexion is the active part of movement [7].

3. STATE OF TECHNOLOGY

In the field of robotic applications and medical devices, lightweight designs, energy efficiency, dynamic behaviors, accuracy and compliance are major issues. An analysis of the developments in the fluidic field in the last decade reveals a trend of replacing the heavy, metallic piston-cylinder assemblies with flexible components with a high degree of structural integration [12].

Especially a lot of effort has been expended in bio-inspired research to find new and flexible fluidic actuators and lightweight motion systems for technical applications. Several developments based on the biomechanical principles of spiders and other animals have been made in the last years. As shown in Figure 3, two main fields can be clustered to categorize the research within the area of “Flexible Fluidic Actuators”.

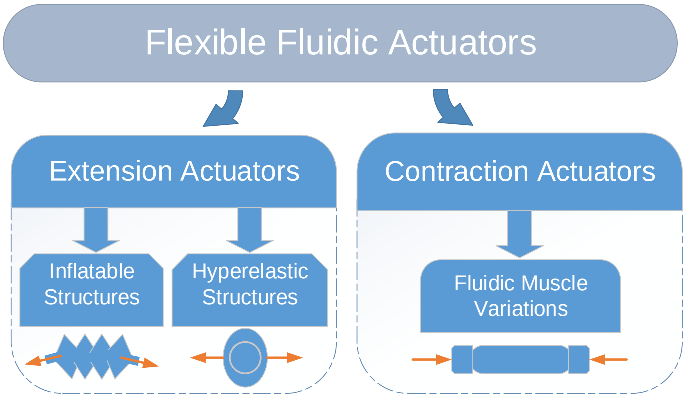

Figure 3. Overview of several kinds of flexible fluidic actuators

Either there are applications with inflatable or elastic structures generating linear, rotary or mixed extensions from fluidic pressure forces [13], [14]; or there are contraction actuators, which arise from fluidic muscle variations based on the “McKibben-Principle” [15]. Both are described in the following section to give an overview on the current state-of-the-art.

3.1 Contraction actuators

Fluidic contraction actuators can be summarized according to the actions of the fluidic muscle variations. These actuators work with a structured, tube-like design, which extends radially but shortens axially when pressure is applied. Pneumatic artificial muscles (PAM), also known as McKibben muscles [15], named by the founder of this technique JOSEPH MCKIBBEN, are widely used for research activities and developments in bio-inspired robotic systems [16], [17], [18] and medical prostheses [19], [20], [21]. Since they are available on the market from the Shadow Robot Company [22] and the German robotic and automation company, Festo [23], the general interest in fluidic muscles is growing and, in turn, advancing the new field of fluidic applications. The maximum pneumatic pressure to operate pneumatic muscles is commonly between 4 bar [22] and 8 bar [23] with a shortening of up to 20% for these standard artificial fluidic muscles. Furthermore, current research activities include evaluating hydraulic artificial muscles

(HAM) by operating muscles with a significantly higher fluidic pressure [24], [25] to produce actuators that are more powerful. Moreover, also some new systems [26], [27] have been developed, which are actuated by hydraulic muscles.

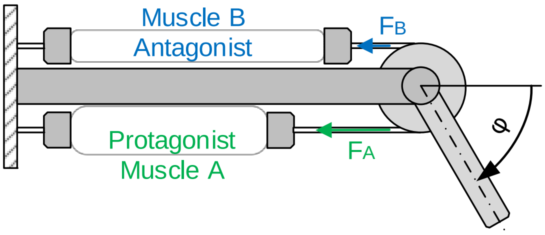

Figure 4. Fluid protagonist and antagonist muscles for a 1-DOF rotary system

However, like real muscles, the artificial fluidic ones can only provide a pulling force and a linear shortening by actuating. Due to the fact that they cannot provide a pushing force, some kind of antagonist is necessary to manage a rotary actuator. As shown in Figure 4, deflection is required. This is generally accomplished either by a second fluidic muscle or a spring mechanism. And it also has to be taken into account that the highly nonlinear behavior of these actuators makes it challenging to control. Nevertheless, PAM's and HAM's success is due to their low inertia and high force/mass ratio which enables them to perform highly dynamic movements. Their compliance, which results from their structural flexibility, is also important for achieving fluent movements and fulfilling safety requirements.

3.2. Extendable structures with an focus spider-inspired devices

The field of fluidic extendable structures is wide and has developed significantly. Our work is focused on biomimetic, especially spider-inspired systems. The mechanism of the spider leg is an ideal biological model for fluidic joint extension and researchers have pursued it from various perspectives. The first abstract mathematical model of a spider leg was established by ZENTNER [28] and based on biological investigations. This model describes the extension of a spider's leg due to increasing fluidic inner pressure. The results were compared to the biological measurements. An active muscular flexion was not focus of the investigation.

Nonetheless, concepts inspired by the fluidic extension of the spider leg were developed based on these calculations. While increasing the inner pneumatic pressure, the expansion of hyperelastic material leads to a movement of the generally monolithic devices. The passive retraction is achieved by the inherent stiffness of the structure. [15], [29]

Besides these spider-inspired developments, which are based on extendible materials, other research activities are using inflatable bellow-like principles to build bio-inspired fluidic driven joints. SCHULZ developed a fluidic actuator consisting of a hinge joint and a bellow-like inflatable polymer, which is reinforced with a fiber braid to allow high inner pressure. Furthermore, the fluid chamber is equipped with an admission and a discharge coupling to connect the fluid power line. Recent research activities have concentrated on the fabrication process, which is either done by compression molding or HF-welding. Over the years, a large variety of these actuators have been developed and the standard operating pressure of up to 10 bar fluidic pressure has been achieved. [30], [31]

Further developments based on spider-inspired mechanisms have been made by MENON and LIRA Limbs are linked in series while an elastic micro-tube is folded perpendicular to the rigid spacers at the joints. Pressurizing the tube leads to an expansion of the material, thereby extending it and pushing the spacers apart from each other. By using a lot of linkages, which are crossed by the same pressurized tube, a large bending movement is possible. [32]

4. NEW CONCEPT

The review of the state-of-the-art shows that while the superior model of the spider leg has influenced research. Current technologies fail to effectively use the whole model; the established technologies make use of either systems with pressure-controlled fluidic extension or various systems with fluidic muscle actuation.

With the presented concept, the entire biomimetic functional principle of the spider's most important leg joints is transferred into a technical application. The bio-inspired fluidic extension as well as the muscular flexion is taken into account and combined into one actuation system. As a result, a novel, bio-inspired actuation system that can be driven pneumatically or hydraulically has been developed for robotic applications.

4.1 Design concept

Inspired by the unique dynamic and powerful legs of the spider, the actuator's design is also lightweight due to its exoskeletal construction. Tube-like limbs provide a high cross-section bending modulus that create a very strong but yet lightweight frame. These limbs are connected by an off-center pivot joint and are covered by a joint membrane with an oppositely disposed inflatable structure. This closed system has a pneumatic or hydraulic connection to apply pressure in a "low pressure domain" which leads to the inflation of the joint membrane and to the extension of the hinge.

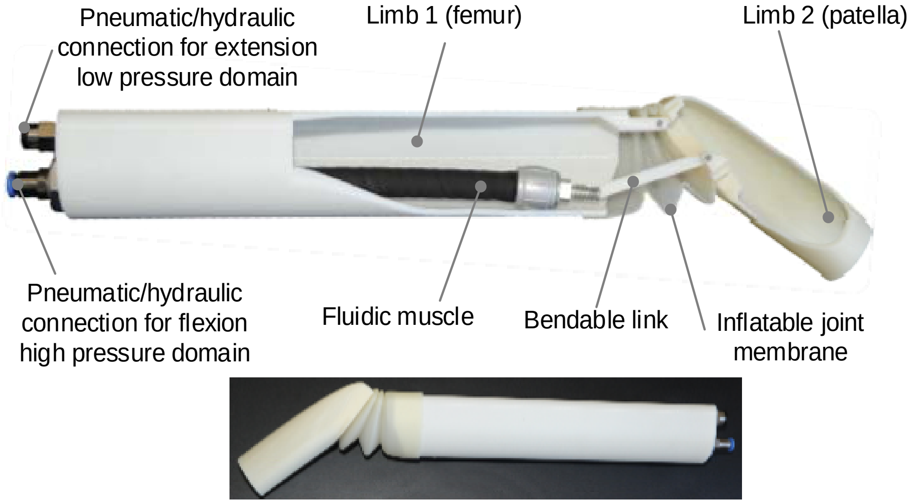

Figure 5. Prototype of the fluidic joint actuator, transferring the entire principle of biomimetic function of the spider leg into a soft robotic application

For powerful flexion, the biological spider has muscles acting as a tractive actuator to retract the extended leg. This is accomplished by an integrated fluidic muscle. By filling the fluidic muscle with high pressure, the difference between the lower pressure for extension and the muscle's high pressure domain leads to a shortening of the muscle and therefore to flexion of the joint actuator. The counterplay of passive "high cross-section – low pressure" extension and actively controlled "low cross-section - high differential pressure" flexion results in a novel, dynamic rotary actuation system. Furthermore, balancing these two pressure levels allows individual adjustment on a case-by-case basis, which increases the energy efficiency. So the same actuator can be driven with a powerful extension mode and a low retracting force or with a strong flexion mode and a weak extension.

4.2 Simulation

Several design variations of the joint membrane were modeled in CAD and FEM-Simulations with ANSYS were carried out to evaluate these variations. As shown in Figure 6, some simplifications were made in the simulation in order to save computing capacity. Symmetry is assumed on the cross-section and both limbs are set to be rigid. Furthermore, the joint membrane is assumed to be closed in the join to the upper limb so that pressure is exerted on all inner surfaces. The flexible membrane is modeled with 42,855 SOLID185-elements. Moreover, key option functions are set to optimize the mixed u-P formulation of the elements and energy based stabilization is used. Material properties are defined using Yeoh-curve fitting according to the stress-strain behavior determined by tension tests.

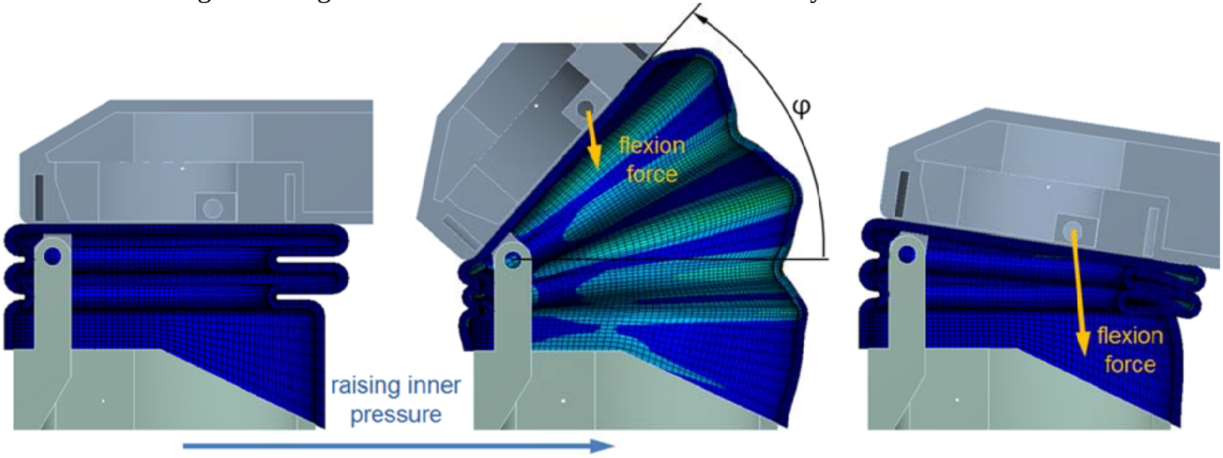

Figure 6. FEM-Simulations – Joint extension by applying inner pressure and flexion by retraction forces

As illustrated in Figure 6, the joint membrane gets inflated by raising the inner pressure. A remote force applied at the upper limb, where the muscle is connected, is defined to simulate the muscular tensile force. The lever of the contraction force to the pivot axis provides torque to flex the joint actuator. In addition, with constantly applied extension pressure, the actuator can be flexed. Depending on the pressure level in the fluidic muscle and the extension pressure acting on the joint membrane, a specific angle can be realized. By analyzing the system, several structural loads are affecting the joint. The applied pressure is providing extension torque, counteracting the internal torque due to the inherent stiffness of the joint membrane. A flexion torque is created by the muscle actuator and possible external torques can be applied. In a static case, they are always in equilibrium and consequently, there is no resulting torque, which would provide motion.
This can be described by:

$$T_{Extension} - T_{Internal} - T_{Flexion} + T_{External} = 0$$

Characteristics of this behavior are shown in Figure 7.

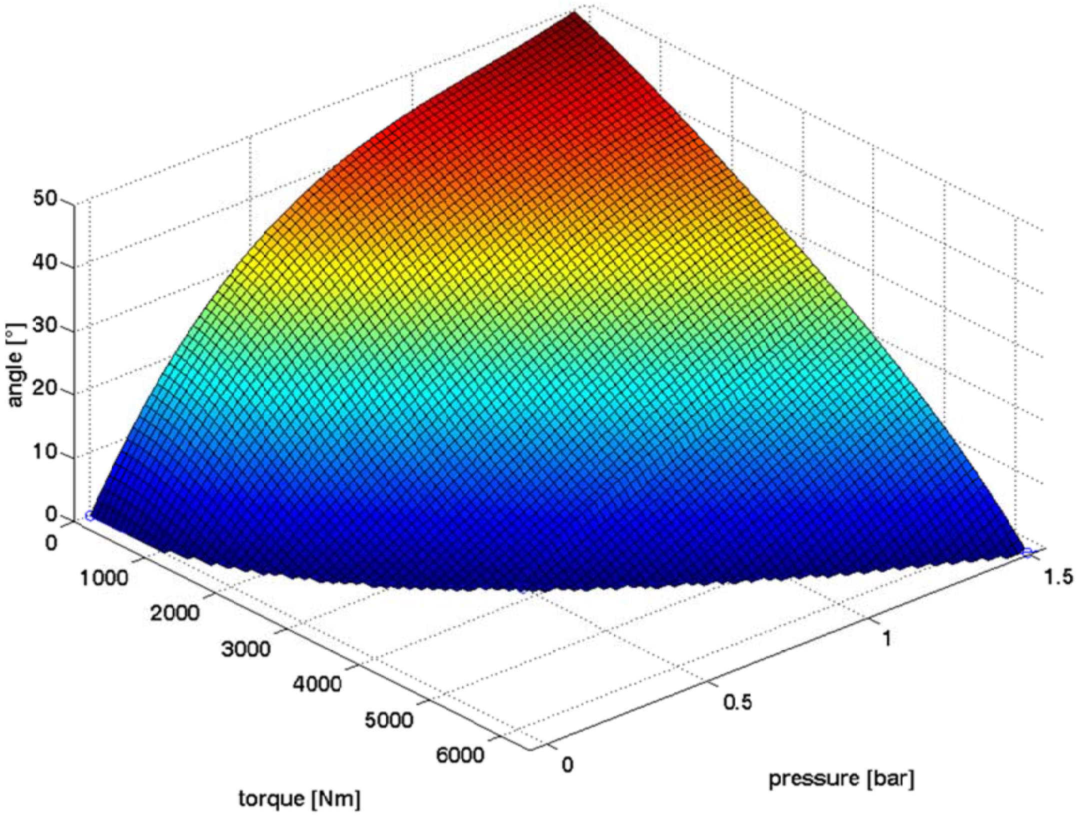

Figure 7. Characteristics of a spider-inspired joint prototype. Exemplary for results of a prototype with the illustrated joint membrane and a Shore 90A material

Without applying any muscle forces or external forces, applied pressure can deform the membrane and rotate the upper limb. By using a Shore 90A material for the joint membran, an inner pressure of 1.5 bar leads to an extension angle of 49.7 degrees to keep the system in balance (Figure 7, torque 0 Nmm). If additional load is applied, the compliance leads to a change of the joint angle until equilibrium is reached again. This is illustrated in Figure 7, for example a torque of ~6000 Nmm leads to an angular change down to 0 degrees. From angles lower than -3.2 degrees, the joint membran gets compressed (Figure 6, right side). This causes an additional damping behavior which is not considered in Figure 7. Depending on the levels and changes of the pressure in the exoskeleton and in the fluidic muscle, rotations can be executed and external loads can be moved in both directions. In general, this dynamic behavior can be described by:

$$T_{Extension} - T_{Internal} - T_{Flexion} + T_{External} = T_{Motion} = J \cdot \ddot{\varphi}$$

5. FUTURE RESEARCH

Basic tests of the prototype show a similar behavior to the simulations, illustrated in Figure 8. At the moment, test rig evaluations are being carried out to verify the theoretical calculations.

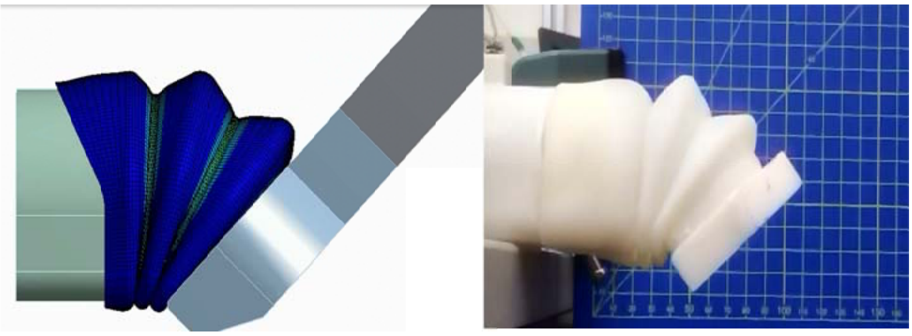

Figure 8. Prototyping tests of biomimetic actuator concepts based on the spider leg

Furthermore, control concepts and a structure-integrated sensor concept for the actuator are being developed. These concepts are necessary for making the system usable in a wide range of applications. In future research and development, a focus will be to optimize this fluidic actuator with regard to geometry, materials and energy efficiency. After this, also a hydraulic variation is envisioned to provide an actuator with significantly higher torque.

6. CRICITAL DISCUSSION AND SUMMARY

The presented work shows a novel and biomimetic actuator. The fluidic extension as well as the muscular flexion based on the biological of the spider leg is combined in this actuator for future robotic applications. The fluidic actuator can be operated pneumatically and provides a high power/weight ratio. Furthermore, a dynamic behavior is provided by balancing the two pressure levels. The compliance of this system enables fluent movements, helps to withstand impacts and to fulfill safety requirements. From our point of view, compliant mechanisms like this will be increasingly important. New rapid prototyping methods and additive manufacturing techniques make it easier to produce flexible parts such as those used in the mechanism we have developed. Besides these positive aspects, it also has to be mentioned that the control of this compliant mechanism with an antagonistic fluid system is very challenging.

ACKNOWLEDGMENTS

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