# Scalable Pneumatic and Tendon Driven Robotic Joint Inspired by Jumping Spiders

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Abstract—Fluidic actuators allow versatile, agile, and powerful motions and are commonly applied in robotics and automation. Likewise, many biological systems use fluidic actuators implemented with tissue for a wealth of tasks and performances. Spiders for example apply a hybrid mechanism of hydraulically actuated joint extension and muscle-based joint flexion to produce movement in two of their seven leg joints. Here, we present a novel spider-inspired joint mechanism employing both pneumatics and electrically-actuated tendons capable of strong, dynamic, and rapid joint movement. The implementation of the joint is closely inspired by those seen in real spiders, with a foldable structured membrane that effectively transfers all the energy from pressure to torque as the leg unfolds. To evaluate the mechanism we derived a static joint model and a simple jumping model, and conducted equivalent experimental tests with a prototype of a single jumping leg robot. Besides applications in robot locomotion, the implementation and modeling of the spider-inspired joint mechanism can be utilized to further explore dynamics and functional biomechanics in spiders. In the future, we hope to use this platform to answer questions related to the impressive jumping and locomotion performances of real arachnids, and explore what morphological traits lie behind efficient spider locomotion at different size scales.

#### I. INTRODUCTION

Arachnids (spiders) are a highly successful species, numbering over 100 000 sorts and found in all climates and areas of specialization, including social and solitary individuals living in webs, burrows, on and even under water surfaces. Spiders span more than 100 times in size. Jumping spiders have a small size of just a few millimeters, whereas the giant huntsman spider [1] scales up to  $30 \,\mathrm{cm}$ . Their role as predators and prey have spurred a wealth of locomotion strategies; spiders, for instance, may run on land and water, jump large distances, navigate complicated vertical surfaces and delicate webs, and some even raise their front legs in an attempt to imitate the look of antennae on ants [2], [3]. It is therefore no surprise that they have served as loose inspiration to a great number of robots both as toys and scientific platforms [4], [5]. Here, we take a closer look at the inner workings of spider leg joints, designing a corresponding mechanical mechanism and demonstrating its use in a jumping robot leg.



Fig. 1: Concept behind the spider-inspired leg joint using hybrid actuation. A. A scanning electron microscope image of the tibia-metatarsus joint of a wolf spider (*Trochosa* spec.), lateral view. The insert shows a stylized version of the bellow-like structure of the exoskeleton, also mentioned in [6]. B. CAD drawing of robotic joint inspired by the spider-joint design. Torque  $\tau$  from internal fluid (air) pressure is applied to extend the joint, and cable force F flexes the joint.

#### II. RELATED WORK

Arachnids have exoskeletons and locomote and interact with their environment with the help of hybrid joint actuation. Interestingly, two of its seven leg joints (femur-patella and tibia-metatarsus) lack extensor muscles, i.e. the ability to stretch those joints through direct muscle force [7]. Instead, researchers have found that spiders create high transient *extra venal* blood ("haemolymph") pressures within their legs to stretch those joints, and use flexor muscles to bend them. Although this theory was first presented in 1957 [7], and has been supported many times since [6], [8], [9], researchers still argue over how this pressure is generated and augmented, and whether it is indeed the primary force of locomotion in larger spiders [10]. The benefit of a central (located in the spider's prosome) hydraulic system is that the majority of mass is located proximally, minimizing the inertial forces when the long legs move. Unfortunately, it also precludes prolonged vigorous activity [8]. As spiders increase in size it takes longer to build up the pressure in their legs; reversely smaller spiders are potentially limited by the flow impedance of narrow veins [11]. The overarching goal of this work is not just to enable more versatile robots, but, more importantly, also to start establishing a feasible model with which we may advance our understanding of the hybrid joint actuation in spiders.

Several researchers have presented spider-inspired mechanisms. Early works involved preliminary design concepts for hydraulic devices [6], [12] and others, flexible joints for medical and robotic applications [13]-[16]. These were all focused on hydraulics or pneumatics only, and did not include the combined use of pressure based joint extension and cables to flex the joint. Notable recent work comprise a four-bar linkage system with a tendon-controlled springloaded joint for front-leg assisted targeted jumping [17]. In contrast to prior work, the mechanism presented here combines a pressurized joint with a flexor tendon, and has a folding bellow-like design reminiscent of the real spider leg, see Fig. 1. To ease the fabrication process, the mechanism is multiple times larger than its biological counterpart; to lower the weight and increase the jumping height we use air instead of liquid inside in the joint. However, the design principles shown work on many different size scales with a variety of (low viscosity) fluids.

In this paper we present the design of joint and tendon mechanisms, static characterization of the joint embedded into a single leg, and dynamic characterization of an onelegged platform capable of jumping. Jumping is a popular form of locomotion for robots, allowing them to traverse unstructured terrain while gaining good visual perspective from above. Correspondingly, researchers have tackled this problem in many different ways, ranging from spring-loaded mechanisms [18], [19] and pneumatic pistons [20], to soft robots powered by explosions [21]. Additionally, an impressive spider-scale jumping robot was presented in 2008 [22], using material buckling instabilities to rapidly jump on the surface of water. Although we are not able to demonstrate jumps as impressive as some of these other robots, we do present a simple, low weight mechanism with proximally located bulk mass, which is closely related to the hybrid joint actuation of real spiders. This approach has many advantages: 1) it works across different size scales, 2) it has a leg joint torque source with mostly linear angle-torque characteristics, and 3) a single driver mechanism may be used for one as well as multiple joints with only small modifications.

## III. MECHANICAL AND EXPERIMENTAL DESIGN AND SETUP

In this section we describe the mechanical design of the spider-inspired leg joint, its flex-hold-release mechanism, and the static and dynamic experimental characterization setup.

#### A. Mechanical joint design

Spider leg joints appear to have a foldable membrane structure (Figure. 1a) that allows the leg to rotate and produce torque when actuated through haemolymph pressure [6]. The specific design of this membrane is critical to translate maximum energy from pressure to torque in the joint, yet the details of how they develop and maintain their functionality remain unknown.

In an optimal design, the membrane keeps its contact angle (CA,  $\gamma$  in Fig. 3) mostly perpendicular to the pressure active chamber area, A (Fig. 3c). Deviation from a perpendicular CA (Fig. 3d) creates force components of smaller amplitude; a perpendicular  $F_{\perp}$  and a parallel  $F_{\parallel}$ . This reduces joint torque production and might even counter extension torque. A CA > 90° [6] is especially pronounced in soft, unrestricted membranes that tend to bulge outwards (Fig. 3d). Bulging creates a parasitic volume  $V_{\text{bulge}}$  which requires energy and time to fill. The volume of the bulge follows a nonlinear (quadratic) radius-volume relation leading to high losses, which subtracts from the pressure generating torque within the active volume  $V_{\text{active}}$  (see also Eqn. 4).

Inspired by scanning electron microscope (SEM) pictures and close-up photos of spider joints (Fig. 1 and [3]), we explore the idea of a joint with perpendicular CAs through multiple stacked, rigid shell elements with an internal, sealed membrane (Fig. 2, Fig. 4b). In the flexed leg posture, shell



Fig. 2: CAD drawings and image of real leg joint, emphasizing functional components. The overall weight of the system is 36 g, the ground to hip height in the flexed state is 105 mm, at a leg segment length of 70 mm.



Fig. 3: a) and c) Geometric parameters:  $\alpha$  angle between leg segments, b width of shell segments, r height of shell segments, A pressure area, p pressure within the chamber,  $r_{\rm flexor}$  is the flexor tendon lever. b) Schematic drawing of a leg joint actuated by a telescopic actuator: a linear change in actuator length leads to a nonlinear (cosine) change of joint angle. c) If the contact angle  $\gamma$  (green) between membrane and active area is perpendicular, all pressure vectors contribute fully to joint extension. Radial pressure vectors on the inside of shell elements (membrane) are captured through their stiff radial suspension. d) Especially in soft membrane actuators the membrane tends to bulge and  $\gamma > \bot$ . Pressure vectors located at the rim between active area and membrane, and pressure vector components applying force to the membrane will lead to parasitic forces lowering the joint extension torque. Further, a large volume V<sub>bulging</sub> must be filled and pressurized, at the additional cost of energy and time.

elements are stacked within each other. During joint extension, shell elements extend in a rotatory fashion (Fig. 5). The shape of the shell elements follows a perpendicular CA and limits the internal pressurized bag to the same shape (Fig. 1, Fig. 2, Fig. 4b).

We tested several materials for the internal bag which seals the air in the actuator joint. Latex balloons and fingers cut out of latex gloves have the advantage of adapting well to uneven shell shapes. When pressurized, however, large friction between the internal bag and the shell elements prevented dynamic and fast leg extension. Instead, we settled on custom-made low-friction thermo-bonded freezer storage bags (Fig. 4b). A custom-made plug seals the connection between the tube and the internal bags. Leg segments, pressure volume, and leg shell elements are 3D printed in VeroClear (Stratasys Objet 226). Leg and shell elements are connected via small metal pins of 1.6 mm diameter.

The implemented leg has two leg segments with a length of 70 mm, a diameter of 15 mm, and a wall thickness of 1.5 mm. The three moving shell elements (Fig. 5, blue, green, and red) have an external height of r = 24 mm : 1.5 mm : 27 mm, an

external width of  $b = 15.5 \,\mathrm{mm} : 1.5 \,\mathrm{mm} : 18.5 \,\mathrm{mm}$ , and a center axis of radius c = 3 mm, leading to a maximum active area of  $A_1 = (r-c) \times b = 444 \text{ mm}^2$  (Fig. 5). The total weight of the two leg segments, connector pins, internal bag, and shell elements is 14 g. The assembly of the internal bag, connector, and chamber segments weigh  $\approx 4 \,\mathrm{g}$ , corresponding to  $11 \,\%$ of the weight of the leg mechanism. A reservoir volume of  $V_{\rm reservoir} \approx 12\,000\,{\rm mm}^3$  between pump and active leg volume consisted of the interconnecting silicone rubber tubes and a small extra, reservoir volume. The externally mounted miniature air pump has a weight of 14g, and produces a maximum of 55 kPa gauge pressure, at 98.5 kPa ambient air pressure. The maximum rotational working range of the implemented leg is  $3 \times 23^{\circ} = 69^{\circ}$ . Experimentally, we observed that between  $30^{\circ}$  to  $60^{\circ}$  actively unfolded in the dynamic jumping while in ground contact.

#### B. Flexing and release mechanism

The second part of the hybrid, spider-inspired joint concerns the instantaneous power a spider can produce to jump. Muscles have instantaneous force and velocity characteristics that might limit jumping performance. Alternatively, the integration and slow build-up of energy through a charging mechanism is plausible; leg joints are flexed and held by muscle force, then pressure is increased at fixed joint posture until eventually the joint is rapidly released by relaxing flexor muscles. In our setup the flexor muscle is replaced by a flex-hold-release cable-driven mechanism actuated by an onboard miniature DC motor (Fig. 2). This flex-hold-release mechanism is inspired by the Dash crawler clutch mechanism [23]. We initially implemented a cam-based mechanism similar to [18]. However, the fixed charging and release range limited the leg design, and added complexity and weight. The finally implemented flex-hold-release mechanism weighs 23 g, including a 300 : 1 geared DC motor of 10 g, and comprises  $\approx 60\%$  of the total weight of the leg mechanism.

#### C. Static and dynamic experiments

We characterized the joint in a static setup by recording simultaneous data of the internal chamber pressure, external joint torque, and leg joint angle (Fig. 4a). Initially, the leg joint was flexed and held against a load cell, with the internal bag at ambient air pressure. The chamber was then connected to a miniature air pump through a 3.5 mm diameter, 1 m long silicone tube and a small reservoir volume of known volume. The pump motor worked at 3 V and an average of 0.3 A for 10 s to increase to the maximum gauge pressure of 55 kPa. For data collection, the leg was slowly released (quasi-static test), typically within a 3 s to 5 s time window.

The applied torque was measured by a 5 kg, single-axis load cell connected to a Buster 9236-V100 strain gauge supply and amplifier. Analog output data was read in a National Instruments NI USB-6363 data acquisition board at 1 kHz, through a custom LabVIEW interface. Chamber pressure was measured with a Phidget 1140 pressure sensor, its output data was processed through the National Instruments acquisition board

and the LabVIEW interface. Leg joint positions were obtained with a Sony camcorder camera at 30 Hz, by recording colored markers on the leg joint and extracting marker positions with Physlets Tracker software (http://physlets.org/). Pressure and torque data was automatically synchronized through the common LabVIEW interface, video data was synchronized by a modest tap against the load cell. All data was processed in Matlab; outliers such as from initially tapping the force sensor were removed manually.

Next, the joint was dynamically characterized by a simple, free vertical jump. The leg was placed in a vertical position against a holder, the air pressure tube and a small reservoir volume were connected to the air pump, and the flex-holdrelease mechanism was connected to an external power supply. The jumping movement was recorded with a high-speed camera model Phantom V461 at 1 kHz. Electrical supply cables for the release motor and the pressure tube were placed to hang loosely on the leg, and not hinder the jump. The motor was engaged to flex the leg joint through the tendon cable mechanism (see Fig. 2 and video in supplementary material) until the motor stalled. Air pump pressure was applied for 7 s. Immediately after the onboard motor was activated rapidly releasing the joint-flexing cable. Jumping height based on the robot's approximate center of mass (COM) at hip height, and working angle  $\Delta \alpha$  defined as the change of angular leg joint angle during ground contact were extracted from the high speed video footage.

#### IV. CHARACTERIZATION AND MODELING

In order to characterize the spider-inspired joint we a) modeled extension torque based on leg angle and internal pressure, and b) potential jumping height based on positive work releasing the air-spring, and working angle. We compare modeled values with the experimentally obtained data in a static and a dynamic testing setup.



Fig. 4: *a*) Setup to characterize the static torque-pressureangle characteristics of the spider-inspired joint: 1 miniature air pump, 2 Wheatstone bridge supply and ADC, 3 pressure sensor, 4 force sensor, 5 spider-inspired robot joint. *b*) Robot leg with shell elements removed to show the internal custommade pressure bag. Without the mechanical restraints of its shell elements, the inflated internal bag bulges outwards and extends largely beyond the optimal shape.



Fig. 5: Opening sequence of the shell elements. Also observed in high speed recordings, joint segments begin rotation starting with the largest to smallest; red first, then green, then blue. This leads to a sequential, non-continuous change of the pressure-active area  $A_{\text{active}}$  (between arrow heads) from the largest area  $A_1$  to the smallest area  $A_3$ . With changing  $A_{\text{active}}$ the active volume changes in a non-continuous fashion.

#### A. Static Joint Torque Model

In this section we show how torque develops as a function of pressure and angle, within the active volume of the joint. After switching off the external pump, pressure  $p(\Delta \alpha)$  changes as a function of joint angle with the consecutive opening of the shell segments (Fig. 5). Instantaneous pressure further depends on the external reservoir volume  $V_{\text{reservoir}}$ . Torque  $\tau$  is a result of force acting perpendicular  $(F_{\perp})$  onto the center of the instantaneously active pressure area  $A_{\text{active}} = (r_{\text{var}} - c) \cdot b_{\text{var}}$  at a lever length of  $\frac{1}{2}(r_{\text{var}} + c)$  of the active chamber, with c as the radius of the joint axis (Fig. 3a). Width  $b_{\text{var}}(\Delta \alpha)$  and height  $r_{\text{var}}(\Delta \alpha)$  of the active area vary with the consecutive opening  $(\Delta \alpha)$  of each shell element. The acting force  $F_{\perp}$  is a direct result of chamber pressure  $p(\Delta \alpha)$  applied at the active area  $A_{\text{active}}$ .

$$F_{\perp}(\Delta \alpha) = p(\Delta \alpha) \cdot A_{\text{active}}$$
 (1)

$$\tau(\Delta \alpha) = F_{\perp} \cdot \frac{1}{2}(r_{\text{var}} + c)$$
(2)

$$\tau(\Delta \alpha) = 1/2 \cdot p(\Delta \alpha) \cdot b_{\text{var}} \cdot (r_{\text{var}}^2 - c^2) \qquad (3)$$

Eqn. 3 shows that the width b of the active chamber contributes linearly to the output torque p. Torque depends linearly on instantaneous pressure  $p(\Delta \alpha)$ . Pressure is reduced stepwise due to stepwise change of volume, but is majorly governed by the working angle  $\alpha$ . Importantly, height r of the pressure chamber contributes quadratically to the externally accessible torque. Hence small mechanical design variations of r lead to large changes in externally observable output torque. This comes at a quadratic cost for chamber height r contributing to the volume  $V(\Delta \alpha)$  of the active chamber.

$$V(\Delta \alpha) = \frac{\Delta \alpha}{360} \cdot b_{\rm var} \cdot r_{\rm var}^2 \cdot \pi \tag{4}$$

The active volume  $V_{\rm active}$  increases stepwise with the volume  $V(\Delta \alpha)$  opened-up with every shell element (Fig. 5). The active pressure area  $A_{\rm active}$  is adjusted stepwise to the change in height  $r_{\rm var}$  and width  $b_{\rm var}$  of the respective shell element. The resulting pressure p can be estimated as a function of

volume change  $V_{var} = V_{active} + V_{reservoir}$ . The pressurevolume relationship depends on the assumed model;  $\gamma = 1/1$ for an isothermal model, and  $\gamma = 7/5$  for an adiabatic model assuming air as a diatomic gas.

$$p_{\rm var} = p_{\rm init} \cdot V_{\rm init}^{\rho} \cdot \frac{1}{V_{\rm var}^{\rho}}$$
(5)

Both models show a stepped torque response to a changing pressure or the related working angle, as can be seen in the jagged-line plots of Fig. 6 and Fig. 7. The *isothermal model* with  $\rho = 1$  (Eqn. 5) should be valid for experiments with sufficient time and surface area to settle the temperature difference between chamber and environment, as we assume for the static experiments in Section IV-B, with data shown in Fig. 6 and Fig. 7. For fast movements like the jumping experiments in Section IV-D and no time to adapt chamber temperature to outside temperature, we assume an *adiabatic model* ( $\rho = 7/5$ ) including a temperature drop through rapid volume expansion.

The difference between the isothermal and the adiabatic model is significant in our application example. With the assumed fixed reservoir volume and the volume change per chamber, the adiabatic model drops pressure and volume faster compared to the isothermal model. This results in zero gauge pressure (the chamber pressure is equal to the outside, atmospheric pressure) already at  $\Delta \alpha = 40^{\circ}$  working angle. Further increase of the joint angle under the adiabatic model assumption would reduce the chamber pressure below external atmospheric pressure, and the internal bag would start deflating.

The isothermal model shows at a joint angle change of  $\Delta \alpha = 40^{\circ}$  still 0.1 Nm remaining joint torque. The isothermal model expends the leg joint up to 70° (Fig. 7), 30° more than the adiabatic model. Both models show, roughly, piecewise linear angle-torque and pressure-torque behaviour. Globally, the angle-torque behaviour is governed by a  $\frac{1}{q} - r$  tendency. The pressure-torque relationship (Fig. 6) shows also a hybrid, but globally more linear behaviour.

#### B. Static Experimental Joint Characterization

Experimental, static measurements include sensor values of force (torque) and pressure, which where synchronized to the measurements of the working joint angle, according to the setup in Fig. 4.

Experimental torque values are plotted as a function of joint pressure (Fig. 6), and are compared to the adiabatic-model and isothermal-model torque (Eqn. 3 and 5). 11 experimental runs indicate a piecewise linear decrease in torque with decreasing pressure, starting from 0.4 Nm at 58 kPa (gauge pressure) to 0 Nm at  $\approx 4 \text{ kPa}$ . The modeled torque of both models is slightly higher than the measured values (Fig. 6).

The experimental torque-angle relationship (Fig. 7) also follows both models, experimental data lies roughly between both models. The experimentally measured joint torque drops to zero after  $35^{\circ}$  to  $50^{\circ}$  joint angle change  $\Delta \alpha$ . We added a hypothetical, simple linear joint torque model in Fig. 7, such



Fig. 6: Joint extending torque  $\tau$  depending on pressure; experimental data (marker points) and isothermal and adiabatic modeled data (solid and broken lines) from the static characterization experiment. The x-axis is horizontally flipped, for reading convenience: chamber pressure drops and reduces joint torque. Data points are experimental recordings of 11 repeated, static experimental measurements. Torque value under 0 Nm are not possible in this joint design, the pressure bag only produces positive forces. Negative values for the adiabatic model are shown for clarity.

that  $\kappa_{\text{linear}}$  roughly matches the global, linear stiffness of the experimental data. The analytical model for  $\kappa_{\text{linear}}$  has the following torque-angle form:

$$\tau_{\kappa \text{linear}}(\Delta \alpha) = -\frac{0.4 \,[\text{Nm}]}{45 \,[^{\circ}] \cdot \pi / 180 \,[^{\circ}]} \Delta \alpha + 0.4 \,[\text{Nm}] (6)$$
$$= -0.509 \Delta \alpha + 0.4 \tag{7}$$

This linear model emphasizes the difference between joint torque generation through spring relaxation with air as pressure medium (isothermal or adiabatic model), versus a theoretical, purely linearly decreasing torque-angle relationship.

#### C. Modeled Jumping Height

In Fig. 7 we established an isothermal, adiabatic and a linear model for the joint torque-angle relationship. During joint release movement, the spider-inspired leg joint produces positive work equivalent to the area under the torque-angle curve. For a very simplified estimation of the maximum jumping height we assume that all energy released from unloading the joint (work done) converts fully into potential energy, i.e. height of the jumping robot. All  $\kappa$  i.e. in Nm/rad, and  $\alpha$  in rad.

$$E(\alpha) = \int_{\alpha_1}^{\alpha_2} \tau(\alpha) d\alpha = E_{\text{pot}} = mgh$$
(8)

$$h(\alpha) = \int_{\alpha_1}^{\alpha_2} \tau(\alpha) d\alpha \cdot \frac{1}{mg}$$
(9)



Fig. 7: Joint extending torque  $\tau$  depending on changing joint angle  $\Delta \alpha$ . Experimentally recorded data (markers) is identical to Fig. 6,  $\Delta \alpha$  was extracted from video data. Overlaid solid and broken lines show the modeled angle-torque relationship under the assumption of an isothermal or adiabatic model, respectively. The -. line (violet) indicates a hypothetical  $\kappa_{\text{linear}}$ behaviour.

The model estimation of jumping height is visualized in Fig. 8. Positive work done by the joint follows the *release* direction of a virtual spring, eventually leading to a jumping height characteristics following an inverted parabola relationship, until the maximum height. The isothermal model predicts a max jumping height of 46 cm at 70°, the adiabatic model 31 cm at 40°. A simple linear model as in Eqn.7 predicts a max jumping height of 45 cm at 45°. Increase of the working angle  $\Delta \alpha$  beyond reaching peak height (zero-crossing in Fig. 7) does not lead to a decrease in jumping height, as the applied pressure bag is one-directional, and never flexes the leg joint.

#### D. Experimental Jumping Height

The working angle  $\Delta \alpha$  in the jumping experiment was extracted from high-speed recordings during the first 15 ms to 20 ms until lift-off, as range of angular leg angle rotation (Fig.9). The extracted working angle of 27 recorded jumps varied between 30° and 60° (Fig. 8). Jumping height varied between 6 cm at 35°, and 11.5 cm at 56°. A typical jump off sequence starting from joint release until leaving ground took 20 ms (Fig.9), and a full jump lasted around 200 ms, until landing.

### V. DISCUSSION

We presented a novel, scalable pneumatic and tendon driven robotic joint with a design inspired by the hydraulic and muscle driven joints of spider legs.

Jumping experiments: The maximum, experimental jumping height reached was 11.5 cm, only 37% of the modeled (adiabatic) jumping height. Due to the fast expansion of the joint



Fig. 8: Jumping height depending on working angle  $\Delta \alpha$ . Continuous line: modeled jumping based on a linearised rotational joint stiffness  $\kappa_{\text{linear}}$ . Height depends on joint angle passed during leg extension, while in contact with the ground. Individual data markers are extracted experimental jumping heights over working angles from 27 high speed video camera recordings of dynamic jumps.



Fig. 9: Snapshot sequence of a dynamic jump of the spider legjoint inspired robot leg-joint. Lift-off is reached after 17 ms, apex height after 110 ms. A flex-hold-release mechanism initially flexes the leg joint through a cable. The shell-element actuator joint is then pressurized by an external miniature air pump to 55 kPa gauge pressure. The tensioning motor is reversed, releasing the joint at t = 0 ms. The pressurized chamber acts as an air-spring, rapidly extends the leg joint, and catapults the robot leg upwards.

we make the assumption that an adiabatic model is the best fit. Our simplification of full work conversion into jumping height disregards several potential losses: translational and rotational movements not contributing to gaining maximum height, losses due to elasticities, deflections and sliding within the mechanism and on the ground, drag losses from attached cables and the pressure hose, and losses due to friction between components. Parameters for the adiabatic model were estimated based on geometric, CAD extracted parameters, and deviations between model and hardware also increase the discrepancy. We further observe that robot jumping heights did not increase with increasing working angle above  $40^{\circ}$ , which is in accordance with the adiabatic model predictions. We are assuming that for working angles over  $40^{\circ}$  chamber pressure reached atmospheric pressure, and the pressure bag stopped providing torque to the leg joint.

Shell structure and pressure bag: The spider-inspired joint mechanism assembled from shell elements allows a working angle up to 69°. Experiments and the adiabatic model show that likely not more than  $40^{\circ}$  were utilized. Higher working angles will require a larger external reservoir, for fast joint movements, due to adiabatic pressure losses. Torque losses experienced through the finite shell thickness are visible in the torque-angle characteristics (vertical steps in Fig. 7), and amount to roughly  $0.05 \,\mathrm{Nm}$  (13%). A more optimal joint design would apply shell elements as thin as possible to reduce these losses. Our torque-angle measurements and the corresponding adiabatic model show not a linear but reasonably good torque-angle characteristic leading to a relatively efficient leg actuation. With further geometric improvements and especially a change in actuation medium (i.e. hydraulics). this spider-inspired leg joint design can potentially compete with piston actuated leg joints which require a carefully placed piston, and have an overall more restricted working range [24]. A drawback of our proposed system is its double-membrane design composed of shell elements and internal pressure bag. Friction between shell elements and the inner bag lead to a reduced jumping height. Adapted material with low friction values, or a single-membrane design could reduce such losses.

Actuation mechanism and medium: The spider-inspired joint actuation mechanism includes a pneumatic extension mechanism and a flex-hold-release system inspired by Dash robot's clutch mechanism [23]. The leg including the release mechanism weighs 36 g. Currently, its pressure pump and power source are not placed onboard, and are not included in the weight calculation. Small battery solutions i.e. for micro gliders exist, and onboard miniature pumps in the gram range could replace the 14 g heavy external pump. An important experimental component was a robust and rapidly acting flex-hold-release mechanism. Our implementation could easily withstand up to  $0.45 \,\mathrm{Nm}$  joint torque, and released within a few milliseconds. The internal bag is reusable and lasted more than 100 experimental runs for a tested pressure range up to 55 kPa. Spiders with a size range from a few millimeters to several centimeters apply a similar geometric actuator design as our mechanical implementation. Our model shows that rotatory fluidic extensor systems like the spider-inspired leg joint mechanism scale well with increasing size, with the cost of a larger pressurized volume depending quadratically on the radius of the pressure chamber. For several reasons we applied air pressure as actuator medium. However, the comparison between the isothermal and the adiabatic model shows that a 30% loss in (modeled) jumping height is due to the adiabatic pressure loss at rapid volume expansion. Spiders applying haemolymph as actuator medium would not experience this type of losses.

#### VI. CONCLUSION AND FUTURE WORK

We presented the design of a compact, 36 g lightweight, spider-inspired, fluidic air pressure and electrically actuated leg joint mechanism. It jumps 11.5 cm in 110 ms, with an initial supply of 55 kPa joint pressure, from a crouched hip height of 10 cm. We modeled its torque-angle and torque-pressure characteristics and jumping height based on a isothermal, a adiabatic, and a linear model. We compared experimental, statically obtained torque-angle and torque-pressure recordings, and dynamic jumping experiments to the model predictions.

The major and novel design component of the presented system is a fluid-actuated, rotational leg joint with a) a perpendicular contact angle between the leg joints' active pressure area and the actuator's shell elements, and b) an arc-shape, nested shell structure. This effectively transfers all the energy from pressure to joint torque as the leg unfolds. This design mimics the observable morphology in spider leg joints. For sealing the chamber pressure, a custom-designed, lightweight, low friction bag is placed inside the shell elements. Torque-pressure characteristics of the joint show a good match between the adiabatic model and the experimental data, and reach up to 0.4 Nm torque at a pressure of 55 kPa, at a mechanism radius smaller than 27 mm.

By electrically actuating a flex-hold-release mechanism connected via a joint-flexing tendon, the robot leg joint can be folded, then charged with air pressure, and rapidly released. Free vertical jumps lifted the robot 11.5 cm up in the air, more than double the hip height of the folded leg. The adiabatic model estimates that 3 times higher vertical jumps should be possible, with improvements to the mechanism to avoid losses.

While details about the exact morphology and functional biomechanics of pressure extended joints in spiders are not yet available, our physical and simulation models can start shedding light at several aspects; we assume that our twolayered mechanical design is relatively strong-damped for high speed movements, likely leading to losses in jumping height. If spiders would apply a similar design, a solution to decrease damping is necessary for rapid jumps. Further, to produce strong joint torque for dynamic jumps we applied pressurized air inside the shell segments and inside a connected reservoir. Spiders apply incompressible haemolymph fluid inside their joints. In case spiders charge their leg joints in a similar manner, elastic energy would have to be stored in a different medium.

Although the joint mechanism presented here is able to extend with very little parasitic torque especially at slow speeds, it might be worth sacrificing optimality for a simpler mechanism. In future work, we will examine the potential of joints connected by soft membranes, i.e. fiber-reinforced flexible actuators [25]. Such designs could offer advantages such as: inexpensive, easy, and rapid manufacturing, low wear, lightweight, and inherent ability to seal fluids. It is also of interest to investigate the size scaling characteristics of our spider-inspired torque joint, i.e. by implementing a full system in the small centimeter range. Our model indicates a favourable torque output to pressure input relation. However, physics behaves differently especially in small and narrow volumes, and i.e. a very small sized physical model could contribute much to the understanding of fluid actuator characteristics in spiders leg joints.

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