DEVELOPMENT OF A HYDRAULIC ARTIFICIAL MUSCLE WITH HIGH FORCE DENSITY

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ABSTRACT

The actuation of mechanism like exoskeletons or devices for medical rehabilitation by means of fluid artificial muscles are convincing solutions due to their light weight, exceptional power capacity, remarkable resiliency, and low investment costs. The artificial muscle consist of an inner elastomeric hose surrounded by a textile, braided and reinforced by aramid fibers. The muscle is activated by fluid supply with a radial expansion of the inner pressurized hose accompanied by a corresponding axial contraction. Consequently circumferential stress in the textile reinforcement of the muscle converts into axial contraction force. The focus of this project is the development of high power hydraulic muscles that enable a significant higher pressure level as well as force density than known artificial muscles. Prototypes of new hydraulic artificial muscles have been developed and experimentally evaluated by means of a customized hydraulic test setup. Relating to the initial length of the muscle without fittings, a contraction of 32% has been measured. In this experiment the associated pressure level is 5 MPa. In a second experimental test the force depending on pressure has been measured and a high force density per mass of 60 kN/kg has been calculated.

Keywords: Hydraulic artificial muscle, McKibben muscle, High force density

1. INTRODUCTION

New innovative actuator systems for robotics, exoskeletons and devices for medical rehabilitation with hydraulic artificial muscles (McKippen principle) are remarkable powerful, compact, lightweight, robust, and less expensive solutions. The focus of the paper presented is a high power hydraulic muscle that enables a significant higher pressure level and force density than currently known artificial muscles. An overview of the known hydraulic muscle performances supplemented by results of the new developed hydraulic artificial muscle is shown in **Table 1** (compare section 6).

2. HYDRAULIC ARTIFICIAL MUSCLE

The actuator effect of a pressurized muscle towards a non-pressurized hydraulic artificial muscle is outlined in **Figure 1**. Fluid supply activates the initially non-pressurized muscle with the fiber angle α_0 (**Figure 1**, left). A radial expansion of the inner pressurized hose of the muscle leads to increasing circumferential stress in the surrounding textile sleeve and to a rising fiber angle α_1 (**Figure 1** right). The actuation effect is an axial contraction of the muscle that enables to lift a load F. The non-pressurized artificial muscle has an initial length of l_0 with a radius of r_0 and the pressurized muscle has a length of l_1 with a radius r_1.

The mechanical tensions of the hydraulic artificial muscle in axial direction (σ_a) and in circumferential direction (σ_c) have been determined according to strength calculations for cylindrical containers with thin walls under internal pressure. The axial stress of the artificial muscle consist of two overlay causes, at first an internal hydraulic pressure and secondly an additional axial load F. Considering both causes, the axial stress can be calculated by the equation (1).

$$\sigma_a = \frac{p \cdot r}{2 \cdot t} + \frac{F}{2 \cdot r \cdot \pi \cdot t} \quad (1)$$

The circumferential stress of the artificial muscle, caused by an internal pressure, can be calculated by the equation (2).

$$\sigma_c = \frac{p \cdot r}{t} \quad (2)$$

The axial specific normal force can be calculated by the equation (3)

$$n_a = \sigma_a \cdot t \quad (3)$$

as well as the axial force F_a by the equation (4).

$$F_a = n_a \cdot 2 \cdot r \cdot \pi \quad (4)$$

The circumferential specific normal force can be calculated by the equation (5).

$$n_c = \sigma_c \cdot t \quad (5)$$

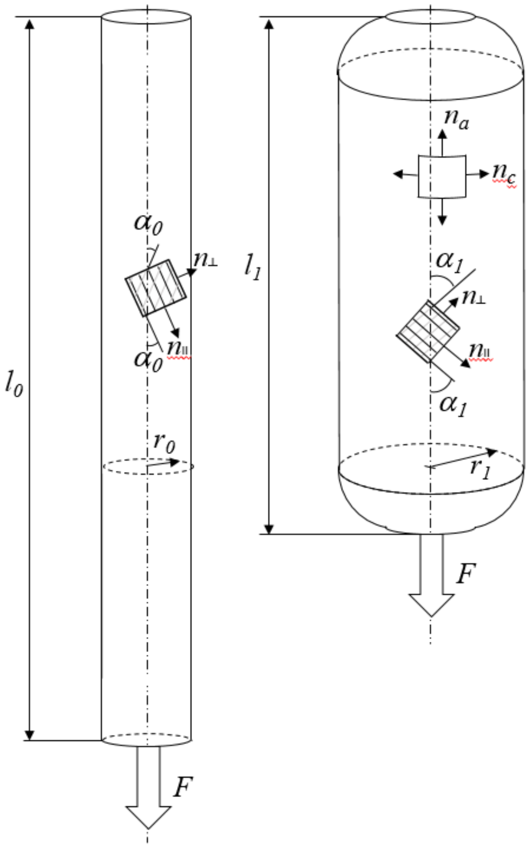

Figure 1: Actuation effect of a hydraulic artificial muscle (left: non-pressurized, right: pressurized)

The axial force F_a generated by the muscle enables the actuation effect, here the lift of the load F. The specific normal force in circumferential direction grows with increasing pressure and increasing radius as well as accordingly with increasing fiber angle. The forces in circumferential direction are always balanced.

3. DESIGN OF THE HYDRAULIC ARTIFICIAL MUSCLE AND OF THE TEST SETUP

The focus of the project is the development of high power hydraulic muscles that enable a higher pressure level, a higher force density than known artificial muscles and accordingly an improved compactness. Prototypes of the new hydraulic artificial muscles have been developed and manufactured. A sectional view of a prototype of an artificial muscle is shown in **Figure 2**. The muscle has an inner elastomeric hose surrounded by an aramid fiber textile sleeve connected by a fitting. The fitting consist of a swage nipple and a swage ferrule, as well as a screw coupling with an O-ring sealing element.

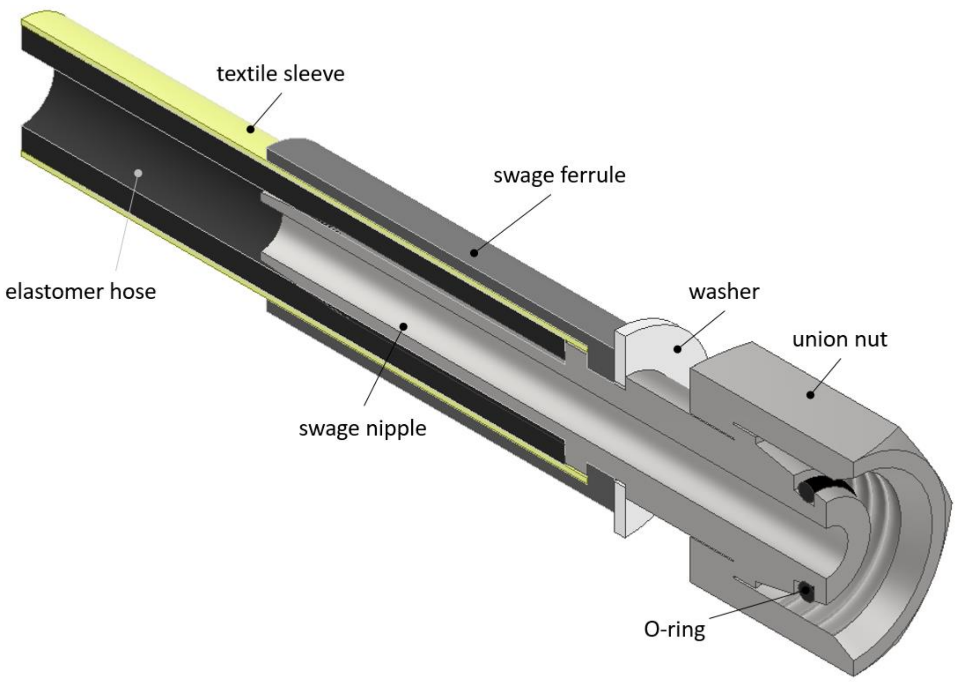

Figure 2: Sectional view of the hydraulic artificial muscle

The evaluation of the performance of hydraulic artificial muscles requires an appropriate hydraulic test setup, which has been designed and built for experimental investigations. The experimental setup is shown in **Figure 3**.

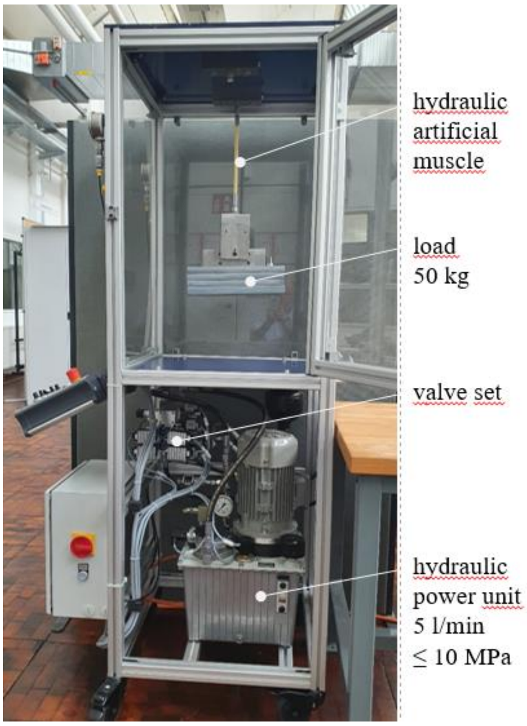

Figure 3: Hydraulic test setup for the investigation of the muscle contraction

4. EXPERIMENTAL DETERMINATION OF THE MUSCLE CONTRACTION

A non-pressurized hydraulic artificial muscle with an initial length of l_0 = 340 mm and a diameter of d_0 = 10 mm (radius r_0 = 5 mm) (compare **Figure 1**) has been configured. The mass of the muscle including fittings and filled with fluid is m = 0,145 kg. The artificial muscle has been activated by a volume flow with a corresponding increase in pressure up to 5 MPa. In **Figure 4** the non-pressurized muscle is shown on the left and the pressurized muscle on the right hand side. The actuation effect is a contraction of the artificial muscle with a remarkable action of force (depending on the small muscle diameter) to lift a load of 50 kg (F = 490 N). The pressurized artificial muscle is shortened to the length of l_1 = 232 mm, and has an expansion of the diameter to d_1 = 24 mm (radius r_1 = 12 mm). Relating to the initial length l_0 of the non-pressurized muscle, a contraction of ε = 32% has been calculated with equation (6). **Figure 5** shows the fiber angle of the non-pressurized muscle α_0 and of the pressurized muscle α_1. Initially the non-pressurized muscle has a fiber angle of α_0 = 25° (**Figure 5** left hand side). The volume flow into the muscle leads to an increasing pressure inside the muscle, to an increasing radial muscle volume, to an increasing circumferential stress in the textile sleeve, to an adaptive change of the fiber angle to α_1 = 50° (**Figure 5** right hand side) and finally to a muscle contraction with an intended actuation effect (**Figure 4** right hand side).

The contraction is calculated by the equation (6), without considering the length of the fittings.

$$\varepsilon = (l_0 - l_1) / l_0 \cdot 100 \tag{6}$$

The stress in axial direction of the textile sleeve (thickness t = 0.45mm) has been calculated using equation (1) with the result of σ_a = 81.1 N/mm^2. The stress in circumferential direction calculated using equation (2) is σ_c = 133.3 N/mm^2. The internal hydraulic pressure dominates the stress in the textile. The stress of the artificial muscle under load is not critical for the aramid viber, due to a tensile strength of the aramid viber of σ_{AV} = 2800 N/mm^2. Improvements of the muscle robustness are carrying out at the connection of muscle (elastomer hose, textile sleeve) and swage ferrule/nibble.

Figure 4: Hydraulic artificial muscle non-pressurized (left) and pressurized (right)

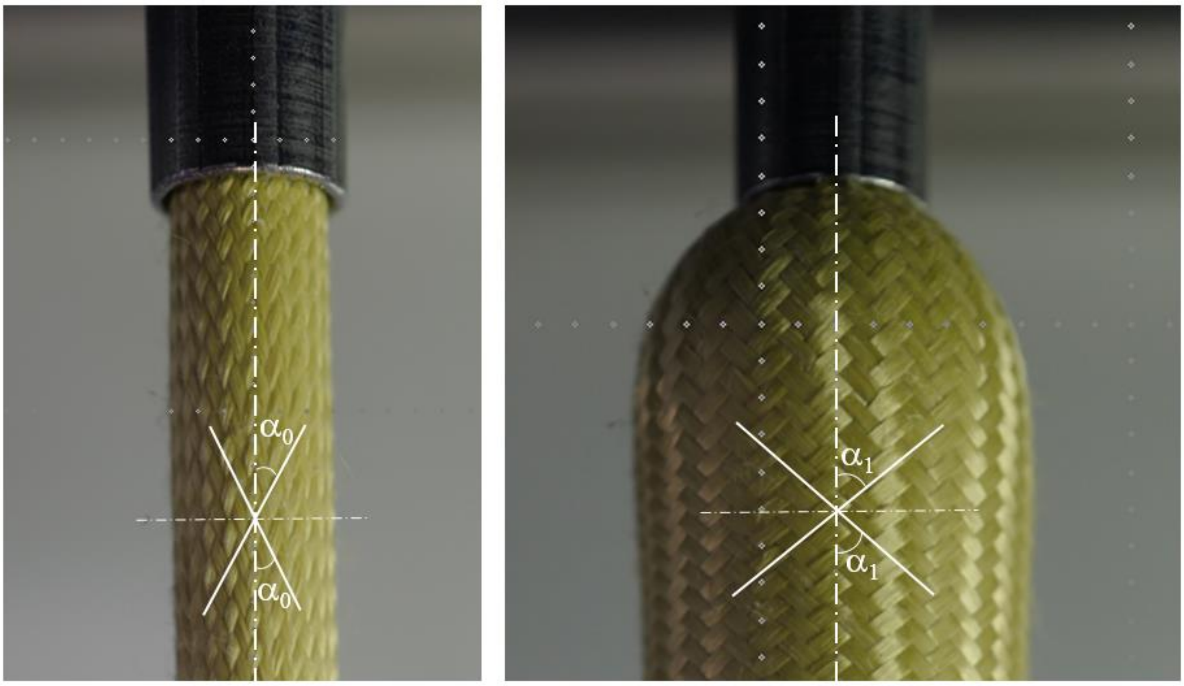

Figure 5: Fiber angle with a non-pressurized muscle α_0 = 25° and with a pressurized muscle α_1 = 50°

The conducted experimental test shows already a competitive contraction of ε = 32% with regard to the initial length of the muscle, without considering the fittings (compare **Table 1**). The relationship of the contraction and the applied pressure have been measured and is shown in **Figure 6**.

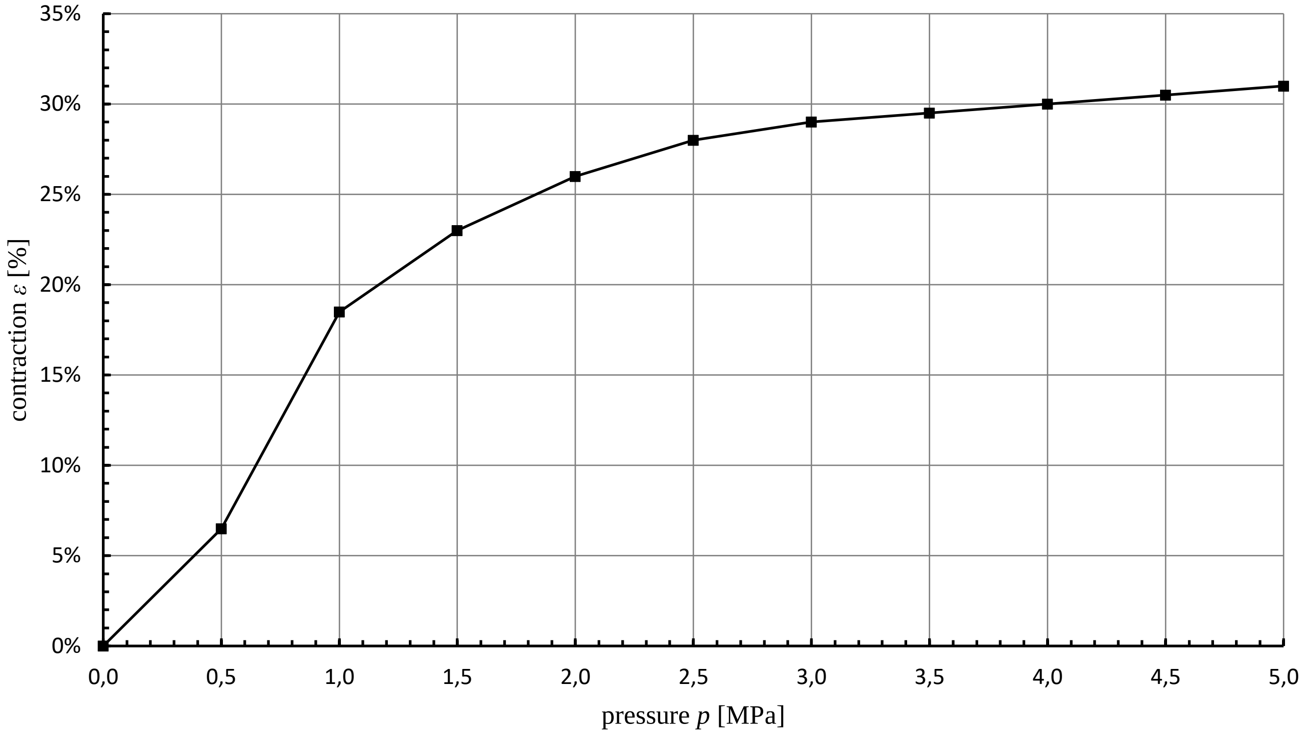

Figure 6: Measured contraction of the muscle with a load of 50 kg depending on the applied pressure

5. EXPERIMENTAL DETERMINATION OF THE FORCE DENSITY

To investigate the maximum force generated by the hydraulic artificial muscle, a measuring device has been developed (compare **Figure 7**). The measuring device has been equipped with a force sensor (20 kN) and a pressure sensor (10 MPa), and has been integrated in the chamber of the hydraulic test setup. The hydraulic artificial muscle has been clamped as shown in **Figure 7** to measure the blocked force and to prevent an axial contraction of the hydraulic artificial muscle. The muscle has an initial length of l_0 = 200 mm, a diameter d_0 = 10 mm, and a mass with fittings and filled with fluid of m = 0,120 kg. The measured force results of the blocked muscle depending on a continuous increased pressure within the muscle are shown in **Figure 8**. With a pressure level of 5.6 MPa a force of F_t = 7200 N has been measured and a force density per mass of δ_F = 60 kN/kg has been calculated with equation (7).

$$\delta_F = F_t / m \tag{7}$$

The energy performance of the hydraulic artificial muscle consists of muscle contraction and actuation force. The evaluation of the performance of the new muscle towards the state of the art is challenging, due to the variety of muscle specifications in terms of geometric dimensions, used materials, fiber angles, and pressure levels. To enable a comparability of the various muscle performances, the force density per mass has been calculated or estimated for the considered muscles, if possible. **Table 1** show a summarized representation of the specifications and performances of selected relevant hydraulic artificial muscles, supplemented by the data of the new developed hydraulic muscle. The conducted experimental test shows already a very competitive result with a high force density per mass of δ_F = 60 kN/kg.

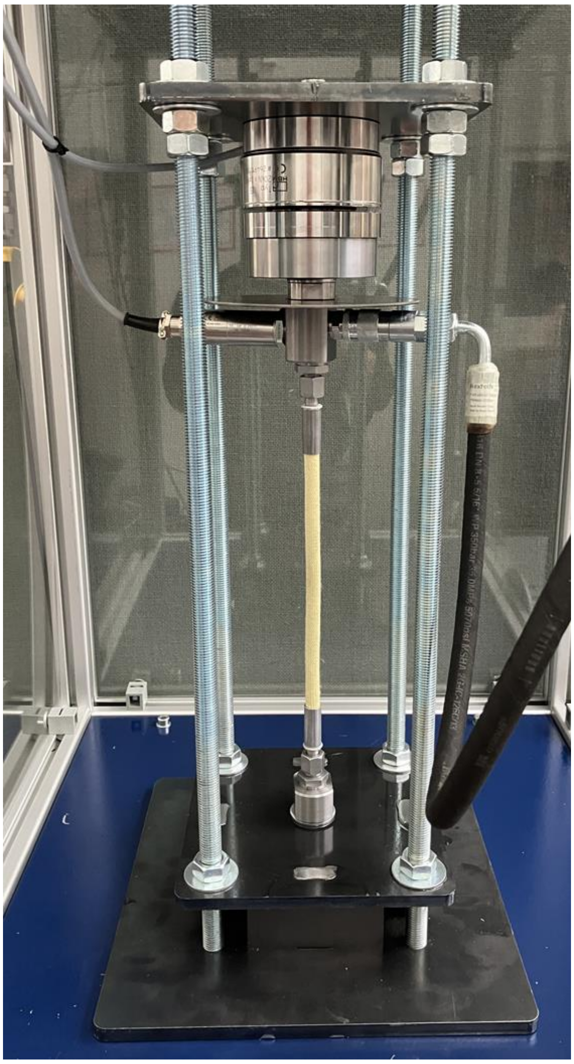

Figure 7: Measuring device to determine the maximum blocked force F_t of the clamped muscle

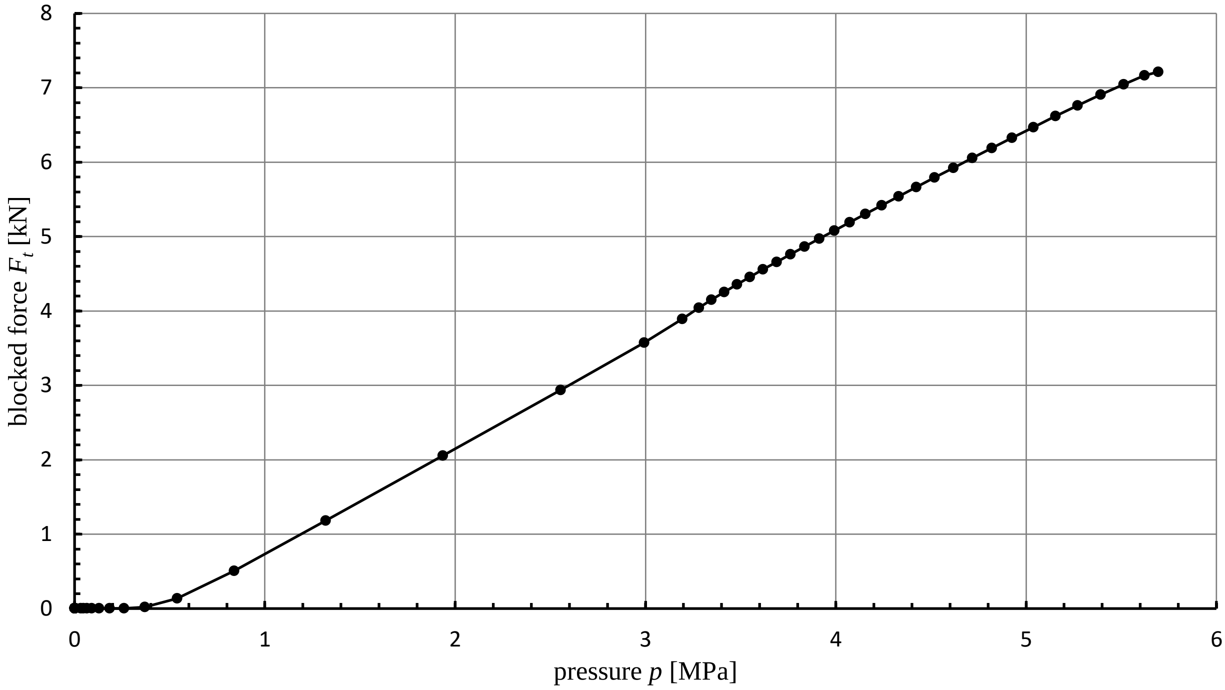

Figure 8: Measured force F_t depending on the pressure p within the hydraulic artificial muscle

Table 1 shows a selection of known publications of artificial muscle concepts with their specification data and the belonging force density per mass.

Table 1: Comparison of muscle specifications and performances

	present paper (2023)	Zhang et al. (2021) [1]	Zhang et al. (2017) [2]	Tiwari et al. (2012) [3]	Sangian et al. (2015) [4]	Iwata et al. (2012) [5]	Mori et al. (2009) [6]	unit
initial muscle length l_0	200	300	200	160	80	300	700	mm
initial outer diameter d_0	10	30	30	3.17	6	21	40	mm
initial fiber angle α_0	25	25	43		35	23.5	25	°
maximum pressure p	5.6	4	6	0.69	0.25	7	4	MPa
maximum contraction ε	**32**	23	20 [1]	19 [1]	28	23 [1]	25	%
maximum force F_t	7 200	23 500	12 000	40	26	8 000	28 000	N
mass of muscle m	0.12	0,6 [3]	0.5	0.002	0.0018	unknown	3	kg
force density per mass δ_F	**60**	40 [3]	24 [2]	20 [2]	14.4 [2]	not estimated	9.5	kN/kg

[1] calculated with equation (6)
[2] calculated from published measured forces and mass of the muscles
[3] estimated from published data in [1] and [2]

6. SUMMARY

The focus of the paper presented is the development of high power hydraulic artificial muscles that enable significant higher pressure levels and force densities. That is crucial for small and lightweight drives, for e. g. medical rehabilitation. Experimental results show a remarkable action of force depending on the small muscle diameter to lift heavy loads. The observed contraction of the artificial muscle is ε = 32% with regard to its initial length, without considering the fittings.
By means of a further experimental test the possible maximum blocked force F_t of a hydraulic artificial muscle (l_0 = 200 mm, diameter d_0 = 10 mm) has been measured. With a pressure level of 5.6 MPa a blocked force of F_t = 7200 N has been measured with a very competitive force density per mass of δ_F = 60 kN/kg (muscle mass m = 0,120 kg).

Those results show, that hydraulic artificial muscles are attractive future actuation solutions for e.g. robotic and exoskeleton applications or for various devices for medical rehabilitation.

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NOMENCLATURE

d_0	diameter of the non-pressurized muscle	mm
d_1	diameter of the pressurized muscle	mm
F	force of the axial load	N
F_a	axial force generated by the artificial muscle	N
F_t	measured total force, caused by the internal pressure of the muscle	N
l_0	initial length of the textile sleeve	mm
l_1	length of the contracted textile sleeve	mm
m	mass of the contracted muscle including fittings and fluid	kg
n_a	specific normal force in axial direction (per unit of the circumference)	N/mm
n_c	specific normal force in circumferential direction (per unit of the textile mantle length)	N/mm
p	internal pressure	MPa
r	radius of the artificial muscle	mm
r_0	radius of the non-pressurized muscle	mm
r_1	radius of the pressurized muscle	mm
t	thickness of the textile mantle	mm
α_0	initial fiber angle of the non-pressurized muscle	°
α_1	fiber angle of the pressurized muscle	°
δ_F	force density per mass	kN/kg
ε	maximum contraction	%
σ_a	stress in axial direction	N/mm^2

σ_c	stress in circumferential direction	N/mm^2
σ_{AV}	tensile strength of aramid viber	N/mm^2

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