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Development of a miniaturised hydraulic actuation system for artificial hands

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Abstract

This article will present a powerful miniaturised hydraulic system of compact design that is used for the actuation of artificial hands. This system was developed as an alternative to today's commonly used electromechanical prosthetic actuation systems. System components and hand prototypes reflect many years of experience of our laboratory in rehabilitation medicine, CAD design and prototyping, mechanical engineering, electronic construction, and programming. Prototypes of hydraulically actuated hands were tested by patients under support of orthopaedic companies. The latest hydraulic prostheses have advantages in construction, design, and performance, including adaptivity during grasping and holding of objects. The newly developed miniaturised hydraulic system is competitive with standard mechanical systems of electrically driven prosthetic hands. The modular construction of the system developed allows for customising the mechanical construction of each prosthetic hand and its functional abilities. Contributions of patients concerning grasping activities of prostheses may be taken into account when choosing the hand components already. The components of the new hydraulic actuation system and their technical characteristics will be interesting for specialists in automation technology, actuator development, mechanics, prosthetics, and rehabilitation.

Keywords: Flexible fluidic actuators; Hydraulic pump; Valves; Miniature hydraulic system; Artificial hands

1. Introduction

The development of externally powered prosthetic hands (EPPH) that were controlled by muscle contraction in the residual limb started in the 1950s. One of the most advanced artificial prototypes was the Russian Hand [1] that was presented to the public at the world exposition in Brussels in 1959. However, it took another decade until the first EPPH was ready for series production. This so-called "Heidelberg Pneumatic Arm prosthesis" [2] was driven by pressurised carbon dioxide that was stored in pressure tanks (Fig. 1). In the 1960s, it was the thalidomide tragedy that initiated the further development of EPPH, as there was an international need to provide children suffering from upper-limb dysplasia with prostheses. The pneumatic-hydraulic prosthesis was presented in 1974 in Germany [3]. This prototype allowed for active flexion of the elbow joint, hand rotation, and the separate control of thumb and index finger. Several prototypes of hydraulically driven hands were developed in the 1970s [4–8], but there are no reports about one of these devices having left the laboratories and been fitted to patients. At the same time, new small-sized, powerful DC motors and rechargeable batteries became available and electrically driven hands have set a standard until the present. Since 1960, many thousands of patients worldwide have been fitted with electrically driven prostheses [9]. Due to their compactness, reliability, and simplicity of recharging the energy source, this actuation principle has been superior to others when designing an EPPH that allows for a single grasping pattern. However, surveys that determined the needs of prosthesis wearers showed that additional grasping patterns and more natural hand movements were wanted for future designs of EPPH [10,11]. When an artificial hand is powered by several geared mini motors, the weight of the resulting device increases and a compromise has to be made between grasping at slow speed, but with sufficient force and grasping at high speed, but with low grasping force.

In the meantime, modern production technologies and materials have allowed for the development of hydraulic prosthetic hands meeting demands like compact design, safety,

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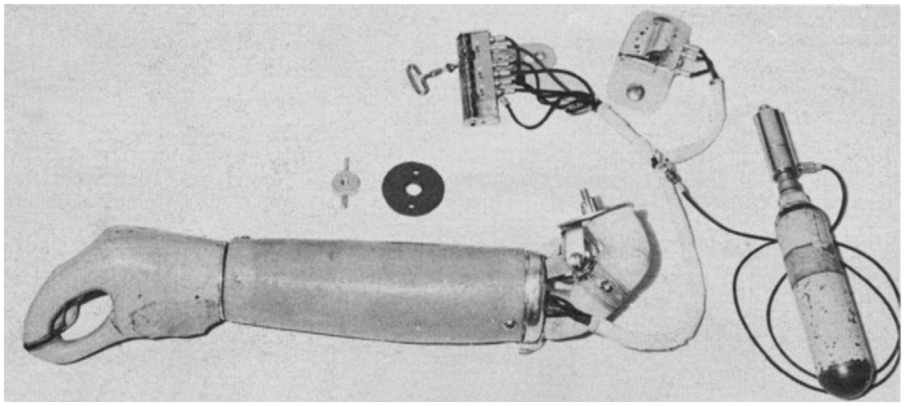

Fig. 1. Heidelberg pneumatic arm prosthesis of 1956 [2].

controllability and simplicity of use, and autonomy from external mechanisms. Adaptive grasping is an additional criterion in the design of prosthetic hands [12]. Its implementation requires an increase in the degrees of freedom that extends the range of the motion and allows for different grip types for prosthetic hands. Thus, hydraulically driven prosthetic hands may be competitive with electrically driven ones as far as the functionality of prosthetic devices is concerned.

2. General system specification and design

In order to define general system specifications for EPPH, the status of existing devices has to be analysed first. All EPPH that are currently commercially available are electrically driven prostheses exclusively, like the Electro System Hand from Otto-Bock, Duderstadt, Germany. These hands are very reliable and allow for a maximum grasping force of 110 N. Due to their rigid digits, however, these hands do not conform to the shape of an object and higher grasping forces are needed compared to multi-articulated hands [12]. Current universal general standards for the construction, functioning, and control of prosthetic hands are lacking. As a result, recommendations by experts and results from user surveys [11,13–16] were considered when establishing general system specifications for a prosthetic hand. In [16], both prosthesis users and rehabilitation professionals were asked to answer sets of questionnaires that were aimed at determining the importance of different aspects of functionality of prosthetic hands in daily life. Along with technical demands on prosthetic devices, such as opening span, opening velocity, and maximum grasping force, the main aspects for amputees were aesthetics, excessive weight, and lack of functional capabilities. Rehabilitation professionals also pointed out the necessity of enhanced functionality of prosthetic devices, which should provide five main types of grasping, such as tip grasp, hook grasp, precision grasp, cylindrical grasp, and lateral grasp. A survey of prosthetic hand users [11] revealed that one of the most wanted features for a future generation of prosthetic hands with advanced functionality was the ability to operate a switch or computer keyboard with a stretched index finger. Conventional prosthetic devices have coupled fingers that limit their grasping abilities to a pincer-like grasp and a cylindrical power grasp. Individual finger movements and different grasping patterns can only be achieved by several independent degrees of freedom. Hence, additional actively actuated joints are needed. Nevertheless, the total weight of the EPPH should be reduced to meet the user's requirements and a compact design is wanted. As a consequence, a hydraulic actuation system was developed as an alternative to conventional electrically driven systems.

The schematic structure of a hydraulically actuated prosthetic system is presented in Fig. 2. It consists of following general components:

- one hydraulic pump, one fluid reservoir, five electric valves, and an electronic unit, which are integrated in the metacarpus of the new adaptive hand;
- eight flexible fluidic actuators of compact design, which are integrated in the finger joints. They will be filled with fluid by the pump that also deflates the actuators;
- one battery for power supply and two myoelectric electrodes which are placed in the socket.

Based on a hydraulic system, a prosthetic hand prototype was designed, which is presented in Fig. 3. The general technical specifications of a hydraulically driven prosthetic hand are presented in Table 1.

Table 1
General specifications of the hydraulically driven prosthetic hand

Actuator principle	Fluid
Operating pressure	0–8 bar
Operating voltage	7.5 V
Number of actuators	8
Number of hydraulic pums	1
Number of hydraulic valves	5
Number of grasping types	5
Max. grasping force	110 N
Noise level	55 dB
Opening span	100 mm
Opening velocity	1 rad/s
Max. opening time	1 s
Max. power consumption	22 W
Weight	0.350 kg
Battery	Li ion 1200 mA/h

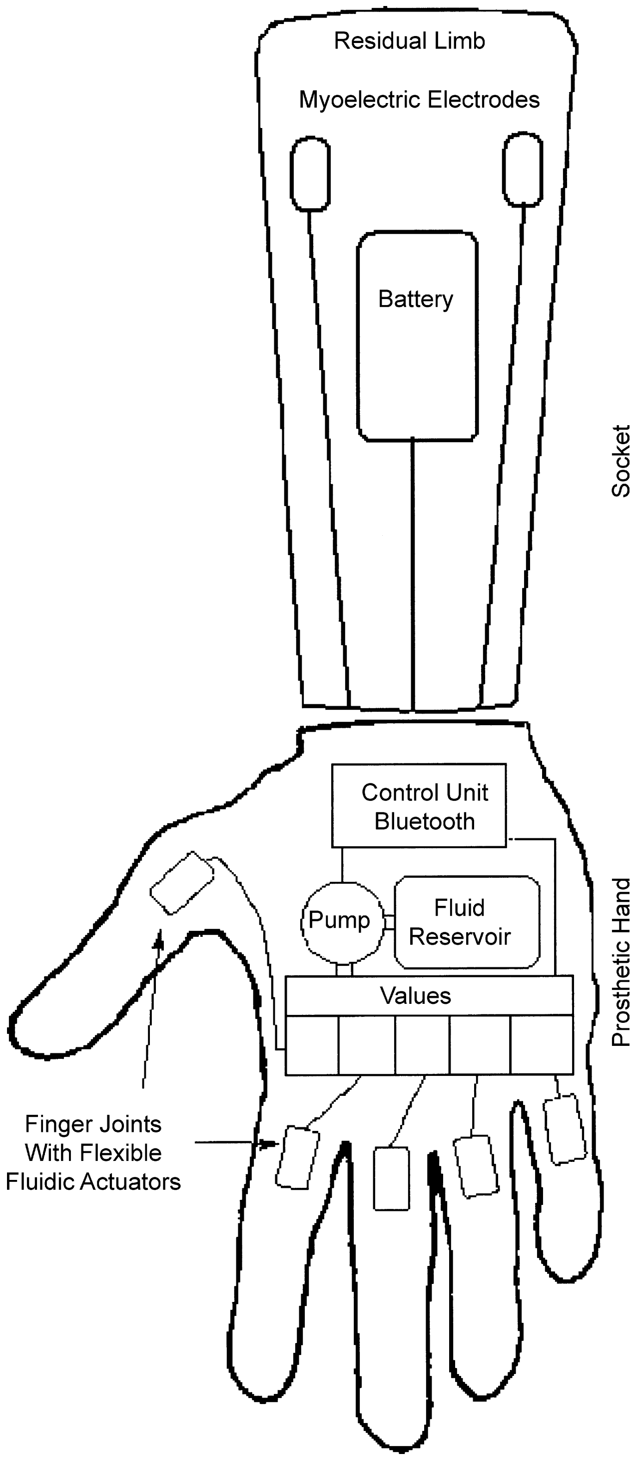

Fig. 2. Structure of the new hydraulic system.

Fig. 3. The modern prototype of the fluidically driven prosthetic hand.

According to the design concept of the electro-hydraulic system, the artificial hand does not need any other external components for functioning, except for a rechargeable lithium battery and myo-electrodes that are housed within the socket to contact the user's skin. The joints of this prosthesis are actuated by flexible fluidic actuators which are connected to the microvalves. Some actuators are coupled, like the base joints of fingers IV–V and both joints of fingers II and III accordingly. Actuators of the thumb can be controlled independently of each other. Consequently, the prosthetic hand prototype may accomplish up to five grasping patterns: power grasp, precision grasp, tripod grasp, hook grasp, and stretching of an index finger. The grasping patterns are pre-assigned in the control unit of the hand and accomplished as follows. Firstly, the electronic unit receives the control signals from the user. The control system of the prosthetic hand collects control signals from the upper limp muscles via myo-electrodes [17]. The control unit is responsible for the analysis of control signals, selection of pre-programmed grasping patterns, and operation of the hydraulic pump and valves. Afterwards, the hydraulic pump generates the fluid pressure in the actuators, and electric valves control the action of the actuator. Depending on the grip type selected, the corresponding actuators will be filled and the joint will move. The pump and valves will be controlled by the hand electronics as well. The electronic unit consists of a custom-made, multi-layer, small-sized circuit board that fits into the metacarpus of the hand. It includes a programmable microcontroller (type PIC16F877 by Microchip Technology Inc., USA), drivers for the valves and the pump, an analogue–digital converter, and a serial RS232 and Bluetooth interfaces to change settings of the controller.

3. Components of the electro-hydraulic system

3.1. Flexible fluidic actuators

The design of artificial hands and their resulting functionality depend largely on the characteristics of the actuator principle used. These characteristics include compactness, weight, compliance, and efficiency. Hydraulically driven actuators are widely used in automation applications, as they provide an excellent power-to-weight ratio. However, hydraulic actuators that meet all requirements of a prosthetic hand have not been available in the past. Consequently, new flexible fluidic actuators were built by our research group in 1999 and presented in detail in [18]. The first actuators were composed of thin plastic films in a very compact two-layered body with two separated chambers. By inflation of each of these chambers with fluid medium, the rotational movement was achieved. Many different prototypes of actuators based on this principle have been built in our laboratory up to date [19].

The current flexible fluidic actuator consists of a reinforced flexible bellow which forms a closed elastic chamber (Figs. 4 and 5). Both ends are attached to solid fittings that are connected with the levers of a joint. Both of these fittings are equipped with a connector for the fluid supply line. A special tissue covers the bellow to reduce the radial expansion of the actuator under pressure. The axial expansion of the flexible bellow exerts a pulling force on the joint fittings, as the actuator is inflated with the fluid. These actuators have a compact dimension of 12 mm in diameter and 16 mm in length (Fig. 4). Hence, they can be integrated directly in the joints. This ensures a direct connection of the actuator with the joint, easy replacement, and servicing. Low weight and inherent compliance are two major attractions of this actuator. The low weight of 2.6 gram is achieved by using lightweight materials for construction. Still, these materials can transmit energy as well as a cylinder, but they have a higher power-to-weight ratio at the same pressure and volume. The maximal torque of the artificial joint of 0.69 Nm can be achieved at 6 bar pressure (Fig. 6). Moreover, the modular construction allows for the independence of the actuators of each other and of the position of the joint in the artificial hand. Consequently, actuators can be interchanged or the number of degrees of freedom can be changed. This may be useful when redesigning the end manipulator for the special application without a reconstruction of the whole system.

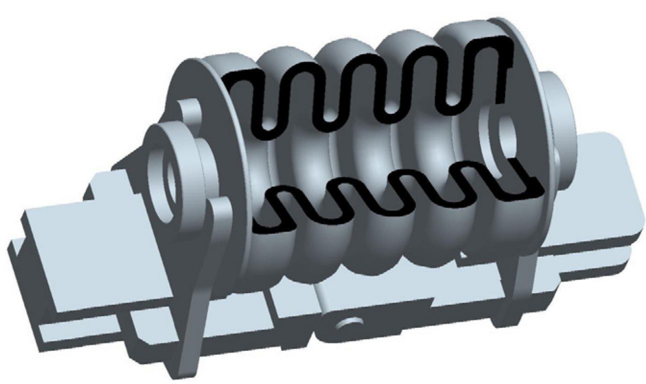

Fig. 4. Technological design of the flexible fluidic actuator and an artificial finger joint (US Patent 2005/066810A).

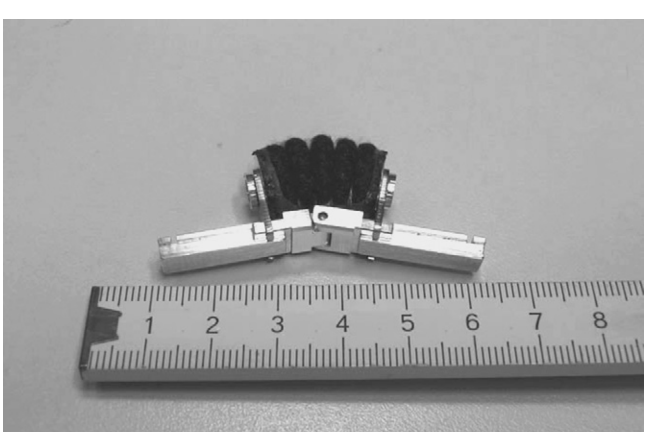

Fig. 5. The prototype of the flexible fluidic actuator with an artificial joint.

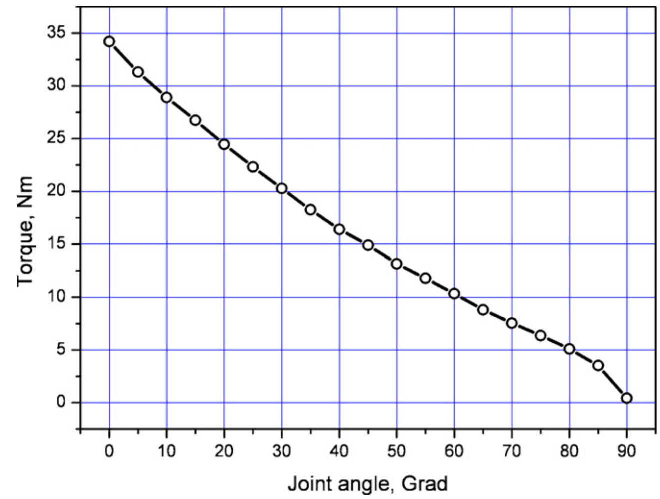

Fig. 6. Torque characteristic of the FFA at 6 bar pressure.

If the fluid pressure is applied to the actuator, the torque does not only depend on the pressure level, but also on the state of inflation. This behaviour can be characterised in general by the following equation:

$$M(p,\varphi) = \sum_{k=0..3} a_k\varphi^k + \left[\pi\left(\frac{d}{2}\right)^2\left(\frac{d}{2}+e\right) - C_A\varphi\right]p \tag{1}$$

In Eq. (1), φ is an angle of the joint, d the inner diameter of an actuator, e the distance from the actuator to the joint surface, and C_A is the constant which depends on the material and actuator geometry (Fig. 7).

The total torque of an actuator $M(p,\varphi)$ results from the torque M_0 of preliminary tension of an actuator:

$$M_0(\varphi) = \sum_{k=0..3} a_k\varphi^k \tag{2}$$

In Eq. (2), a_k are constants which characterise the spring-like behaviour of an actuator.

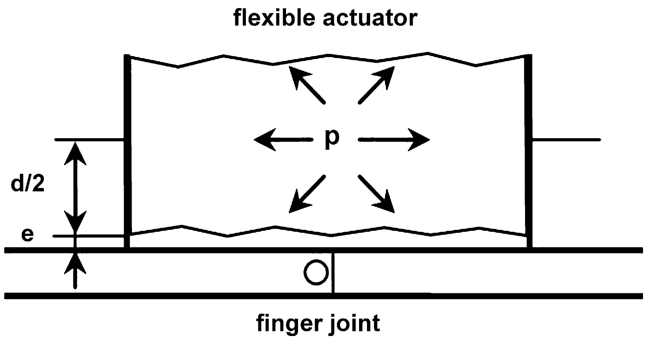

Fig. 7. Flexible actuator with a finger joint.

M_1 is the torque that results from the pressure p acting on the circular front surface inside the actuator:

$$M_1(p,\varphi)=\pi\left(\frac{d}{2}\right)^2\left(\frac{d}{2}+e\right)p \tag{3}$$

The torque will change depending on the joint angle. The passive stiffness behaviour of an actuator can be described in analogy to the non-linear spring, if the pressure remains at the fixed level:

$$c^{-1}(p,\varphi)=\left.\frac{\partial M(p,\varphi)}{\partial\varphi}\right|_{p=\text{const}} \tag{4}$$

Inherent compliance is an important property of flexible actuators, which makes these actuators suitable for applications in the area of prosthetics and man-machine interaction. Due to the compliance of actuators, adaptive grasping and soft touch can be achieved, which is important for handling fragile objects.

3.2. Miniaturised hydraulic pumps

A large variety of principles and sizes of hydraulic pumps is commercially available. Proper selection of the pump depends significantly on the application as well as on the system requirements and demands on pump performance.

In the general system concept for applications in prosthetics presented in Section 2, a hydraulic pump is responsible for pressure generation in the hydraulic actuation system and efficient pressure supply to the fluidic actuators. A number of characteristics are relevant to the selection of the hydraulic pump for upper-limb prosthetic devices:

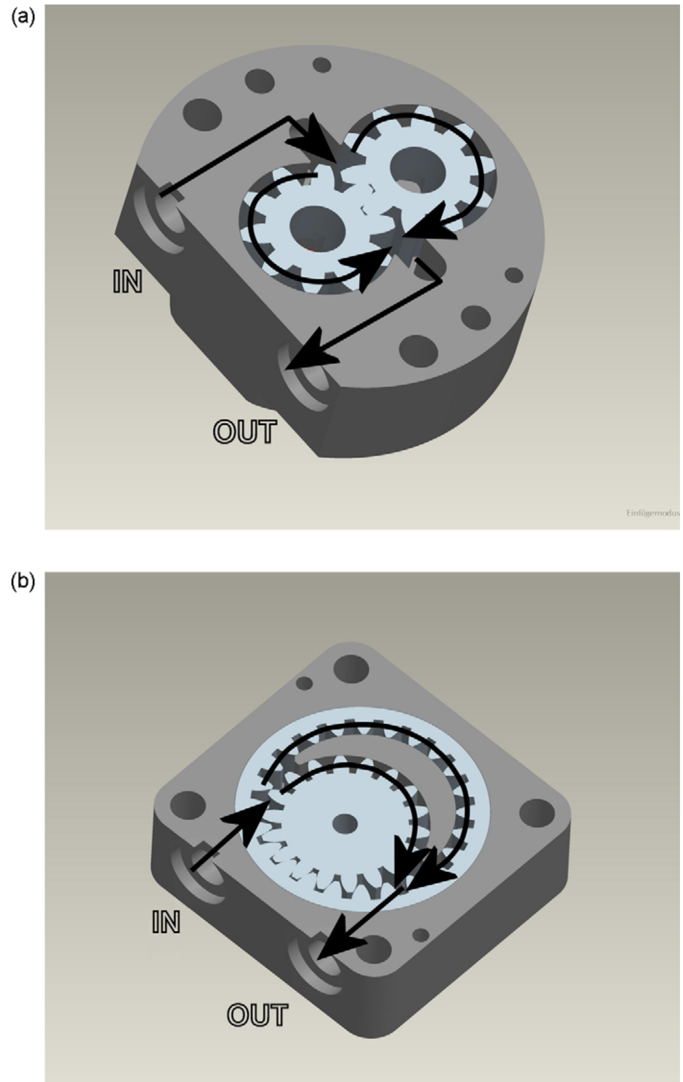

Fig. 8. (a and b) Functional principle of internal and external gear hydraulic pumps.

- the pump has to be housed in the metacarpal region of the hand, together with the valves, the fluid reservoir, and the control electronics. Hence, the pump dimensions should not exceed a volume of $20\,\text{cm}^3$;
- operation voltage should not exceed 7.4 V to ensure compatibility with commercially available power supply units used for upper prosthetic devices;

Table 2
Comparison of different pump principle characteristics

Pump feature	Type of pump: Centrifugal	Piston	Impeller	Screw	Gear
Self-priming	No	Limited	Yes	Limited	Limited
Pressure range	Low	Low to high	Low to high	Low	Low to high
Weight	Low	High	Low to high	High	Low to high
Two-way pumping	No	Limited	Yes	Yes	Yes
Wide speed range	No	Limited	Yes	No	Yes
Efficiency	Low	High	Low	Low	Low to high
Complexity of construction	High	High	Low	High	Low

Table 3
Technical characteristics of hydraulic gear pumps in comparison

Type of the gear pump	Standard A	Standard B	Custom A	Custom B
Type of pump	External gear	External gear	External gear	Internal gear
Sound level (distance of 1 m) (dB)	75	64	52	52
Max. pressure difference (bar)	13	5	9.2	5.1
Max. flowrate (ml/min)	480	367	625	625
Max. power consumption (W)	60	12	18.9	16.9
Efficiency (%)	10	17	28	12
Weight (g)	92	56	56	58
Diameter (mm)	32	24	21	21
Length (mm)	69	44	42	42

- as the current is supplied by accumulators, power consumption of the pump should not exceed 5 W to ensure an average operation time of the hand of 1 day;
- a pressure of 6 bar is needed by the fluidic actuators to generate a sufficient grasping force;
- a flow rate of 600 ml/min is necessary to reach a sufficient grasping speed for all eight actuators;
- another important criterion is noise emission. When using the prosthesis, noise can be very disturbing. However, a level of 40–50 dB will be acceptable.

Prior to choosing a hydraulic pump, different types are compared in terms of small dimensions and low weight. The most usable hydraulic pumps of today, such as magnetic piston pumps, axial piston pumps, radial piston pumps, impeller pumps, centrifugal pumps or screw pumps comply only partly with the criteria above and cannot be integrated in a prosthetic hand due to their big dimensions and high weight [20].

Discussion of the functioning principle of the pump finally led to the decision to use a gear pump. Recommendation of the gear functioning principle was based on the criterion of small dimensions acceptable for prosthetic devices. Compared to other pump principles, gear pumps appeared to be the best alternative also in terms of possible high efficiency, low weight, two-way pumping, self-priming, and simple construction (Table 2).

Gear pumps can be subdivided into internal and external gear pumps. Both were designed and used for the hand prosthesis.

The external gear pump contains two geared wheels engaged with each other (Fig. 8a). These wheels are run in two cylindrical recesses in the housing with little friction and play. In the engagement area of the two wheels, the pressure side is isolated from the suction side. In the suction volume, the tooth gaps take up the fluid. By the rotation of the wheels, the pumping cells are closed. In the engagement area, a so-called squeezing oil groove ensures the outflow and inflow of the oil enclosed by the teeth on both the suction side and the pressure side. On the suction side, fluid flows through this groove into the squeezing volume that expands when the teeth are opened.

In the internal gear pump, the driving wheel drives a somewhat larger tooth ring (Fig. 8b). Between the gear wheel and the tooth ring, a sickle-shaped element in the pump housing provides for the sealing of the tooth cavities. At the ends of the sickle, inlet and outlet openings are located. Due to homogeneous tooth engagement, the pulsation is smaller than in case of the external gear pump. The freely running tooth ring in the housing, however, causes higher friction losses.

The next step in the selection of a proper hydraulic pump was a comparison of alternatives of gear pumps. Only a few hydraulic gear pumps are suitable for implementation as a hydraulic pump

Fig. 9. Five different gear pumps. (a) Standard diaphragm pump (Type 5002F from ASF Thomas, Germany); (b) standard A commercial pump (Type Speed 300 from Behotec, Bergkirchen, Germany); (c) standard B commercial pump (MTH Modelltechnik Häusl, Apfelberg, Austria); (d) external gear custom-made pump; (e) internal gear custom-made pump.

for prosthetics. A comparison of two commercially available gear pumps is presented in Table 3. Fig. 9a represents a standard diaphragm pump in comparison with commercially available and custom-made gear pumps, regarding their dimensions. The standard A gear pump (Fig. 9b) was also too large to be placed within the hand. The standard B gear pump (Fig. 9c) could be integrated in the miniaturised hydraulic system due to its acceptable dimensions. However, its drawbacks are either a high power consumption and an unacceptable noise emission or an insufficient flow rate.

Having analysed the technical characteristics of standard gear pumps, our research group started to develop custom-made gear pumps tailoured to the requirements of the hand prosthesis. Firstly, an electric motor with a better stop torque and efficiency factor was chosen from 8 suitable alternatives. Afterwards, the technology of manufacturing of gear wheels was optimised by improving the precision of tools and instruments. As a result, two custom-made gear pumps were designed and constructed.

The first version was an external gear pump (Figs. 9d and 10a). It contained standard gear wheels. A long service life of this pump was guaranteed by the combination of steel and bronze gear wheels. All housing parts were made of a high-strength aluminium alloy with an accuracy of 0.01 mm and tailoured to the gear wheels. Sealing was achieved by an O-ring between the housing and the lid and by a radial packing.

The next generation of custom-made external gear pumps is equipped with custom-made gear wheels. Their involutes ensure rolling at lower noise. In addition, the pump housing is hardened by coating. This improves the surface quality and significantly increases wear resistance. The previously applied radial packing is replaced by a space-saving higher-quality seal. The latest version of the pump is equipped with roller-borne gear wheels to prevent wear of a sliding bearing and minimise friction losses.

The internal gear pump (Figs. 9e and 10b) has passed development stages similar to those of the external pump. The optimisation expenditure, however, only resulted in a smaller size, but did not increase the performance. With a slightly lower noise emission, the efficiency of the internal gear pump remains below that of the external gear pump.

Based on the criteria of noise emission, flow rate, power consumption, and dimension, the hydraulic external gear pump was chosen for integration in the miniaturised hydraulic system.

3.3. Valves

In the same way as the hydraulic pumps, suitable hydraulic valves were chosen from the multitude of alternatives available. The following requirements were established for the design of hydraulic valves during the development of the actuation system:

- the valves should have small dimensions. This allows for the integration of all valves in the prosthesis;
- operation voltage should not exceed 7.4 V. This makes valves compatible with commercially available power supply units used for upper prosthetic devices;

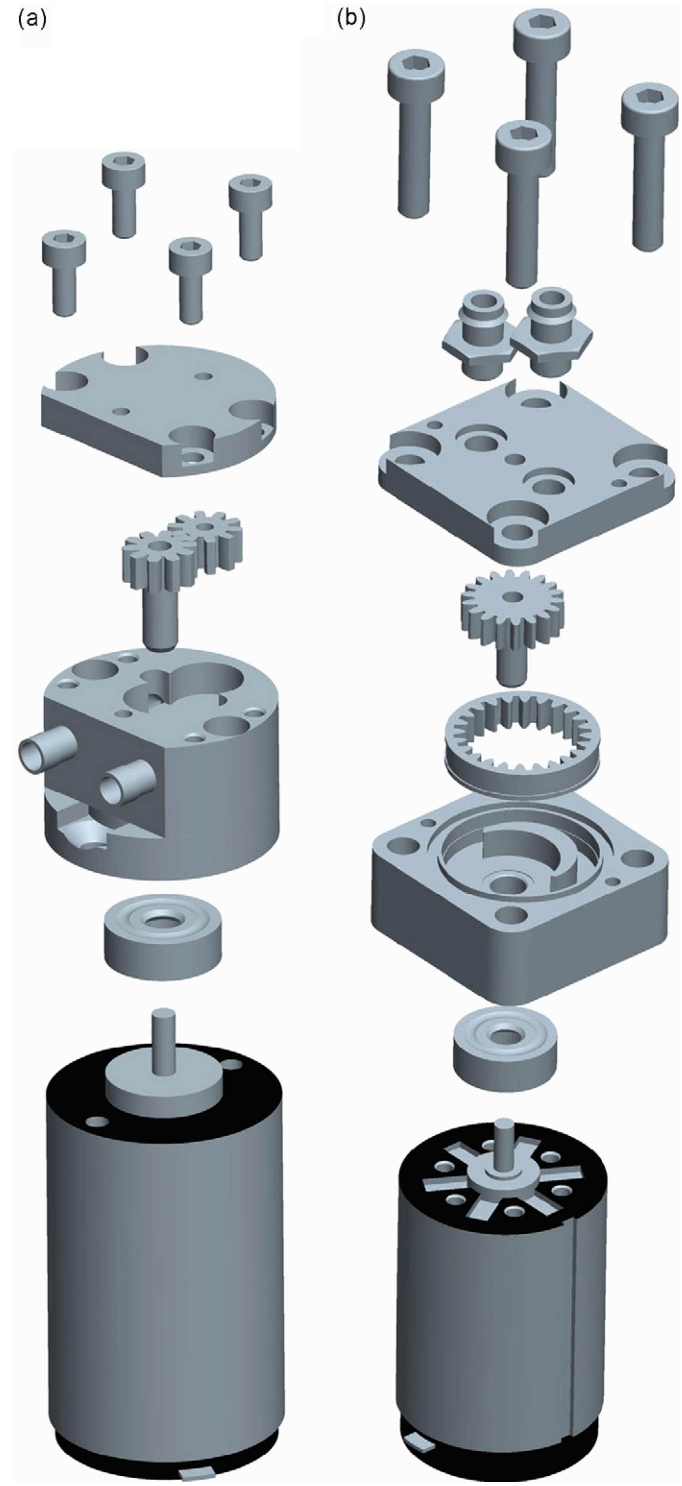

Fig. 10. Design of an external und internal gear custom-made fluid pumps.

- valves should have a low power consumption for the power supply of the hand prosthesis being sufficient;
- a minimum flow rate of 8 ml/s should be achievable to ensure dynamic movements of all actuated hand fingers;
- valves should operate at a maximal pressure of 10 bar. The connection with the valve that is impermeable even at high pressure is referred to as inlet, the other as outlet.

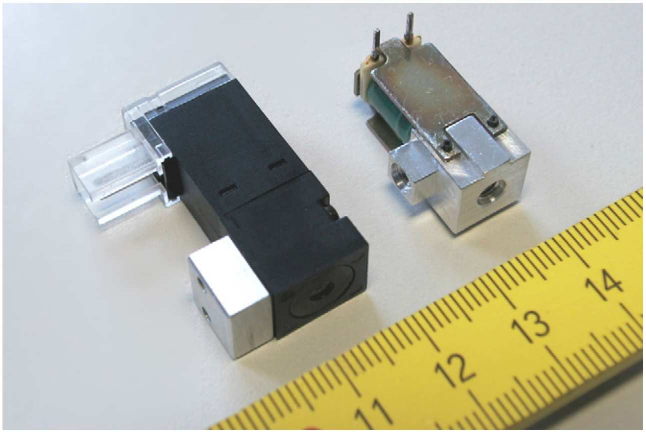

Fig. 11. Standard valve and custom-made valve.

Table 4
Technical characteristics of valves in comparison

Valves	Standard	Custom-made
Standard operating voltage (V)	5	6 V
Number of ways	3	2
Function	Normally closed	Normally closed
Action	Direct acting	Direct acting
Orifice size (mm)	0.5	0.9
Dimensions	32 mm × 27 mm × 10 mm	23 mm × 11 mm × 13 mm
Pressure range	From 0 to 5 bar	From 0 to 6 bar
Max. flow rate (ml/min)	274	600
Power consumption (W)	1	1
Weight (g)	24	12
kv flow factor fluid (air)	0.26 (0.12)	0.57 (0.34)
Media type	Air, neutral fluids	Air, neutral fluids
Response time (ms)	10	10
Life expectancy	100 million cycles	100 million cycles

Only a few alternatives of valves on the market fulfilled these requirements. One of the best-suited valves in terms of size and flow rate was a 3/2-way valve (FAS, Switzerland, type picosol) which may be used either hydraulically or pneumatically (Fig. 11).

The standard valves applied require a switching voltage of 5 V and a current of about 140 mA. The orifice of this valve has a diameter of 0.5 mm. With a size (without valve bench) of 27 mm × 24.2 mm × 10 mm (=6534 mm^3), the valves are relatively large. However, the flow rate of this type of valve is rather moderate and the desired gripping speed and compactness of the hand prosthesis could not be reached.

For this reason, development of compact valves with a high flow rate was started. 2/2-way normally closed valves with two connections to the hydraulic system and two switching modes “valve closed” and “valve open” were developed (Figs. 11 and 12). The inlet of the valves goes into the valve chamber. When the valve is open, the hydraulic fluid entering via the inlet can leave the valve chamber through a small bore-hole in the bushing installed at the bottom of the valve chamber. The inner diameter of the orifice has a major effect on the maximum flow rate of the valve. The inner diameter of 0.9 mm is chosen for the orifice to achieve an adequate flow rate.

The bushing is manufactured separately from the valve housing, as its exact fabrication is decisive for the parameters of the valve. The roughness of the orifice surface decides on how well the valve may be sealed by the fitting. Furthermore, the bore-hole of the bushing is the smallest inner diameter in the valve. If manufacture is imprecise, turbulences of the hydraulic fluid may result.

The technical characteristics of 20 self-made valves are presented in Table 4. The test fluid used was a synthetic oil which had a viscosity of 10 mm^2/s (at 25 °C). The characteristics were determined at a decreasing pressure difference (6–0 bar pressure difference). In addition, the flow rates were measured at a fixed pressure difference of 1 bar (from 6 to 5 bar).

Hydraulic valves separate the fluid supply line between a hydraulic pump and actuators. Under real conditions, the pressure level differs continuously while inflating and deflating the fluidic actuators. Hence, hydraulic valves should provide for an absolute interruption of fluid supply for the finger joints to stabilize at a defined position during grasping. A special test rig was constructed for the determination of flow rates. Each valve was connected with two pressure gauges and pressure reduction valves on both the inlet and the outlet side to adjust the pressure difference between them. Flow rates were measured at different pressure differences simulating the real functioning of the hydraulic system, including pump and actuators. Fig. 13 represents the flow rate characteristics of both standard and custom-made valves in comparison. Compared to commercially available valves, the novel development has a smaller size and a higher flow rate. This is confirmed by a comparison with the standard 3/2-way valve that had been applied for the hand prosthesis before. Custom-made valves have stronger spring elements compared to standard ones. They have a major influence

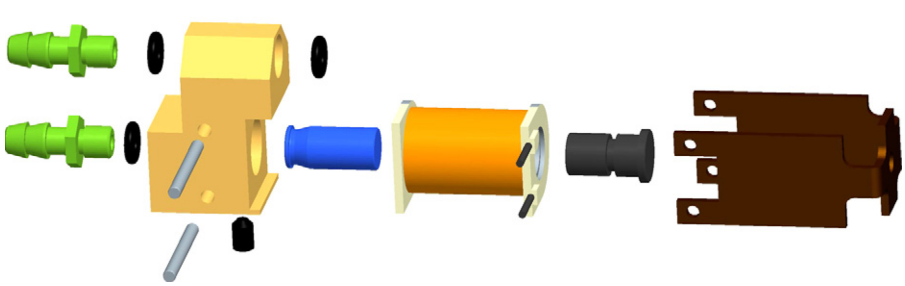

Fig. 12. Design of the custom-made valve.

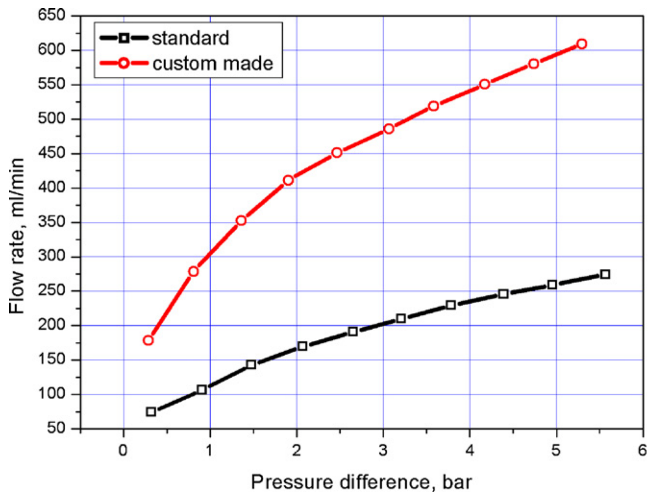

Fig. 13. Flow rate versus the pressure difference of standard and custom-made valves. Fluid: synthetic oil, viscosity: 3.7 mP.

on the maximum pressure range of the valve. Hence, the standard valve needs a lower switching voltage (only 5 V for the model used) and less current (about 140 mA instead of about 200 mA), but more space than the self-developed valves. A self-developed valve requires up to 23.47 mm × 11.2 mm × 13 mm (=3417 mm^3) (at 0.9 mm) (see Table 4).

At a pressure difference of 5.57 bar, the standard valve tested reaches a flow rate of 274 ml/min only. This is less than half of the flow rate of the custom-made valve. The custom-made valve reaches a flow rate of 609 ml/min at a pressure difference of 5.3 bar.

3.4. Fluid characteristics

As a fluid medium, synthetic, non-toxic, and biocompatible oil with a viscosity of 3.7 mPa and a density of 0.94 g/cm^3 at 25 °C was used for our actuation system. This oil can be operated in a wide temperature range that makes it suitable for application in the hydraulic system. The silicone oil is an appropriate lubricant, and corrosion of the gear pump can be avoided. Water has a viscosity of 1 mm^2/s and a density of 0.998 g/cm^3. Furthermore, a positive side effect of silicone oil is that it may be classified as cavitation retardant.

4. Conclusion

The newly developed miniaturised hydraulic system allows for adjusting both the geometry and functionality of the artificial hand. It can be used as a basis of the construction of a functioning prototype of a hydraulic artificial hand of increased quality in use. This hand can be tested clinically for use by limb-deficient people and applied for service robotics as an artificial gripper. Prosthetic prototypes are being developed in cooperation with orthopaedists in Germany, taking into account any request by patients. For example, grip functionalities of the artificial manipulator may either be customised for outdoor jobs, such as a forester, or for indoor applications in the office. The number of degrees of freedom and functions of each finger, several fingers or joints may be tailoured accordingly. Each prosthesis can be built of standard components, including the actuation system, and adapted to the patient.

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Biographies

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