Robotica (2005) volume 23, pp. 293–299. © 2005 Cambridge University Press
doi:10.1017/S0263574704001316 Printed in the United Kingdom

A hydraulically driven multifunctional prosthetic hand

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SUMMARY

In this paper a new prosthetic hand is presented that closely approximates the grasping abilities of a human hand. A large variety of different objects can be grasped reliably and the movements of the hand appear to natural. This five-finger hand has 15 degrees of freedom driven by small sized flexible fluidic actuators. The drives are within the fingers allowing a very compact and lightweight hand. Also, a concept for the control of different grasp types is presented. The characteristics of the new hand are illustrated.

KEYWORDS: Artificial hand; Exo-Prosthetics; Fluidic actuators; Control.

INTRODUCTION

"Instead of all these, man has by nature his reason and his hands, which are 'the organs of organs', since by their means man can make for himself instruments of an infinite variety, and for any number of purposes".[1] More than 7 centuries after St. Thomas Aquinas (1225–1274) wrote his doctrine it is more valid than ever. Many achievements of our civilization are inconceivable without the capabilities of our hands. Therefore, the loss of an upper limb results in a drastic restriction of function and effect on the appearance of the individual. In the last decades an increasing number of limb deficient persons have been provided with externally powered prosthetic hands. One reason for this is that they can be operated without attracting undue attention to themselves. The alternative active devices, body-powered prostheses, have a restrictive and often uncomfortable harness system.

Since the first application for a patent on an electric driven prosthetic hand by Edmund Wilms in 1950,[2] the basic principle of the drives has not changed. In contrast to a natural hand being able to perform a large variety of different grasp types this hand can only perform palmar prehension, cylindrical prehension and optionally rotate the wrist. The thumb of the leading prosthetic hand is always in direct opposition to the index and middle finger. The posture of this prosthetic hand is a consequence of functional considerations,[3] but it does not appear very natural, especially in the relaxed position. The opening and closing of the hand is performed by a DC motor with reduction gear train.

Surveys on the use of externally powered prosthetic hands have revealed that more than 30% of the potential population do not use their artificial limb regularly.[4,5] The main factors for the rejection of conventional prosthetic hands are the restricted functionality, the unnatural appearance and the heavy weight. Other research groups have already demonstrated that the functional range of an externally driven prosthetic hand can be improved by enabling the thumb to be moved independently from the other fingers.[6] Hence, their hand can either perform a powerful hook grasp (without contribution of the thumb) or a precision grasp (where the tips of the fingers oppose the tip of the thumb). As a result of extensive research prototypes of prosthetic hands with more independent DOFs have been constructed.[7–10] However, the series production of these designs has been prevented because of the devices' weight and poor reliability. A more recently published design concept indicated the possibility for overcoming the problem of excessive weight.[11]

To achieve a better acceptance another new concept for the design of an improved prosthetic hand has been developed at the Forschungszentrum Karlsruhe, Germany (FZK). It is driven by 15 flexible fluidic actuators. The miniaturised actuators are integrated in the fingers of the new artificial hand. This enables the construction of a very lightweight hand with high functionality and movements similar to a natural hand. With this design the most common prehension patterns[12] can be performed which allows the grasping of many objects or tools of different sizes and shapes.

The development of pneumatically driven prosthetic arms started in 1948 at the orthopaedic clinics in Heidelberg.[13] More than 350 adults profited from this technology, but it was not successfully used with children. All 60 persons with thalidomide-induced limb deficiencies rejected this prosthetic arm because the devices were too bulky for them. Therefore, instead of using them they learned how to grasp with their residual limbs and with their feet. The handling of the carbon dioxide cartridge during exchange was difficult and leakage led to local icing injuries, so fluidic prostheses were replaced by electrically driven hands. For the re-emergence of fluidic devices requires the availability of new materials, production technologies and miniaturised pumps, valves and actuators. These are fundamental for the construction of a lightweight multifunctional fluidically driven artificial hand.

FLEXIBLE FLUIDIC ACTUATORS

The basic drive principle of flexible fluidic actuators can be observed in nature: the extension of a spider's knee joint is performed by a hydraulic mechanism. A liquid is pressed into a cavity that is connected to the levers of a joint. As the

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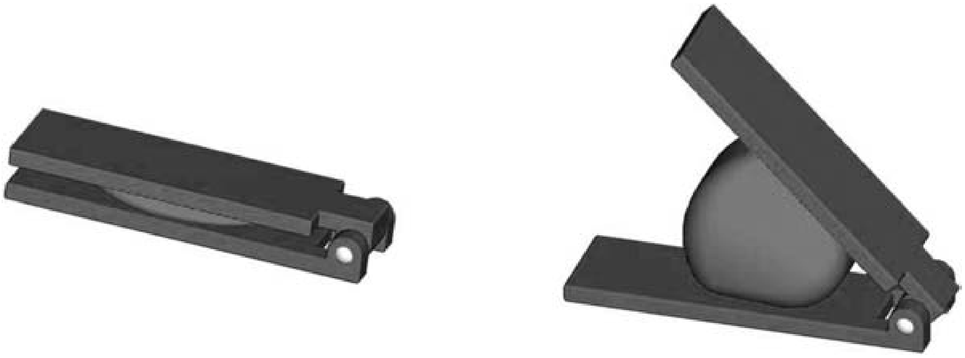

Fig. 1. Extension Principle of a Flexible Fluidic Actuator.

volume of the cavity increases the joint levers move apart and an extension is performed (see Fig. 1). The resulting force and the range of motion depend on the actuator geometry and pressure. The mathematical models to calculate the resulting force of a flexible fluidic actuator is given in reference [14].

Like other fluidic actuators they have a very good power to weight ratio and high dynamics.[15] For this reason fluidic actuators have already proven to be salient for robotic applications. Contrary to conventional actuators the mechanical design of the joint is restricted less by the geometry of the actuator. Other advantages over conventional actuators are the lack of friction in the actuator itself and the lower cost.

CHARACTERISTICS OF THE MULTIFUNCTIONAL PROSTHETIC HAND

The new prosthetic hand is a further developed version of the *Bionic Hand Prosthesis*.[16] It also uses the extension principle of flexible fluidic actuators. The resulting force at the tip of one single finger was increased by 45% to 8 N at a pressure of 7 bar (see Fig. 2). The maximum holding force of 65 N tallies with the minimum grasping force of 68 N that has been proposed as a standard for the maximum prehension for single DOF prosthetic hands. However lower values might be acceptable in adaptive hands where objects can be encompassed within the hand. For example in natural prehension a grip force of below 10 N has shown to be sufficient to perform most grasps.[6]

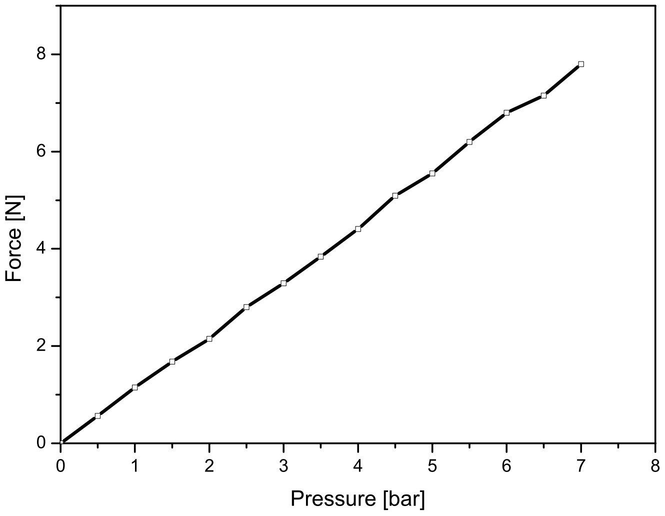

Fig. 2. The force at the fingertips.

In a prosthetic hand all components have to be integrated into the forearm and the hand itself. To reduce the mass of the artificial hand only lightweight materials with good mechanical properties are used. The skeleton of the actual prototype hand consists of high tensile strength titanium and the metacarpus contains lightweight custom made microvalves. The other components; two myoelectric sensors, power supply (two rechargeable standard lithium-ion batteries, from NEC Electronics Corp.), an Infineon C164CI microcontroller (supplied by Silica/Avnet Company, Munich, Germany), and a custom made micropump are housed in distal part of the forearm of the prosthesis. At the moment a residual forearm up to the wrist can be fitted with the new prosthesis. The mass of the complete prosthetic arm (including socket, batteries and glove) is 891 g. The user of the hand is habitually wearing a 2 DOF Otto Bock System Electrohand with a total mass of 1150 g. In order to approximate the range of motion of a natural hand each finger has 3 joints each driven by a flexible fluidic actuator. The joint in the middle of the finger (proximal interphalangeal joint) and the one that is at the end of the finger (distal interphalangeal joint) are coupled. The second independent DOF is the joint that connects the fingers with the palm (metacarpal phalangeal joint). The design of the thumb differs from the fingers by allowing an adduction towards the index finger and an opposition towards the other fingers. It also contains 2 coupled joints for a flexion movement. The angle of flexion of a whole finger with 3 joints was measured with a protractor. It depends on the pressure that takes effect on the flexible fluidic actuators and is given in Fig. 3. The maximum angle of flexion between the longitudinal axis of the metacarpus and the tip of the finger is 249^0 at 5 bar. So the multifunctional prosthetic hand offers a much higher finger flexion than a conventional prosthetic hand.

The new prosthetic hand is covered with an artificial skin that has multiple functions. First, it covers the actuators and electronics and gives mechanical protection. The second function is the improved cosmesis by imitating the shape and colour of the original hand. Third, the texturised skin material reduces the lubricating effect of liquids, so the friction coefficient remains high enough to hold objects without slipping. In a conventional prosthetic hand the fingers

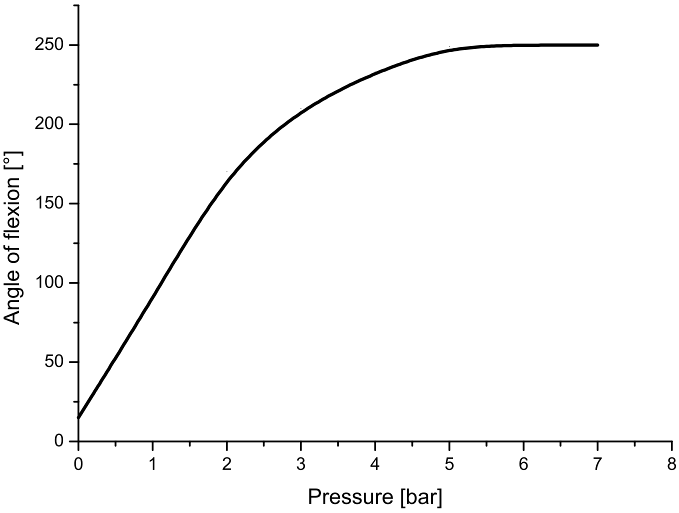

Fig. 3. Range of motion of a single finger.

do not adapt to the shape of an object because they have only one or two DOF and the materials have a low compliance. An increased friction coefficient at lower contact forces was found for compliant materials.[17,18] Larger contact areas by conforming to rough surfaces is an important factor for gripping more efficiently and therefore for saving energy.[18] For this reason compliant materials have been chosen.

A comparison of the contact area in a natural hand, a conventional electrical prosthetic hand and the multifunctional prosthetic hand was performed. The palmar surface of the hands was covered with black ink and a book with the dimensions of 27 × 123 × 214 mm and a cylindrical bottle with a diameter of 54 mm that were covered with white paper. These objects were then grasped. The right hands of 5 male subjects with glove sizes ranging from 8 to 9, an Otto Bock System Electrohand with glove size 8 1/4 and the new prosthetic hand with glove size 8 1/2, were examined. Grasping experiments were repeated 5 times for each hand. The contact prints were digitised using a conventional desktop scanner (HP Scan Jet 6350C) with a resolution of 300 dpi. Afterwards image files were thresholded and the contact area was determined from the number of the black pixels and the resolution. An accuracy of 99.9% was achieved for this method of image analysis when scanning an black square with an area of 100 cm^2. Although the size of the tested hands was not exactly the same and it was biased slightly in favour of the natural and the new prosthetic hand, the results are distinct (see Tab. I and fig. 4 a–c)

Table I: Contact areas between different hands and a bottle and a book.

	Natural Hand	Otto Bock System Electrohand	Multifunctional prosthetic hand
Book	48,2 cm^2	3 cm^2	32,9 cm^2
Bottle	59,6 cm^2	9,2 cm^2	35,6 cm^2

Another advantage of the compliant properties of the new prosthetic hand is that it feels more natural when touched. The self-adaptable properties of the hand mean that the precise torque and position of the joints do not necessarily have to be known which simplifies the control.

CONTROL SCHEME

It is widely accepted that the control of a prosthetic hand with several independent DOFs is difficult. However, high reliability is one of the most important issues regarding functional prostheses. Compared to the human hand, the execution of a movement must not originate from a complex variety of bioelectric signal patterns, but must be controlled easily without burdening the user with exhaustive training [8]. As long as implantable microsensors are not compatible for long term use in the human body, non-invasive sensors have to be used. An established and widely used method to control externally-powered upper limb prostheses with one or two DOF is the use of myoelectric surface electrodes (EMG electrodes). These sensors are positioned over antagonistic muscle groups (flexors/extensors) in order to monitor and detect muscle activity. Unfortunately, myoelectric signals are noisy, low in amplitude and originate from the superposition of several muscle fibres.[19] These reasons decrease signal quality and may lead to misinterpretation of the signal when controlling more than two independent DOF.

Using two myoelectrical surface electrodes (Otto Bock, sensor type 13E153, Duderstadt, Germany) a new sequential

Fig. 4a–c. Contact areas between a bottle and a natural hand (left), an Otto Bock System Electrohand (middle) and the multifunctional prosthetic hand (right).

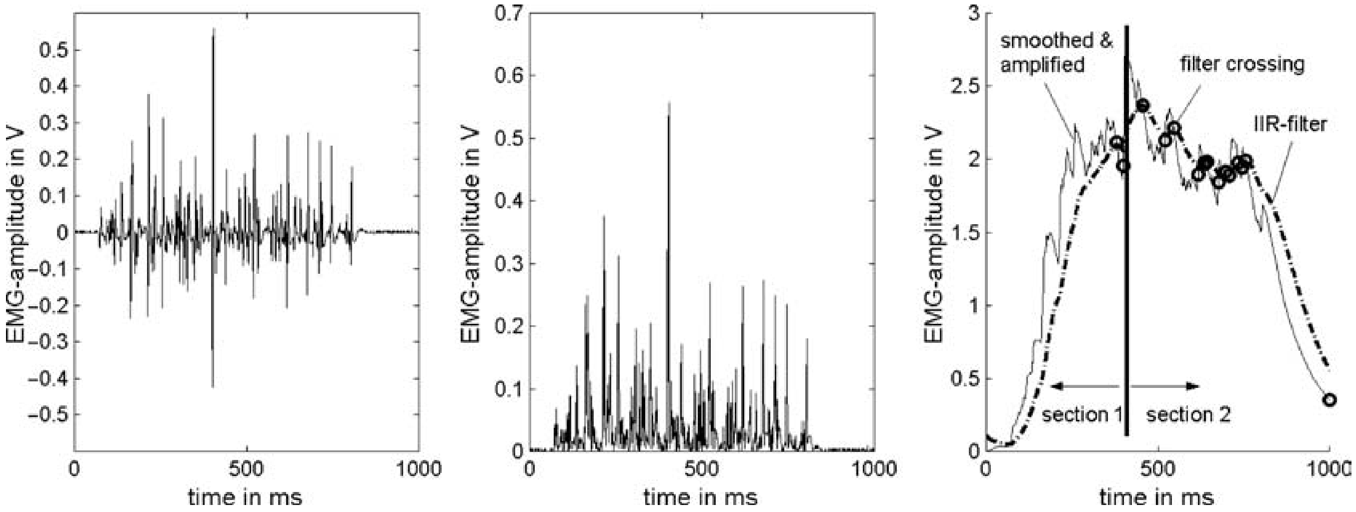

Fig. 5a–c. Example for an EMG signal: left: raw EMG signal, middle: rectified, smoothed and amplified EMG signal, right: feature selection for switch signals.

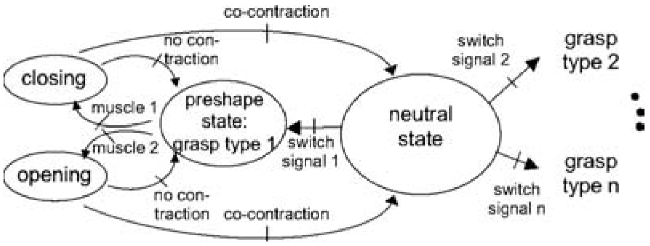

Fig. 6. State machine for grasp type classification.

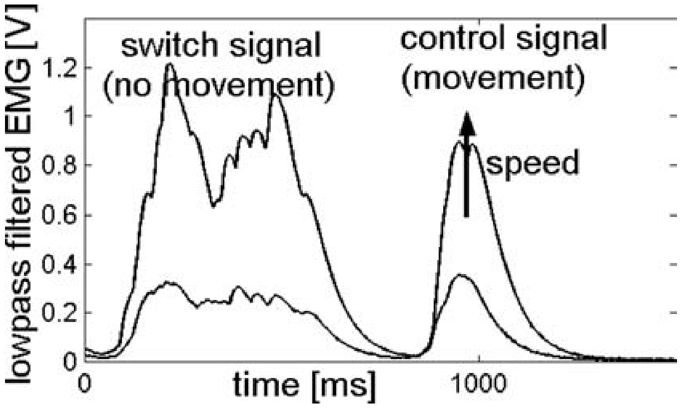

Fig. 7. Myoelectric control sequence for grasp type selection.

mode control concept has been implemented that gives a person with an amputation easy control over several grasp types. Analogous to the human motion sequence during grasping[20] it is divided into two phases:

At first the fingers of the prosthetic hand are transferred from a resting hand position into a preshape position by a switch signal, depending on the grasp type the user wants to perform. This is comparable to the co-contraction signal that is used in conventional prosthetic hands to switch between a rotation of wrist mode and the hand opening and closing mode. A following signal is given to open and close the designated grasp type.

In particular, the integrated hardware unit of the myoelectric sensors amplifies, rectifies and filters the raw myoelectric data. Thus, the signal generated, gives information about the intensity of muscle contraction (see Fig. 5a–b).

The beginning and the end of a muscle contraction (start-stop-detection) may now be detected by applying time variant thresholds with hystereses on the signal.[21] After having detected the beginning of a muscle contraction, a *state machine* ascertains the users desired grasp type: Starting in a neutral state of the state machine (see Fig. 6), the user has to generate a unique signal pattern (switch signal), which is related to a certain grasp type (Fig. 7).

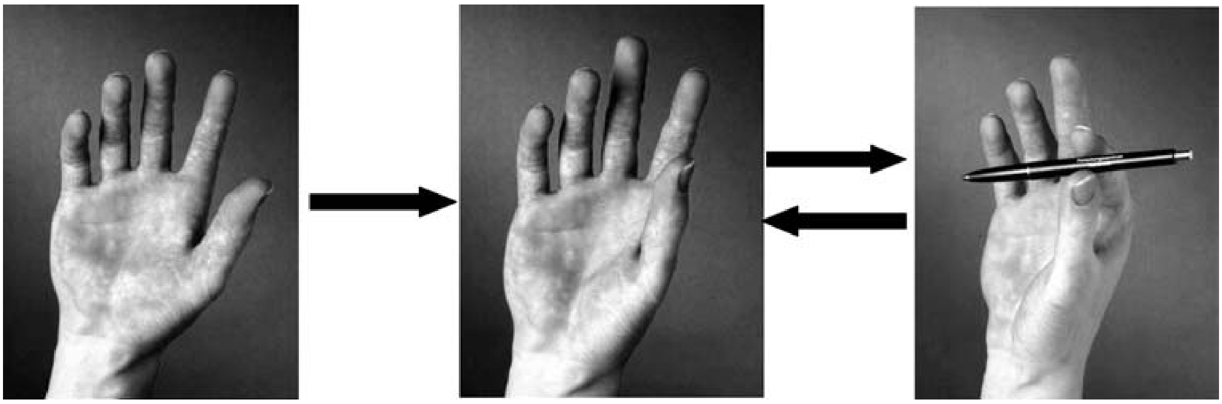

Fig. 8. A switch signal leads to a preshape state of the prosthesis, where a grasp type can be opened and closed proportionally.

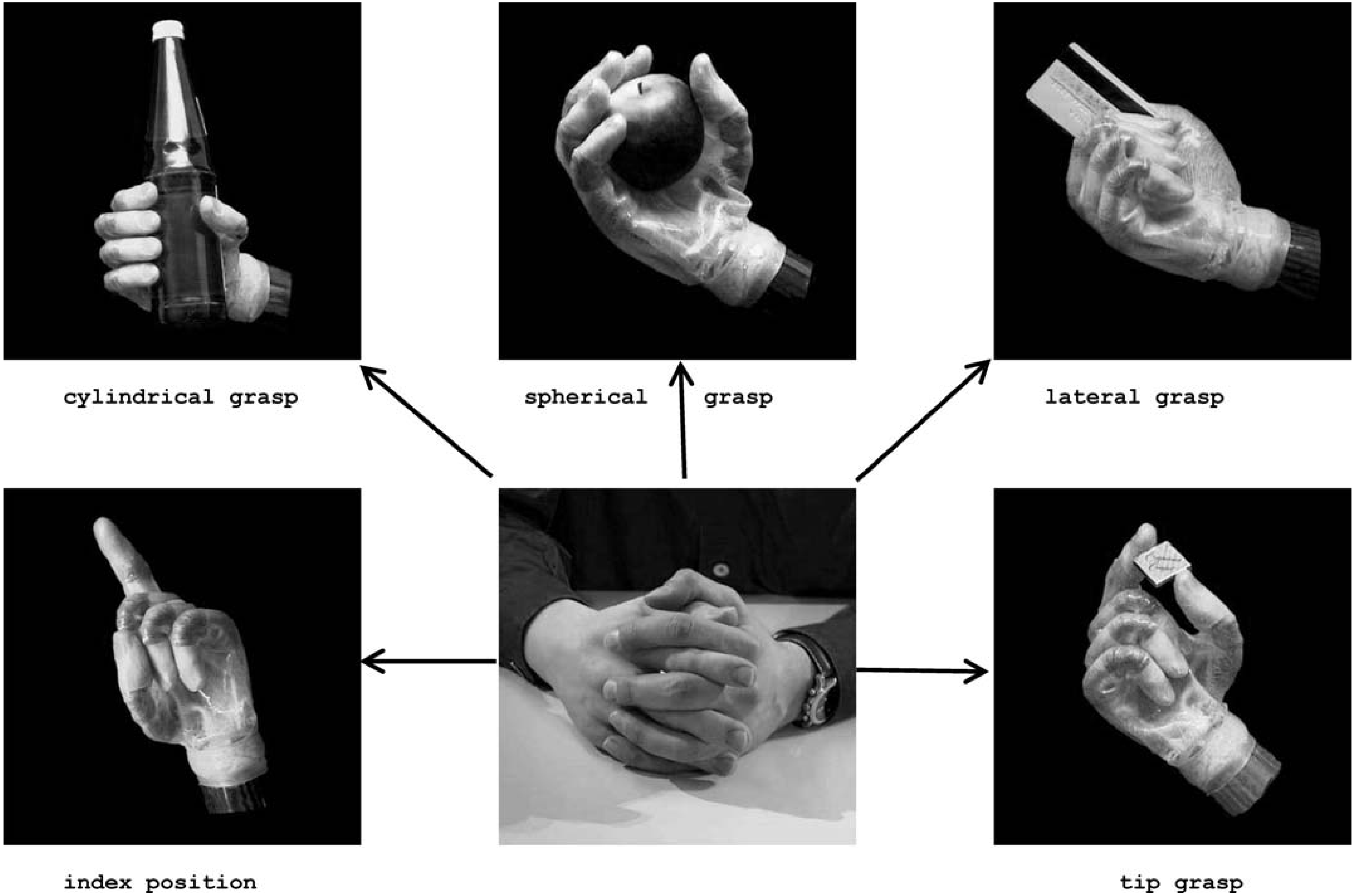

Fig. 9a–e. Different grasp types and the movement of a single finger are possible. The fingers of the prosthesis are flexible and can be folded.

Having interpreted the switch signal by a Bayesian classifier, the state machine moves forward into the pre-shape state (see Fig. 8), now knowing, which grasp type the user wants to perform.

A second signal (control signal) given by the operator serves to open or close the associated degrees of freedom for the selected grasp type. The type of contracted muscle (flexor/extensor) determines the movement direction, the amplitude determines the opening/closing speed. This state will remain, until a co-contraction is used to return into the neutral state (see Figs. 6 and 7). Many different grasp types can be executed by varying the given switch signal.

In comparison to a control concept proposed by Hudgins et al.[22] the user will recognize a short time delay when generating the switch signal and no delay when executing the opening and closing movements of the prosthesis.

However, users should be able to operate the prosthesis on a subconscious level after a short period of training. Therefore, a software platform for training and simulation of prosthetic devices has been developed.[21] Using this system, contraction patterns can be taught to the system as switch signals independent from differences among users (length of residual limb, condition of remained muscles, etc.).

In particular, the teaching algorithm divides the switch signal into 1–4 sections, depending on distinct local extrema (see Fig. 5, right). Features are calculated for each section, using low pass IIR-filters, which are implemented according to reference [23]. Based on similar algorithms, a filtered standard deviation is calculated.

Subsequently, a feature set is calculated for each section consisting of:

- values of the local extrema,
- time duration,
- area below the curve,
- amount of crossings between filtered and measured signal and
- the filtered standard deviation at the point of time of the local extrema.

Altogether, there are five features for each section, which results in a maximum of 20 features for one switch signal. Depending on the properties of the patient's signal a multivariate analysis of variances (MANOVA) selects the most significant features. They are used to build the Bayesian Classifier, which assigns the switch signal to a desired grasp type. Therefore, any kind of switch signal may be implemented, as long as the contraction patterns are reproducible and comfortable for the patient and the features are sufficient to discriminate switch signals from each other. Additionally, the platform serves to support the adaptation of necessary control parameters like filter parameters and thresholds semi-automatically and is used for simulation of the prosthetic device. Thus, necessary training time will be reduced and the wearer may use convenient contraction patterns to select grasp types. In this manner, each switch signal can be customized to the users comfort. Having found appropriate parameters, the whole algorithm is programmed into a C164CI microcontroller. As a result, the control concept is specially adapted to each user.

The first subject using this system was instantly able to operate the controller. After 10 minutes of training he achieved a classification accuracy of 92% in a series of 80 switch signals discriminating eight different grasp types.

The present prosthesis is able to execute commonly used grasp types like spherical grasp, cylindrical grasp, tip grasp, lateral grasp and the use of a single finger e.g. to operate a switch (see Fig. 9 a–e).

Future research is directed towards identifying phantom hand effects and therefore increase possibilities for subconscious control.

A practical solution to maintain a stable grasp seems to be hierarchical control as already used in the Southampton Adaptive Manipulation Scheme (SAMS).[6] In this scheme the details of the grasp selection control is left to a microcontroller. Therefore, customised position sensors and touch sensors are under development to provide the microcontroller with information about the fingers and about the shape and contact area of the object and the prosthesis.

CONCLUSIONS

A novel approach for a lightweight multifunctional prosthetic hand is presented. The hand is driven by 15 compact and low-mass flexible fluidic actuators integrated into the fingers of the hand. As in a natural hand different grasp types can be performed by a simple but effective control scheme. Because of the self adapting fingers many different objects can be grasped stably and the movements appear to be more natural than in a conventional prosthesis. We propose this hand as an alternative for users requiring an aesthetic skilful hand for lighter work, such as operating a computer keyboard. Clinical trials with a function assessment are currently underway and first results are very promising. The mechanical construction has also proved to be particularly suitable as a soft gripper in applications of automatic control and further development of a mobile service robot to help elderly and disabled people has commenced recently.[24] Future work will include further minimisation and weight reduction of the components to allow the integration in the metacarpus of the hand.

Acknowledgements

This research project was partially supported by the Deutsche Forschungsgemeinschaft (DFG), Cooperative Research Centre SFB 588, and by the limb fitting centre of the Heidelberg Orthopaedic University Hospital. The authors thank them for their help and support.

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