# A Human-like Robot Hand and Arm with Fluidic Muscles: Biologically Inspired Construction and Functionality

Ivo Boblan[1], Rudolf Bannasch[1,2], Hartmut Schwenk[1], Frank Prietzel[2], Lars Miertsch[2],Andreas Schulz[1]

[1] Technische Universität Berlin, FG Bionik und Evolutionstechnik, Ackerstr. 71-76, 13355 Berlin, Germany
{boblan, bannasch}@bionik.tu-berlin.de
http://www.bionik.tu-berlin.de
[2] EvoLogics, F&E Labor Bionik, Ackerstr. 71-76, 13355 Berlin, Germany

**Abstract.** Humanoid robots are fascinating from two points of view, firstly their construction and secondly because they lend life to inanimate objects. The combination of biology and robots leads to smoother and compliant movement which is more pleasant for us as people. Biologically inspired robots embody non-rigid movement which are made possible by special joints or actuators which give way and can both actively and passively adapt stiffness in different situations. The following paper deals with the construction of a compliant embodiment of a humanoid robot arm, including a five-finger hand with artificial fluidic muscles. The biologically inspired decentralized control architecture allows small units to be responsible for each main movement task. The first section gives a short introduction as to how bionics engineers think and tries to motivate us to build compliant machines. The second section looks at mechanical aspects, limitations and constraints and furthermore describes a human-like robot arm and hand. Section 3 presents the fluidic muscle actuator of the company FESTO[3]. The fourth section describes the decentralized control architecture and the electronic components. The last section concludes the paper while looking at further prospects.

## 1 Introduction

Nature has been creating sub-optimised individuals over a period of millions of years. Therefore, in a technical sense nature itself is a massive environment of optimisation. The question is, is it possible to understand and derive the methods underlying Darwinian evolution teaching and if so, can we generally manufacture products for specialized application which optimise the use of energy. Two directions are possible:

[3] This project was supported by Dr. Werner Fischer and Univ. Prof. Axel Thallemer, FESTO AG & Co. KG.

- To use the optimisation method of nature, the "Evolution Strategy" [1] and fulfilment of nature's evolution in vitro.
- To extract the underlying methods of optimised phenotypes directly from nature and use the underlying ideas to develop technical products.

The field of engineering science called "Bionics" is concerned with decoding 'inventions' made by living organisms and utilising them in innovative engineering techniques. Bionics is a made-up word that links biology and technology. However, nature does not simply supply blueprints which can merely be copied. Findings from functional biology have to be translated into materials and dimensions applicable in practical engineering.

In order to build humanoids we have to look at individuals in nature with the same proportions and environmental conditions and try not to scale the joints of a beetle, for example, which were not designed to carry heavy weights. Nature always develops optimally, based on the respective surroundings conditions. A parakeet in the jungle is subjected to different conditions than an eagle living in high mountainous regions. The law of survival of the fittest determines natural selection and consequently how the individual adapts to its living space. The parakeet, for example, is not optimised to cover long distances, but rather to be beautiful and to appeal the females.

At present there is no accepted theory or system to find bionic solutions, nor is there an accepted approach to systematically screen for systems. Bionic designs which currently exist owe their creation mostly to luck or scientific research over many years.

What can we learn from nature about morphology and physiology for the design of humanoid robots? If we concur with the law of survival of the fittest, then we believe that only optimised individuals can exist in nature in their respective surrounding conditions. Bionics initial task is to search for individuals in nature which have the same characteristics as the object to be developed. In our case, we are searching for a model of a humanoid robot arm and hand. We are thus looking for animals which are able to hold and/or carry several kilograms and which have human-like proportions with respect to weight and inherent compliance. When looking at the problem more closely, the intrinsic problem is how can we produce a multiple of force which are able to hold objects that are heavier than their own weight. This is a so-called power-weight ratio; this ratio is about one to one for electric motors. We have found other solutions for actuators in nature, particularly linear actuators that produce tractive force. The power-weight ratio of these actuators is multiplicatively higher than those known for technical actuators. Thus, it seems that nature has a better solution for our technical problem under the given terms and conditions.

We will not look at industrial robots here, as they carry out rigid tasks among themselves, or in contact with a technical environment. This field, called contact stability [2-5], has been widely investigated and has presented large problems for robotic manipulation tasks till date. Starting or dampening oscillation and performing a task requiring rigid contact from a free movement are related questions. The problem of contact stability arises, if one operates with rigid manipulators without spring-like or compliant properties.

We will instead focus on human-like robots and their interaction with humans and the environment. This contact or physical touching between robot and human is subject to special requirements as regards softness and compliance of motions. The goal of humanoids is not to assemble printed circuit boards that are also hard for humans, but also to master soft and energy-optimised movement in different situations of life.

If we look at the grasp movement of our own hand, we observe a transient effect and if necessary, feelings or vision-based adjustment of the hand. These special characteristics utilised when we touch demands new, innovative embodiment (morphology) and actuators (physiology).

The difference between a machine and a humanoid is its morphology. A human is living and can fulfil several different tasks which have special requirements in construction, freedom of movement and arrangement of weight. If we assume that the human body is an optimised structure, we have to study the load-bearing skeleton and the load transmission via the muscle-tendon system. Both criteria together form a unit which cannot be treated separately.

The study of the physiology of the muscle-tendon system [6-9] and its activation by the central nervous system gives us insight into the functions and activities of the human body. Current walking robots are heavy-weight, unproportional and unable to accomplish human-like performance. The motor actuators located in the joints increase the masses moved and accordingly the torque as well. The human muscle has a high power-weight ratio and transmits tractive power via a tendon across special parts of bones. There are located on the top or proximal to the centre of rotation. This leads to less torque and the ability to carry out fast movement with respect to energy need.

A current humanoid robot project in Germany is the development and construction of a two-arm robot called the "Zwei-Arm-Roboter" (ZAR3) in German. The third prototype has been constructed where a right arm with hand has been attached to a rigid spinal column.

The robot is 190 cm tall and the proportions are similar to humans of this size. Attention has been concentrated on its human size, anthropoid proportions and functionality of the actuators. The radius of action as well as the velocity of movement is anthropoid. The company FESTO has provided the linear actuators of the fluidic muscles. Tendons of Dynema filaments are used to convey the tractive force to the joints as regards tensile strength, lightweight and little bending radius.

The next section will describe the mechanical body with reference to skeleton, joints and tendons.

## 2 Mechanical Aspects

The whole body has been designed by AUTOCAD and the date translated to the special Computer Numerical Control (CNC) code and transferred to a 3 axes CNC milling machine. All parts, about 950 not including the purchased parts, have been manufactured from aluminium. Aluminium is lightweight, strong enough and easy to machine.

ZAR3 consist of a base which can roll, a rigid spinal column, an upper arm, a forearm and a five-finger hand (see figure 1).

**Fig. 1.** This shows a photograph of the current version 3 of the humanoid robot ZAR3

### 2.1 Base

The mobile base houses the control PC, the electronics, valves for the body actuators and the power supply for the whole robot.

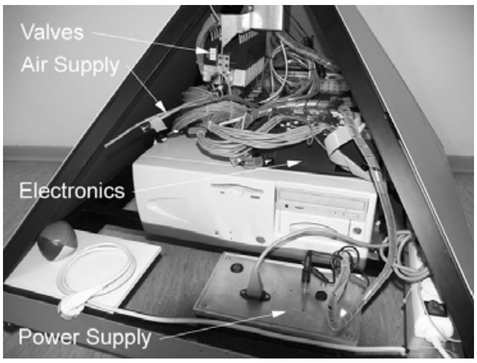


**Fig. 2.** The photograph above shows an inside view of the base which contains the power supply for 24 V and 5 V, the electronic devices for the shoulder and arm, the air tubes for supply and delivery directly connected to the valve cluster and the on-off valves for the shoulder and arm placed on a valve cluster.

The PC in the middle of figure 2 is a geriatric Pentium I with 400 MHz but fast enough to perform the following tasks immediately:

- Managing of the data bus activity and adhering to the time schedule
- Sending of defined goal angle and pressure data to each micro controller (intermediate steps are calculated locally)
- Monitoring of sensor data (angle, pressure) and error processing

A 15´´ TFT panel is located in the middle of the front cover and along with a keyboard and a mouse make up the interface to the operator.

A 5/3-port directional control valve is needed to drive each muscle. The same functionality is obtained with two 3/2-port valves, which are space saving and are assembled as a valve cluster. Fast relay valves of the company FESTO with a discharge of 100 l/min and a maximum switching time of 2 ms of the type MHE2 are used. Integrated electronics are provided with each valve are shown in figure 2 as a black add-on on the white valve, this facilitates a fast switching operation at increased current consumption. A terminal block with two valve packs on each side of the block is used to increase packing density. The inflating valves are located on the left side the deflating valves are on the right. Only the valves for the body muscles are located in the base, thus there are 16 valves for 8 body muscles.

The air supply is directly connected to the valve cluster (see figure 2) and is partitioned into two separate air tubes, one for the body and one for the hand. This becomes necessary as there are body muscles which can be driven with a higher pressure than the small finger muscles. The outgoing air is routed to a common tube and is actually not won back. We presently use two different air supply alternatives. Both alternatives are not really suitable for mobile use. Our in-house compressed air line with 6 bar is used for stationary operation whereas we utilise standard 10 litres 200 bar compressed air bottles encased in a smart aluminium case for 'mobile' use. Current small sized and noiseless air generators cannot produce the required amount of volume flow to fill up the bigger muscles.

To increase the reliability, the power supply is physically split into one for the electronic devices with 5 V and one for the valves with 24 V. We use the switching power supply (SPS) SPS 100PX with an output of 5 V / 10 A. The 24 V output of the SPS does not supply the required current start-up peak of the electronic driven valves. A disadvantage of SPS is the break-down of the voltage by overload a special power supply has been assembled for this task and facilitates the delivery of up to 20 A by 24 V.

The third version of the ZAR comprises a right hand and the associated arm and the shoulder. The hand and arm with shoulder constitute independent units and are steered separately. This basic concept of decentralization by many small 'intelligent' units is found in nature and also has advantages in technical realization. The decentralized control architecture and the associated electronic components are explained in more detailed in section four.

## 2.2 Torso and Shoulder

The torso of ZAR3 only consists of the muscle assembly of the shoulder joint.

The shoulder is the most flexible joint in the human body which it achieves at the expense of stability, less guidance of motion and less arranged limit stops as, for example, the hip joint. The human shoulder joint allows for the placing and rotating of the arm in many positions in front, above, to the side and behind the body. This flexibility also makes the shoulder susceptible to instability and injury. Figure 3 shows the complexity of human shoulder joint.

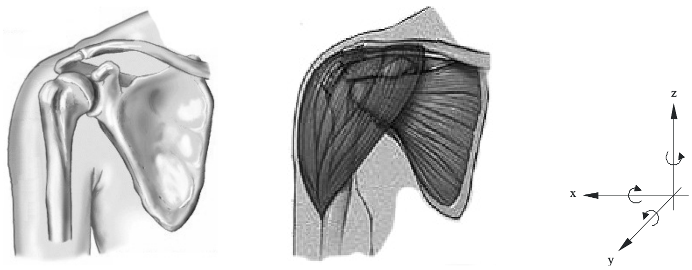


**Fig. 3.** This shows a human shoulder. *Left*: Skeleton only; *Middle*: Skeleton with muscles; *Right*: All movements of the shoulder joint may be understood as a combination of the motions of rotation and translation in the particular plain [10].

The human shoulder is a ball and socket joint. The ball is the head of the upper arm bone (humerus) and the socket is a part of the shoulder blade (scapula). The ball at the top end of the arm bone fits into the small socket (glenoid) of the shoulder blade to form the shoulder joint (glenohumeral joint). The socket of the glenoid is surrounded by a soft-tissue rim (labrum). A smooth, durable surface (articular cartilage) on the head of the arm bone, and a thin inner lining (synovium) of the joint facilitates the smooth motion of the shoulder joint.

A technical replica has proven to be a bold venture; this is because the construction involves a group of muscles (rotator cuff) which covers the shoulder joint (see figure 3 middle) which help keep the shoulder in the socket and enable the movement of the arm. A muscle area or the placing of muscles around the joint to imitate the human shoulder muscle-tendon system is awkward to construct and susceptible in operation.

A better way to build a complex shoulder joint is to split the multi-freedom joint into separate rotational joints each of which have one degree of freedom. These single joints are easier to construct, can be attached directly to the muscle-tendon system and are more rugged in use. Each of the three rotational joints spans a 2D vector space around an axis of the Cartesian coordinate system.

Electric motors are often used to drive the rotational joints. The motor is positioned directly on each axis which results in size increase and means that the design becomes larger than human scale. Another method would be to move the motors away from the joints and convey engine torque via driving belts. This approach is legitimate and appropriate for industrial robots which do not need to move away.

Our approach focuses on anthropoid aspects which comprise biological inspired sensors, actors, design and freedom of motion in consequence of lightweight construction and functional morphology. There are no 'natural' rotary machines in the animal world. Human construction utilises linear actuators in terms of muscles which are able to contract and are consequently then shortened in length.

For one surface of revolution, two muscles are necessary for an active conducted animation. The muscles of the x- and y-axis are arranged to revolve, rotated by the muscles of the z-axis. The actual application of the shoulder joint is shown in the photograph below (figure 4) where the different redirections are clarified in order to be able to complete a 3D radius of action.

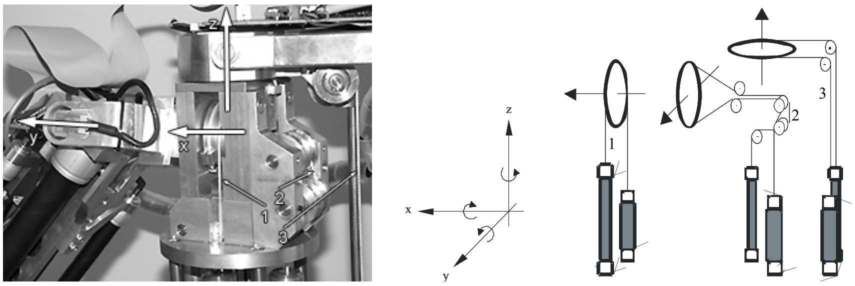


**Fig. 4.** *Left*: This is a photograph of the shoulder joint of ZAR3. The numbers 1,2 and 3 indicate the tendons of the x-, y- and z-axis of the joint. *Middle*: Shows the relation of the rotary directions to Cartesian space. *Right*: Clarification of the muscle-tendon systems and the redirections caused by the mechanical constraints and the acting pulley to drive the distal segments

The construction of the x-axis (see the diagram on the right-hand side of figure 4) of the shoulder joint allows to be able to directly calculate force and torque. The radius of action ranges from -30° when the arm is hanging down vertically (0°) and slightly backward to 150° when the arm is stretch up vertically (180°) and slightly forward. An extended radius would be desirable, but the actual angle measuring electronic can only provide for a radius of 180°. The diagrams show the compressed circle and the deflection pulley where the muscle tendon system drives the belonging distal limbs.

The y-axis, the tendons guidance system, is complex due to the arrangement of the muscles and tendons and a common origin of the coordinate system. The tendons of the y-axis are guided via several deflection pulleys and through the centre of the wheel of the x-axis. The freedom of motion ranging from 0° in the vertically hang down position up to 180° vertically stretching above.

The muscles of the z-axis rotate the whole revolver of the x- and y-axis muscles from 45° horizontally forward up to -45° backward, limited by mechanical limit stops to meet human restrictions.

The aim of the arrangement of the shoulder joint and the rotational revolver is to concentrate the mass of the actuators proximal to the centre of the torso. The smaller the distance between mass and centre of rotation, the smaller is the inertia. This is always a balance between displacement of mass and level of complexity. This type of construction of the shoulder joint only allows the muscle actuators for the elbow, wrist and hand to be placed on the arm. This results in smaller inertia, more speed of movement and less effort required to control the movement.

The muscle pair attached to a joint in a human body is always placed proximally. Therefore, the muscles only actuate the lower parts of the chain (distal segments) and can be powerless. The rule is the correct placing of the actuators so that they don't lift themselves. The other parts of the arm have to be consequent in dealing with this fundamental aspect.

### 2.3 Arm

The arm is divided into upper arm and forearm. The muscle pair for the elbow joint is placed on the upper arm. Up to the current version of humanoid ZAR, the valves for the rest of the arm (forearm and hand) have been placed on the outside of the upper arm. This design has both advantages and disadvantages. On the one hand, the distance between muscle and valve should be as short as possible to compensate for small speed loss by relay operations caused by the inertia of masses and compressibility of the air. Reducing of the air hose length also leads to a reduction of unused air in the system and the calculation effort which should primarily only depend on muscle volume. On the other hand, the unnecessary mass on the arm increases the centrifugal force and therefore the control effort.

Figure 5 (left) shows a photograph of the original adapted elbow joint, the diagram on the right outlines the extracted special moving directions.

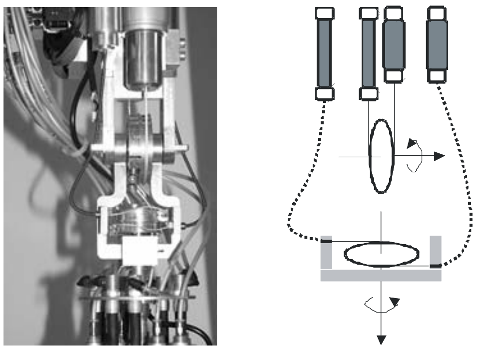

**Fig. 5.** *Left*: A photograph of the actual elbow joint is shown. *Right*: The redirection of the muscle-tendon systems and the displacement of the Bowden cables (dotted lines) are traced

Our first effort at producing an elbow joint tries to imitate the human elbow joint using a technical solution. This turned out be difficult as the versatile joint or the link between ulna and radius is too complex to be able to exactly copy. The analysis of the resulting degrees of freedom facilitated the assembly of the muscle-tendon-pulley-limb system shown in figure 5. The dotted lines in figure 5 (right) depict Bowden cables, which allowed the tendon to be guided without the use of pulleys. This brilliant invention from the bicycle world facilitates the configuration of the actuators in the best possible way and is dependent on mechanical contraction and human design.

The front muscle of the horizontal axis of the elbow joint is the biceps, the back muscle the triceps that move the forearm. The biceps-triceps system was constructed according to the human system. The elbow joint is technically a hinge and allows bending and straightening but does not rotate. The coordinate system is zero on this axis when the forearm hangs down. There are humans who can overstretch their elbow joint, but in order to take into account what is generally possible, the joint is mechanically fixed at the stretched position. That allows 180° up to where the upper arm and forearm contact and constitutes the mechanical limit.

The human twist behaviour of the ulna-radius system is a rotary motion of the wrist which can be simplified by a joint with pulley and vertical rotation axis. This is shown in figure 5. The range of movement is designed to be 45° in both directions.

Therefore, the forearm can be rigid and carry other equipment. In this version of ZAR, the forearm housed the finger-muscle-revolver. The term ‘revolver’ means the assembly of the 16 muscles around the forearm. If we consider the human model to be ideal, all the imaginable muscles of the hand are located on the forearm bones ulna and radius. This leads to a filigree assembly of the five-finger hand and reduces the amount of mass. The tractive forces of the flexors and extensors of the fingers are transferred by tendons which are embedded in connective tissue for guidance. Bowden cables are used to install the appropriate muscle-tendon systems to the finger joints (phalanx). Figure 6 shows the arrangement of Bowden cables connected to the five-finger hand.

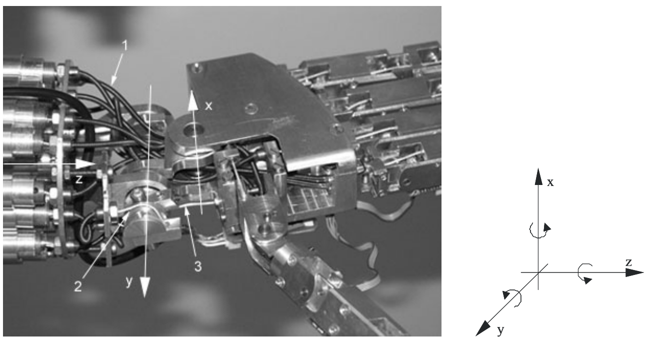


**Fig. 6.** *Left*: A photograph of ZAR’s wrist joint with axes 1 points to a Bowden cable which connects the muscle actuator (fixed end) with a finger root joint inside the palm. 2 points to the tendon which drives the hand lift joint and 3 to the tendon attached to the tilt joint of the wrist. *Right*: The depiction of the corresponding Cartesian coordinate system of the wrist

The challenge of this joint is to duplicate full functionality of the human wrist with a simultaneously simple and durable construction. All the Bowden cables have to be concentrated in the middle of the rotation axes. The mechanical resistance in the joint arise from the guidance of the Bowden cables to the sockets of the fingers. In particular, the tilt and lift muscle works against this rising mechanical resistance, see arrows numbers 2 and 3 in figure 6. For this reason, we have only been able to achieve a degree of movement of 20° in each direction. Two muscles (flexor, extensor, respectively) are used to tilt and lift the joint and are arranged as pairs of antagonists. In the technical sense one speaks of an ellipsoid joint which is a less flexible version of a ball-and-socket joint (shoulder).

### 2.3 Five-finger Hand

The first artificial hand developed and constructed based on the archetype of the human hand was the Waseda Hand (WH-1) in 1964. Since this there have been a multitude of artificial hands which are more or less anthropomorphic, anthropoid, human-like or humanoid. The academic question regarding humanoid hands, which are not actually humanoid in construction and function, will not be discussed here. The following small survey of artificial hand constructions is not exhaustive.

Many three and four finger hands with more-or-less humanoid proportions have been designed. The Utah/MIT dextrous hand [11, 12] has a four-finger system with 16 DOF and is powered by 32 pneumatic actuators. The actuator pack is placed remote from the robot hand and connected by antagonistic polymeric tendons. The Karlsruhe dextrous hand II [13, 14] can be considered to be a non-anthropomorphic approach. Tendons drive the four-finger autonomous gripper. Other artificial hands are the Stanford-JPL hand [15, 16], the Omni hand [17], the NTU hand [18], the DLR hand [19, 20] with a semi-anthropomorphic design, the cybernetic hand prosthesis by IST-FET [21] and the DIST hand by Genoa Robotics [22-24]. These hand projects do not fulfil the requirements for the number of fingers, joints in the fingers and human-like movements. However, the professional design, control architecture and functionality of a couple of them is convincing.

Several artificial anthropomorphic five-fingered hands have been designed with servomotors which are built into the fingers, for example, the “Gifu hand” I-III [25-27] has 20 joints with 16 DOF and is equipped with a six-axes force sensor at each fingertip. The Gifu hand is intended to be a prosthetic application for handicapped individuals. The “Robonaut” [28], designed by NASA’s Johnson Space Center and DARPA, is a dexterous five-fingered hand with 14 DOF and a human-scale arm. The forearm houses all fourteen brushless motors and all of the wiring for the hand. The prosthetic hand described in [29, 30] has 24 DOF and is controlled by EMG signals detected from the forearm of a human handicapped individual. A tendon driven adaptive joint mechanism adjusts velocity and torque functions by use of a spring type wire as an elastic guide. The “Blackfingers” hand prosthesis [31, 32] is a five-fingered hand with traditional pneumatic cylinders which function as linear actuators. The so-called bionic five-fingered hand by FZK (IAI) [33, 34] has 13 DOF and utilises flexible fluid actuators [35]. This fluid actuators approach is the attempt to design muscles similar to those of the human, but which do not have the human-like power-weight ratio. This ratio has been improved by the “Smart Award Hand” from SHADOW [36]. This artificial robotic five-fingered hand has 24 DOF and is complete driven by air muscles from the company SHADOW. The muscle pack of the hand is located on the forearm and use tendons to power transmission. This design and philosophy of a humanoid hand goes in the same direction as those of ZARx.

The hand is the most complicated component of the ZAR3. Not only the small limbs and joints of the fingers, but also the guidance of the tendons in human size proportions render the hand the most elaborated part of the project. The hand was assembled separately, tested on a vice and was finally attached to the arm.

The ZAR3 hand has 12 DOF without the wrist. Taking into account the diameter size of the smallest muscle from FESTO, we decided to only attach the flexor muscle to each finger limb and lay on the extensor as the pullback spring. This construction does not constrict the task of grasping, but only active releasing. However, this results in the forearm revolver being reduced in size and mass and, due to this, to a smaller inertia of masses and control effort. A disadvantage of this concurrence is the unnecessary additional expenses of providing tractive force via the small muscles to overcome the resilience of the springs. See section 3 as regards the dimensions of the muscles.

**Biological Motivation:**
The hand is the human beings’ door to the outside world. The loop of interaction with the environment is that the brain manipulates the information provided by the sense organs which then are executed by actuators to the extremities. The hand has to accomplish a variety of positions, operations and activities in the life of a human, to survive the rat race. The hand has been optimised to fulfil these manifolds task in the hundred million years of human life. The hand is able to sign, to grasp, to hold and carry, to interact with itself, to dig, to write, to play and a lot more. It is still however lightweight enough to run with a complete runner the 100 m in less than 10 sec. A full-grown human hand weighs approximately 500 g and has a far greater degree of freedom than 16.

Trials to copy the human hand have failed due to the concatenation of the many small bones of the palm. The combination of these bones enables the palm to form a cavity. The intention to build a human-like or biological inspired robot is to carry out the science of Bionics. This means to abstract the amount of degrees of freedom and to deviate from joint structures which are too complicated. The question has to be, what joint which is easy to construct can provide the greatest degree of functionality? Is it necessary for a robot hand to form a cavity? I do not think so. I think it is more important to be able to hold a glass and handle it. In addition, the ability of a finger to move in a circle around the root can be neglected.

All other joints of a human hand have been implemented to the greatest possible extent. Each of the four long fingers has three hinge joints. The outer first and middle joint of each finger is coupled because only very few humans can move these joints separately. Consequently, eight muscle actuators are required. All four long fingers are coupled at their roots by a spreading mechanism actuated by one muscle. The fingers fan each other at the same angle around the middle finger which constitute the fixed base. This artifice simplifies the matter and retains the relation. The different spreading of the fingers is also a challenge for humans. One can observe that the middle finger is fixed on one's own hand. The thumb has two hinge joints and a saddle joint at the root; therefore only three muscle actuators are required. Altogether, 12 muscle actuators fulfil full functionality of a real human hand. Figure 7 (below) shows the hand of ZAR3 in comparison to bones of a real hand.

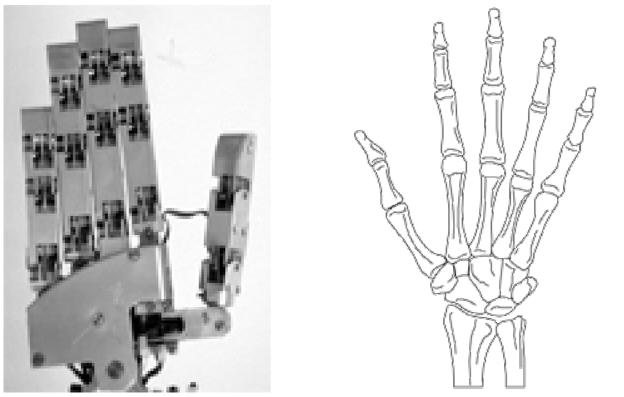

**Fig. 7.** *Left*: A photograph of the five-finger hand in home position. The dark spots between lighter surfaces are recesses to afford the bending of the phalanxes. *Right*: A view of the bones of a human hand is shown; the similarities are clearly visible

The size, weight, morphology and functionality are similar to the human hand and as well the radii of action. The artificial hand can grasp things and hold several poses.

## 3 Fluidic Muscle Actuator

The idea of an inflatable rubber tube to facilitate shortening is not new.

The McKibben muscle actuator [37] was developed in the 1950s and 1960s. The deflated rubber tube was not stiff enough to hold the shape itself, which means without an amount of air inside, the muscles kink off and have to firm up additionally.

The company SHADOW attempted another approach. This muscle actuator is also flexible, but is wrapped in a tough plastic weave to hold the cylindrical form. However, an exact deformation across the whole length and diameter and according to this a geometric measurement is not possible.

A large company called FESTO have constructed a fluidic muscle actuator over the last few years using the above-mentioned characteristics. This muscle sufficiently meets the requirements of dimensional stability, quantity of shortening and lightweight construction.

A muscle actuator works as a linear actuator and has advantages compared to a hydraulic cylinder and an electric motor with leverage. The hydraulic cylinder has significantly more weight, can start without jerking and has no disagreeable leakages. The electric motor can be placed directly at the joint without leverage which leads to an increase of mass and consequently, to greater control effort. A motor does not fit the necessary requirements for a humanoid or human-like robot. The task is to try to emulate or to pattern the functionality, physiology and morphology of the muscle-tendon-bone system of a human. This consequent approach can lead to a rather more human-like robot if we agree with the law of Darwinians survival of the fittest in natural evolution. To address the issue of why this is the case and why an electric motor does not meet these requirements will not be discussed here.

The company FESTO officially provides three different sizes of muscle actuators, namely MAS-40/20/10. A smaller version, MAS-5, is currently being prepared for realise. Only the MAS-5/10/20 is used in our robot ZAR3. The number 5 indicates the inside diameter in millimetres. All muscles have the same characteristic, that is the shortening contraction to the acting force dependent on the level of compressed air inside the muscle. This relationship is shown in the following (figure 8).

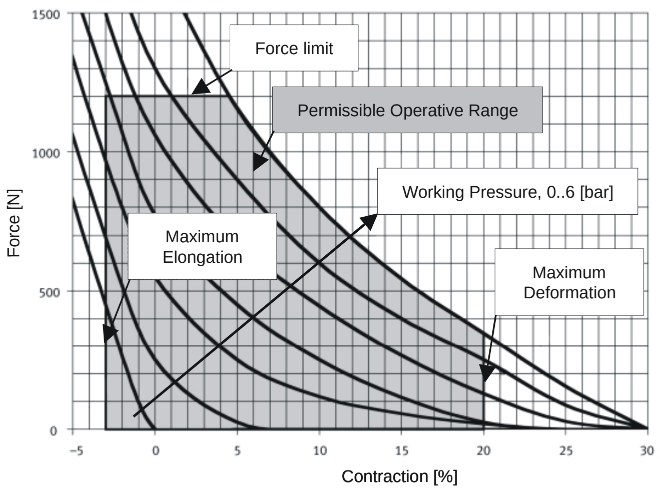


**Fig. 8.** This diagram shows the relationship of the possible produced tractive force in Newton to lift up something to the affordable contraction rate expressed in percentages of the basis length by a given working air pressure in bar of the fluidic muscle MAS-20

This non-linear interrelationship is commonly depicted as force $F$ in Newton over contraction $\Delta l$ in percent with supplied air $p_{\text{air}}$ in bars as constant parameter. The greater the affected force by a constant air pressure, the smaller the shortening referred to as base length $L_0$ of the muscle rubber tube. Moreover, the higher the air pressure by a constant force, the greater the shortening. These relationships can roughly be described as follows

$$F \propto \frac{p_{air}}{\Delta l / L_0} \quad . \tag{1}$$

The McKibben muscle has been extensively researched as regards static modelling and geometric calculations [38-40]. Static physical modelling can take over the characterization of the fluidic muscle from FESTO, however it uses the new measured data and some adapted details of the behaviour of the MAS. The dependence of the produced force of the muscle on geometric quantities such as volume, braid angle and diameter is common to models and is merely of theoretical value.

Although we have not undertaken this in our paper, in order for exact modelling the measured sets of force, air pressure and contractions concerning the time are required. In our opinion, the braid angle at a certain length of the muscle to predict the produced force in this position is not need. Based on the relationship of force, pressure and length determined by a proper invertible model, we have been able to make a model and then control the muscle actuator. Such an approach results in a nonlinear interrelationship which can be dealt with in several ways.

The most acceptable approximation is achieved by an engineering approach using a spring system [38]. The actuator can be considered as an elastic element of variable stiffness where the force is a function of the pressure and the length. Stiffness $k$=d$F$/d$L$ is proportional to the pressure and stiffness per unit pressure $k$~d$k$/d$P$=$k(p)$ which results in

$$l(F,p) = L_{\max} - \frac{F_{\max} - F}{k(p)} \quad . \tag{2}$$

The length $L_{\max}$ is the theoretically possible maximum length when $F$ at its maximum. Due to the decreasing of muscle stiffness when air pressure is increased, the maximum values of force and length have been used. This dependency is the inverse of the behaviour of a general spring. Stiffness directly depends on the air pressure. Stiffness in respect to force can be neglected in a first approximation. The emphasis in this approach is to concentrate on the modelling of the variable stiffness.

The maximum specified air pressure for the FESTO muscle is 9 bar for the MAS-10 and 7 bar for the MAS-20. The operating range expressed in terms of force is 400 N for the MAS-10 and 1200 N for the MAS-20. MAS-5, the smallest muscle, has not yet been specified. Detailed information can be found on the website of the company FESTO (www.festo.com).

The dimensioning of the muscle type, length and the deflection pulley are the most important tasks in order to fulfil the requirements as regards radius of action, velocity of movement and, in the end, the dimension of the possible weight to be lifted. Due to being scaled to human proportions, the type and the length of the muscle is limited. The relationship between muscle length and radius of the deflection pulley has been well defined and is calculated beforehand. The smaller the pulley, the smaller the length of the muscle can be, however the muscle must be the most powerful. If $C$ is the centre of rotation of the joint, $F_{FM}$ the produced force of the fluidic muscle, $G$ the weight of the actuated limb and $F_L$ the load force, then the equation of torque can be depicted as follows:

$$\sum M_C = 0 = F_{FM} \cdot l_{FM} - G \cdot l_G - F_L \cdot l_L \ . \qquad (3)$$

The values of $G$, $l_G$ and $l_L$ are fixed and cannot be changed by human proportions and known mass of aluminium and equipment. The estimate of $F_L$ depends directly on the carrying power of the humanoid and has to be completed before designing the robot whole. The other two variables have to determine iteratively.

**Shoulder:**

The more powerful MAS-20, 400 mm in length, has been assembled for use as the shoulder joint. A length of 250 mm is sufficient for the smaller range of the z-axis. When considering the required space and that a second arm will be added in the future, the MAS-20 seems to be the best choice as regards diameter size, particularly when all muscles are inflated.

The question is now how long should the muscle be and what should the diameter of the pulley be. A reasonable trade-off is that all the joints of the shoulder should have a diameter of 50 mm. This allows the muscles to have a short length of 400 mm but ensures that they have enough power to lift the payload in the critical weight range. The lifter muscle (flexor) of the x- and y-axis in particular has limitations as regard load. The extensor muscle guides the descent of the arm with the help of gravity. The extensor muscle's major task is to control stiffness and compliance of motion. The more this muscle pulls against the flexor, the stiffer the motion. This procedure puts the fringe range of the produced amount of force of the flexor into perspective. The most advantageous thing is that the critical area of muscle shortening has not been attained even when the arm has been extended forward to a 90° angle, that is where the extensor muscle has to generate maximum power. The muscle contraction only reaches the critical level once the arm has reached an angle of around 120°. The muscles of the z-axis of the shoulder can be designed to be smaller as the torso itself holds the mass of the arm and only the horizontal motion has to be executed.

**Elbow:**

The elbow joint can be calculated similar to the y-axis of the shoulder. As the one of the ZAR3's tasks is to be able to lift a glass of beer, the elbow joint is also assembled using the MAS-20. The shoulder hangs and only the biceps lift up the payload, including the revolving forearm and hand. The maximum angle for lifting is controlled to 135° to allow an ulna-radius action which doesn't become mechanically stuck. The diameter of the pulley is set to 50 mm and the muscle length to 220 mm. The smaller radius of action allows a shorter muscle length to achieve this human motion. A pair of muscles called 'agonist' and 'antagonist' drives the motion of rotation of the ulna-radius system. This joint works as well as the elbow joint, the difference being in the axis of rotation. The assembly is described above in section two.

The dimensioning of the muscle type, length and diameter of the pulley follows the same principles as above. The rotation process does not have to lift or hold a mass, but is responsible for adjusting the hand's posture and to act with the payload. Due to the number of air pipes which guide via this joint, the diameter of the pulley has to be limited to 30 mm in order to achieve human-like proportions. Consequently, the shorter muscle length of 200 mm and the power of a MAS-10 seem to be sufficient for this task, also as regards the redirection of force using a Bowden cable (see figure 5).

**Wrist and Hand:**
The MAS-5 muscle is the only way a hand as sufficiently compact to be of human scale can be achieved. The extent of the 16 fully inflated muscles and mechanical fixings is minimally thicker in diameter to that of a full-grown male. The length of the muscles varies in two steps, from 80 mm to 110 mm. The four muscles in agonist-antagonist construction of hand up/down and hand tilt left/right are longer to afford more force enabled by a larger level arm and by the use of larger 16 mm pulleys.

According to the developmental department of FESTO, the MAS-5 can pull up to 50 N. This specification has established by a vertical experiment in ideal conditions without deflection pulleys. In real-life applications, only a fraction of this tractive force of a MAS-x can be achieved and can be calculated in terms of equation (3).

## 4 Electronics and Control Architecture

The electronic components, the communication to the controlled PC together with the architecture to manage and control tasks which is what defines when a machine is a robot and is the counterpart to the human brain and the central nervous system. Engineers till date have not been able to reproduce this data flow and communication network in vitro. The task will be to assemble, place and manage electronic parts in the same way as to achieve results similar to that of the human. Many small activities and reactions are not controlled by the brain, but rather initiated by the spinal cord or local reflexes. The advantage of this is faster reaction time; specialized distributed units can be used as a paradigm to design decentralized control architecture. This approach applied to a technical system is tolerant of failure, enables short distances in the sensor-control-actuator loop and provides for command structure and control hierarchy.

The robot ZAR3 is divided into two units, completely separately assembled and controlled, one for the five-finger hand and one for the arm and shoulder. Both units have identical circuit devices and functional range. Each functional unit consists of two communication directions and can be addressed both separately and independent of each other. The differences lie in the amount of driven outputs, the physical subdivision of input-output channels and the user-defined software of the controller. A diagram of the structural components and communication channels are shown below (figure 9).

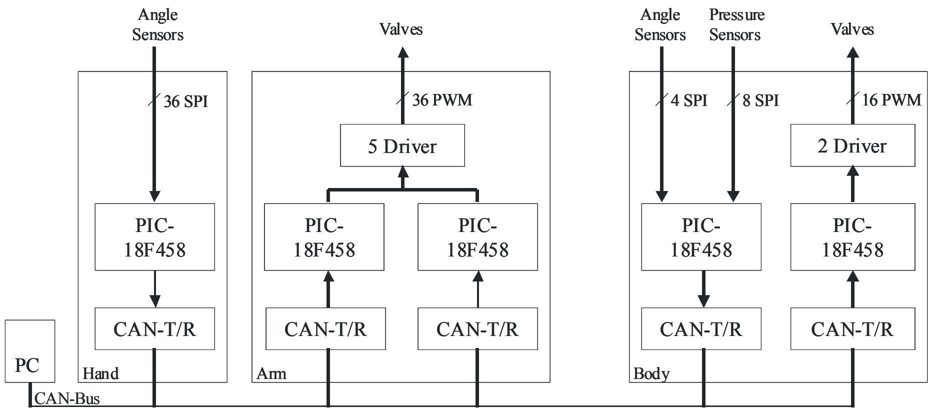


**Fig. 9.** The above shows a schematic plan of the connections of the hand (left) and shoulder-arm (right) electronic devices. The hand consists of two boards, one for sensor inputs and one for valve outputs, which communicate via CAN. The shoulder-arm electronic, in brief 'body', is configured as one printed board and located in the robot's base

The body electronics for reading sensors and driving the valve-muscle actuators are located in the base and is arranged on one printed circuit board.

The hand electronics are separated into a sensor input board and an actuator output board to drive the muscle valves. The hand electronics, located on the upper side of the palm, process the data signals from each measured finger joint. The associated output board is placed near to the upper arm valve block on the shoulder.

The angle sensor uses a magnet, placed on the distal part of the joint, which rotates closely below a sensitive array. This array is implemented as integrated circuit to detects the changing magnetic field and works as a magneto-resistive sensor. This non-linear relation compensates for temperature and is linearized at the sensor spot. The communication protocol Serial Peripheral Interface (SPI) from each angle transmitter is used to transmit the digitalized angle sensor data directly to the PIC micro controller 18F458 from the company MICROSHIP. The SPI interface is used as it requires less effort to wire, has a high data rate and as it provides the possibility of connecting to the controller. The three-wire-bus consist of two data and one clock signal and works in the master-slave-mode.

The two PIC 18F458 controllers, each concerned with one signal path, communicate via the Controller Area Network (CAN) bus and shares the effort of data processing, executing of control loop and generating of Pulse Width Modulation (PWM) signals. The CAN transceiver/receiver allocates the signal level to the physical bus. Driver devices, each of which have eight outputs, realize the 24 V output level for the electronic driven valves and must provide up to 1 A inrush current per valve. To drive each valve, electronics are needed on the one hand to supply current demand and, on the other hand, to enable the height switching time of the PWM output.

The strict separation of different components and data directions enables speedier troubleshooting and is a first step towards of decentralization. The distribution of responsibilities and the break down of information handling reduced data activities on the bus and the complexity of the units. The fast response time of an unit in a control loop in case of emergency cannot be affected by a fewer crucial task of monitoring or finger play. The remote unit receives a command from the control PC or from another unit via CAN-bus and decides about which operations to be done. Without any errors, the unit will initiate the appropriated control loop to reach the demanded goal angle. This stand-alone execution can be interrupted by the control PC or by an exceeded sensor limit value. The CAN-bus only serves as asynchronous communication channel of control and information messages not for the synchronous control loop between sensor, controller and actuator. The transmission of the entire control loop data via CAN-bus leads to an exceeding of the data rate specification of CAN of 1 Mbit/sec at the latest by triggering of the second arm. However, there is a possibility to use the CAN-bus which is carried out between the palm and shoulder board for the hand control loop. The next generation of ZAR will prevent this issue.

## 5 Conclusion and Future Prospects

It is far more difficult to design a practicable human-like robot than it would at first seem to be. Being constrained to human-like proportions increases the manufacturing effort which is compounded by being able to find practicable analogies and solutions for geometrical and functional interrelationships in human morphology and physiology. This has to lead to a completely new process of thought. The science of Bionics aims at analysing the methods behind the processes and to translate them into a practicable technical solution; this helps to construct machines which are similar to the model in nature, particular as regards excellence in shape and function.

This manuscript introduces the humanoid robot ZAR3, the mechanical design and development process is explained and constraints and limitations pointed out. A practicable artificial fluidic muscle is briefly proposed and the fundamental correlation of length, force and pressure introduced.

Evident constraints such as the valve block on the upper or the too faint biceps muscle have arisen already during the construction and test phase. These features will be modified in the next version, the ZAR4. In addition, the mechanical effort in producing the many small parts will be decreased as well as increased simplification of the joints will be promoted. Once the second arm is completed, attention will have to be turned to the control architecture, to converge the conventional information processing in the human nervous system and neuronal processing. The participation of more units or subunits increases traffic on the signal bus and the increase in detail could be the next assignment to meet the requirements for fault tolerance, reliability and prioritisation of the data.

## 6 Acknowledgement

The company FESTO AG & Co. KG which supports the work on the various versions of the robot ZAR.

## References


1. Rechenberg, I., *Evolutionsstrategie '94*. 1994: fromman-holzboog. 434.
2. Šurdiloviæ, D.T., *Synthesis of Robust Compliance Control Algorithms for Industrial Robots and Advanced Interaction Systems*, in *Mechanical Engineering Faculty*. 2002, University in Niš. p. 475.
3. Okada, M., Y. MNakamura, and S. Ban. *Design of Programmable Passive Compliance Shoulder Mechanism*. in *Proceedings of the 2001 IEEE International Conference on Robotics & Automation*. 2001. Seoul, Korea.
4. Ahmadi, M. and M. Buehler, *Stable Control of a Simulated One-Legged Running Robot with Hip and Leg Compliance*. 1996, Department of Mechanical Engineering, Centre For Intelligent Machines, McGill University: Montral, QC, Canada. p. 9.
5. Rocco, P., G. Ferretti, and G. Magnani, *Implicite Force Control for Industrial Robots in Contact with Stiff Surfaces.* Automatica, 1997. **33**(No.11): p. 2041-2047.
6. Fenn, W.O. and B.S. Marsh, *Muscular force at different speeds of shortening.* Journal of physiology, 1935. **85**(3): p. 277-298.
7. Gordon, A.M., A.F. Huxley, and F.J. Julian, *The variation in isometric tension with sarcomere length in vertebrate muscle fibres.* Journal of Physiology, 1966. **184**: p. 170-192.
8. Carlson, F.D. and D.R. Wilkie, *Muscle Physiology*. 1974: Prentice-Hall, Inc.
9. Huxley, A.F., *Muscular Contraction.* Journal of Physiology (London), 1974. **243**: p. 1-43.
10. Gohlke, F., *Biomechanik der Schulter.* Orthopäde, Springer-Verlag 2000, 2000. **29**: p. 834-844.
11. Jacobsen, S.C. and e. al., *The Utah/MIT dexterous hand:Work in progress.* Int. J. Robot. Res., 1984. **3**(4): p. 21-50.
12. Jacobsen, S.C., et al., *Design of the Utah/MIT Dextrous Hand.* Proceedings IEEE Int. Conf. on Robotics and Automation, USA, 1986: p. 1520-1532.
13. Fischer, T. and H. Woern, *Structure of a robot system: Karlsruhe dextrous hand II.* Proc. of Mediterranean Conf. on Control and Systems, 1998.
14. Osswald, D. and H. Wörn, *Mechanical System and Control System of a Dexterous Robot Hand.* Proceedings of the IEEE-RAS International Conference on Humanoid Robots, 2001: p. 8.
15. Salisbury, J.K., *Articulated Hands: Force Control and Kinematics Issues*, in *Stanford University*. 1982: Stanford.
16. Salisbury, J.K., *Design and Control of an Articulated Hand.* Int. Symposium on Design and Synthesis, Tokio, 1984.
17. Rosheim, M., *Robot Evolution.* New York: Wiley, 1994: p. 216-224.
18. Lin, L.R. and H.P. Huang, *"Integrating fuzzy control of the dexterous National Taiwan University (NTU) hand.* IEEE/ASME Trans. Mechatron, 1996. **1**: p. 216-229.
19. Butterfass, J., et al., *DLR's Multisensory Articulated Hand Part I: Hard- and Software Architecture.* IEEE International Conference on Robotics and Automation, 1998: p. 2081-2086.
20. Butterfass, J., et al., *DLR-Hand II: Next Generation of Dextrous Robot Hand.* Proc. IEEE Conf. on Robotics and Automation, Seoul, Korea, 2001: p. 109-114.
21. Dario, P., et al., *On the development of a cybernetic hand prosthesis.*
22. Bernieri, S., et al., *The DIST-Hand Robot.* IROS '97 Conf. Video Proceedings, Grenoble, France, 1997.
23. Caffaz, A. and G. Cannata, *The Design and Development of the DIST-Hand Dextrous Gripper.* Proc. IEEE Int. Conf. on Robotics and Automation, Leuven, Belgium, 1998: p. 2075-2080.
24. Caffaz, A., et al., *The DIST-Hand, an Anthropomorphic, Fully Sensorized Dexterous Gripper.* IEEE Humanoids 2000 Boston, MIT, USA, 2000.

25. Kawasaki, H. and T. Komatsu, *Mechanism design of anthropomorphic robot hand: Gifu hand I.* J. Robot. Mechatron., 1999. **11**(4): p. 269-273.
26. Kawasaki, H., T. Komatsu, and K. Uchiyama, *Dexterous Anthropomorphic Robot Hand With Distributed Tactile Sensor: Gifu Hand II.* IEEE/ASME TRANSACTIONS ON MECHATRONICS, 2002. **7**(3): p. 296-303.
27. Mouri, T., et al., *Anthropomorphic Robot Hand: Gifu Hand III.* ICCA, Muju Resort, Jeonbuk, Korea, 2002: p. 6.
28. Lovchik, C.S. and M.A. Diftler, *The robonaut hand: A dextrous robot hand for space.* Proc. IEEE Conf. on Robotics and Automation, 1999: p. 907-912.
29. Hirose, S. and S. Ma, *Coupled tendon-driven multijoint manipulator.* Proceedings of IEEE International Conference on Robotics & Automation, 1991: p. 1268-1275.
30. Ishikawa, Y., et al., *Development of Robot Hands with an Adjustable Power Transmitting Mechanism.* Intelligent Engineering Systems Through Neural Networks, ASME Press, 2000. **10**: p. 631-636.
31. Folgheraiter, M., et al., *Blackfingers a Sophisticated Hand Prothesis*. p. 4.
32. Folgheraiter, M. and G. Gini, *Blackfingers an artificial hand that copies human hand in structure, size, and function.* Proc. IEEE Humanoids 2000, MIT, 2000: p. 4.
33. Schulz, S., C. Pylatiuk, and G. Bretthauer, *A new ultralight anthropomorphic hand.* Proceedings of the 2001 IEEE International Conference on Robotics & Automation Seoul, Korea, 2001: p. 2437-2441.
34. Pylatiuk, C. and S. Schulz, *Neuentwicklung einer Prothesenhand.* Prothetik, 2002. **8**: p. 4.
35. Pylatiuk, C. and S. Schulz, *Entwicklung flexibler Fluidaktoren und ihre Anwendung in der Medizintechnik.* Med. Orth. Tech., 2000. **120**: p. 186-189.
36. *Design of a Dextrous Hand for advanced CLAWAR applications*. 2003, Shadow Robot Company: 251 Liverpool Road London ENGLAND.
37. Schulte, H.F.J., *The characteristics of the McKibben artificial muscle.* The application of external power in prosthetics and orthotics, National Academy of Science-National Research Council, Washington D.C., 1961.
38. Chou, C.-P. and B. Hannaford, *Static and Dynamic Characteristics of McKibben Pneumatic Artificial Muscles*, in *IEEE*. 1994, Department of Electrical Engineering, FT-10, University of Washington: Seattle, Washington 98195. p. 281-286.
39. Colbrunn, R.W., *Master of Science*, in *Department of Mechanical and Aerospace Engineering*. 2000, Case Western Reserve University. p. 141.
40. Tsagarakis, N. and D.G. Caldwell, *Improved Modelling and Assessment of pneumatic Muscle Actuator.* Proceedings of the 2000 IEEE International Conference on Robotics & Automation, San Francisco, CA, 2000: p. 3641-3646.