A human-like robot torso with fluidic muscles: Biologically inspired engineering

Ivo Boblan[1], Rudolf Bannasch[2], Andreas Schulz[2], Hartmut Schwenk[1]

[1] Technische Universität Berlin, FG Bionik und Evolutionstechnik,
[2] EvoLogics GmbH, F&E Labor Bionik,
Ackerstr. 76, 13355 Berlin, Germany,
boblan@bionik.tu-berlin.de, www.zar-x.de

Abstract. Human-like robots are fascinating from their morphology and physiology. The combination of biology and robots leads to smoother and compliant movement which is in contact more pleasant for us as people. Biologically inspired robots embody non-rigid movement which are made possible by special joints and actuators which give way and can both actively and passively adapt stiffness in different situations. The following paper deals briefly with the construction of a compliant embodiment of a humanoid robot torso, including two arms and two five-finger hands actuated with artificial fluidic muscles from FESTO[3]. The first section motivates the building of compliant machines. The second section looks at mechanical aspects of the robot shoulder joint and section 3 presents an artificial muscle actuator. The last section concludes this short essay.

1 Introduction

In order to build a biologically inspired robot we have to look at individuals in nature with the same proportions and environmental conditions. Nature always evolves optimal individuals based on the respective surroundings conditions.

What can we learn from nature about morphology and physiology for the design of natural motivated 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 with two arms and hands. 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. In animals we find actuators which produce tractive force. The power-weight ratio of these actuators is multiplicatively higher than those known for technical ac-

[3] This project was supported by Markus Fischer, TC-D FESTO AG & Co. KG.

tuators. 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 [1-4], has been widely investigated and has presented large problems for robotic manipulation tasks till date.

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.

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 [5-8] 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.

ZAR5, in German *Zwei-Arm-Roboter* in the actual fifth version, is a joint project of the Technische Universität Berlin department Bionik und Evolutionstechnik, the company EvoLogics and the company Festo. The aim of this project using the fluidic muscle of Festo is to show the current possibilities of biologically inspired construction in embodiment, muscle-tendon system, control architecture, radius of action, and weight saving. ZAR5 is a human-like torso with two arms and two five-finger hands which are strictly developed according to bionical considerations. The robot is 190 cm tall and the proportions are similar to humans of this size [9]. 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 [10]. Tendons of Dynema filaments are used to convey the tractive force to the joints as regards tensile strength, lightweight and little bending radius.

2 Shoulder joint and its technical realization

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 1 shows the complexity of human shoulder joint.

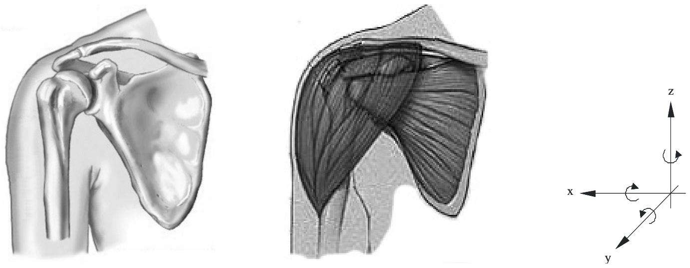

Fig. 1. This shows a human shoulder. *Left*: Skeleton only; *Middle*: Skeleton with muscles; *Right*: All movements of the shoulder joint may be understood as a combination of the motions of rotation and translation in the particular plain [11].

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 1 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.

Our technical approach focuses on anthropoid aspects which comprise biological inspired sensors, actors, design and freedom of motion in consequence of lightweight construction and functional morphology. 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 2) where the different redirections are clarified in order to be able to complete a 3D radius of action.

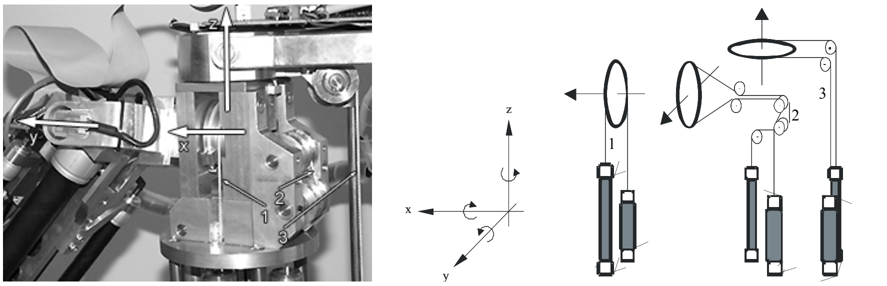

Fig. 2. *Left*: This is a photograph of the shoulder joint of ZAR5. The numbers 1,2 and 3 indicate the tendons of the x-, y- and z-axis of the joint. *Middle*: Shows the relation of the rotary directions to Cartesian space. *Right*: Clarification of the muscle-tendon systems and the redirections caused by the mechanical constraints and the acting pulley to drive the distal segments

The 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 which increases the speed of movement and the quality of control. This is always a balance between displacement of mass and level of complexity.

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.

3 Fluidic muscle actuator and its dimensioning

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

The McKibben muscle actuator [12] 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 technical muscle has significantly less weight, can start without jerking, has no disagreeable leakages and can be placed away of the joint connected by a technical tendon. The task is to try to emulate or to pattern the functionality, physiology and morphology of the muscle-tendon-bone system of a man. This consequent approach leads to a rather more human-like robot.

The company FESTO officially provides three different sizes of muscle actuators, namely DMSP-10/20/40 [10]. A smaller version, DMSP-5, is currently being prepared for realise. Only the DMSP-5/10/20 is used in our humanoid. The number 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 3).

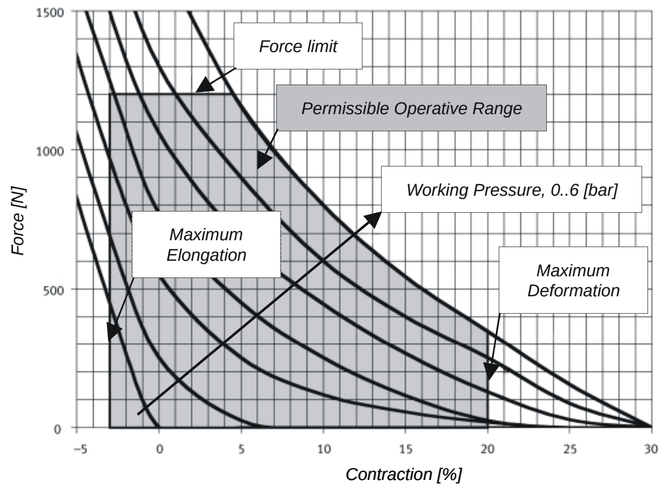

Fig. 3. This diagram shows the relationship of the possible produced tractive force in Newton to lift up something to the affordable contraction rate expressed in percentages of the basis length by a given working air pressure in bar of the fluidic muscle DMSP-20

This non-linear interrelationship is commonly depicted as force F in Newton over contraction Δl in percent with supplied air p_{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

$$F \propto \frac{p_{air}}{\Delta l / L_0} \ . \qquad (1)$$

The McKibben muscle has been extensively researched as regards static modelling and geometric calculations [13-15]. 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 DMSP. 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. 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 [16].

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:

$$\sum M_C = 0 = F_{FM} \cdot l_{FM} - G \cdot l_G - F_L \cdot l_L \ . \quad (2)$$

The values of G, l_G and l_L are fixed and cannot be changed by human proportions. 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.

A more deeper look in the modelling and control of the FESTO muscle actuator can be found in [16].

4 Conclusion

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 gives a short insight in the humanoid robot project ZAR. The mechanical design and functionality of a technical shoulder joint is pointed out and a practicable artificial muscle is proposed.

5 Acknowledgement

The company FESTO AG & Co. KG supports the work of the humanoid robot ZAR.

References

1. 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.
2. Okada, M., Y. Nakamura, and S. Ban. *Design of Programmable Passive Compliance Shoulder Mechanism*. in *Proceedings of the 2001 IEEE International Conference on Robotics & Automation*. 2001. Seoul, Korea.
3. 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.
4. Rocco, P., G. Ferretti, and G. Magnani, *Implicit Force Control for Industrial Robots in Contact with Stiff Surfaces.* Automatica, 1997. **33**(No.11): p. 2041-2047.
5. Fenn, W.O. and B.S. Marsh, *Muscular force at different speeds of shortening.* Journal of physiology, 1935. **85**(3): p. 277-298.
6. 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.
7. Carlson, F.D. and D.R. Wilkie, *Muscle Physiology*. 1974: Prentice-Hall, Inc.
8. Huxley, A.F., *Muscular Contraction.* Journal of Physiology (London), 1974. **243**: p. 1-43.
9. Boblan, I., et al., *A Human-like Robot Hand and Arm with Fluidic Muscles: Biologically Inspired Construction and Functionality*, in *Embodied Artificial Intelligence*, F. Iida, et al., Editors. 2004, Springer-Verlag: Berlin Heidelberg. p. 160-179.
10. FESTO, *Fluidic Muscle DMSP/MAS, https://xdki.festo.com/xdki/data/doc_de/PDF/DE/MAS_DE.PDF*. 2005, FESTO AG & Co. KG.
11. Gohlke, F., *Biomechanik der Schulter.* Orthopäde, Springer-Verlag 2000, 2000. **29**: p. 834-844.
12. 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.
13. 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.
14. Colbrunn, R.W., *Design and Control of a Robotic Leg with Braided Pneumatic Actuators*, in *Department of Mechanical and Aerospace Engineering*. 2000, Case Western Reserve University. p. 141.
15. 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.
16. Boblan, I., et al. *A Human-like Robot Hand and Arm with Fluidic Muscles: Modelling of a Muscle Driven Joint with an Antagonistic Setup*. in *3rd Int. Symposium on Adaptive Motion in Animals and Machines*. 2005. Technische Universität Ilmenau, Germany.