Soft Robotics: Self-walking, self-learning bipedal robot

Lukasz Grzesiak
Department of robotics and intelligent systems.
University of Oslo
Oslo, Norway
lukaszmg@ifi.uio.no

***Abstract*—The goal of the paper is to familiarize the reader with the concept of McKibben [12] muscles, their static and dynamic properties models as well as the challenges accompanying use of said actuators in the field of soft-robotics. Paper presents and briefly discusses the two major trends in use of McKibben muscles in construction and control of bipedal walker robots. Additionally the text introduces 4 distinctive successful prototypes of walking robots serving as the design templates for future Master's Thesis in robotics.Lastly the paper gives some directions as to how to interpret available data regarding the McKibben muscles and points out possible directions in which further research can be done.**

I. INTRODUCTION

The so-called McKibben muscle or "McKibben Pneumatic Actuator" [MPA] is a soft pneumatic actuator utilizing the elastic properties of rubber. The MPA has been initially developed as part of the artificial limb research in the 1950s and 1960s [12], being used as an artificial muscle to actuate orthotic devices for the handicapped. The MPAs are regarded as safe actuators even while failing, due to their power source being primarily the air pressure, although newer research explores the viability of operating McKibben muscles as hydraulic actuators [9] and as the hybrid of the two modes of operation [5]. Due to the high safety factor associated with the use of McKibben muscles, the soft actuators have been widely used for human rehabilitation and development of power-assistance exoskeleton suits [17].

Due to their dynamics being comparably close to those of actual biological muscles, MPAs have been used in number of researches focused on humanoid robots [16], [14]. The results of these studies affirm the viability of use of MPAs as the method of actuation for self-walking robots. The prototype robots achieved stable dynamic motions such as walking and jumping, utilizing simple control schemes and significantly simplified models of the actuators dynamics. This approach of severe simplification of both the dynamics and control for the robots, can be seen as one of the two main research trends within soft-robotics. The second being, research into developing very detailed and sophisticated dynamics models for the MPAs, in order to alleviate challenges caused by great number of nonlinear effects present while actuating of MPAs. These two opposite approaches constitute the basis for this paper, as we take a look at the examples of developing robots based on both notions, compare them and discuss possible benefits of combining the two approaches.

Fig. 1. McKibben actuator adapted from [18]

II. MCKIBBEN PNEUMATIC ACTUATOR

MPA is a relatively easy to construct actuator, consisting of: inner elastic rubber cylinder, serving as inflatable bladder and an outer braided mesh of nylon fibers. An example of a McKibben muscle is shown in Figure 1. The actuator is sealed off at one end, then a pneumatic valve matching the inner diameter of the cylinder being inserted in the opposite end, for the purpose of inflation and deflation. The compressed air expands the bladder, resulting in the volume of the muscle increasing. As the muscle expands outwards, it shortens in the direction perpendicular to the expansion.

This behaviour as previously discussed is very similar to that of human muscles, and is the main reason for continued research into areas of use for this type of actuators. The expansion of the muscle is constrained by the outer nylon fiber mesh, allowing for control of the amount of force the muscle is able to exert due to its contraction. Physical configuration of the McKibben muscles allows the actuators to have such desirable features as variable stiffness, spring-like characteristics, nonlinear passive elasticity, physical flexibility and very high weight-strength curve.

A. Static physical model

As stated previously, although simple in its construction, the MPA's dynamics are very complex, due to the nonlinear coupling between bladder expansion and muscle shortening. Therefore in order to present the major characteristics of the MPA, we are forced to make some simplifications. We base our understanding of the dynamics of the muscles, on the previous research done by Chou and Hannaford [4] as well as the further work by Hannaford and Klute [3]. It appears that this approach is widely regarded as a sufficiently accurate description of the actuator dynamics in the scientific field and serves as the basis for further experimentation. First we introduce the static physical model derived by Chou and Hannaford based on the energy conservation. This is done in order to find the tension as a function of pressure and actuator length. Following equations and explanations are extracted from their paper [4].

The input work (**W_{in}**) is done in McKibben muscle when gas pushes the inner surface of the bladder, which is:

$$\begin{aligned} dW_{in} &= \int_{Si} (P - P_o) dl_i \doteq ds_i \\ &= (P - P_o) \int_{S_i} dl_i \doteq ds_i = P' dV \end{aligned} \tag{1}$$

where P is absolute internal gas pressure, P_o, environment pressure (1 atm), P', relative pressure $(P- P_o)$, S_i total inner surface, d_{s_i}, area vector, $d\boldsymbol{l_i}$, inner surface displacement, and dV, volume change. The output work W_{out} is done when actuator shortens associated with the volume changes, which is:

$$dW_{out} = -FdL \tag{2}$$

where F is axial tension, and dL is axial displacement. From the view of energy conservation, the input work should equal the output work if a system is loss less and without energy storage. Assume actuator is in its ideal condition. We can then use the "virtual work" argument:

$$dW_{out} = dWin, \tag{3}$$

thus (1) and (2) lead to:

$$-FdL = P'dV, \tag{4a}$$

$$F = -P' \frac{dV}{dL}. \tag{4b}$$

In order to estimate the dV/dL the muscle bladder is assumed to have perfect cylindrical shape (2), where the L is the length if the cylinder, θ, the angle between nylon braided mesh and cylinder long axis, D, the diameter of the cylinder, n, number of turns if a thread, and b, the thread length. L and D can be expressed as functions of θ with constant parameters n and b,

$$L = bcos\theta \tag{5}$$

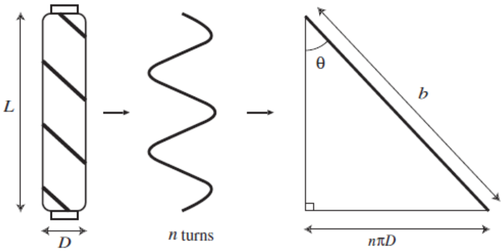

Fig. 2. The geometry of the actuator. The middle segment of the actuator is modeled as perfect cylinder where length of the actuator is L, the diameter is D. n is a number if turns of a thread and $b$is thread length. The relationship between the above parameters is illustrated by the triangle. Adapted from [18]

$$D = \frac{bsin\theta}{n\pi} \tag{6}$$

The Volume of a cylinder is,

$$V = \frac{1}{4}\pi D\ 2L = \frac{b\ 3}{4\pi n^2} sin^2\theta cos\theta. \tag{7}$$

B. Addition of an elastic energy storage model

The physical model of the McKibben muscle was further refined by including the material properties of the inner bladder, utilizing the Mooney-Rivlin mathematical description of the bladder. This approach led Hannaford and Klute [3] to introduce additional term to the preciously established model. The revised equation is:

$$F = P\frac{dV}{dL} - V_b \frac{dW}{dL}, \tag{8}$$

where V_b is the volume occupied by the bladder, and dW is the change in strain energy density (also known as the change in stored energy on a per volume basis). Equation (8) describes the behaviour of the McKibben muscle under static condition i.e at rest or under constant load. Further research [18] [13] [9] [5] has proved the model insufficient and justified necessity of deriving a model taking into account the properties of the MPA under dynamic conditions.

C. Dynamic properties of MPA

Multiple research groups have attempted to characterize the dynamic properties of McKibben muscle, resulting in multiple distinctive models varying in the complexity of the solution. We will primarily focus on the solution proposed by the Sugimoto, Naniwa, Osuka and Sankai in their research paper [18], however other readily available solutions such as those presented in [15] [7] and **??** are all viable approaches. Reasoning for the choice of solution to the dynamic properties problem is quite simple and straightforward. Proposed model is easy to understand and implement, simultaneously providing satisfactory estimation of the actual phenomenon. The revised model supposes the existence of some damping force f_v as a function of only velocity $v_{fm} = -\dot{L}$. Then the actuator force f_m is expressed as:

$$f_m = -P' \frac{dV}{dL} + V_b \frac{dW}{dL} - f_v(v_{fm}) \quad (9)$$

Sugimoto and his team managed to prove that although difficult to formulate the damping force f_v does in fact increase in the direction of muscle's contractile velocity.

III. CURRENT RESEARCH TRENDS IN USE OF MPAS

Research regarding viability of use of McKibben pneumatic actuators as the actuators of choice for the purposes of soft-robotics, focuses largely on two areas: complex mathematical models of MPAs, followed by applications based on use of simple dynamics models. The former aims to quantify and describe such aspects of the actuator's dynamic properties as; non-cylindrical shape while inflated, friction between braided mesh and inner rubber bladder and inter thread friction. The latter exploring possible applications of utilizing the MPAs in robotics rather than the muscle dynamics themselves. Both approaches are discussed closer in their own separate sections III-A and III-B.

A. Simple Dynamics

Experiments utilizing simple static physical model (8) of the McKibben actuators, concentrate on the utilization of the muscles, coupled with exploitation of desirable features of the actuators, rather than further improvement of the model. This approach is very well illustrated with the continued work done by dutch Delft University of Technology. The dutch developed multiple prototypes of autonomous bipedal robots which use McKibben muscles as the locomotion actuators in some capacity. In this paper we will focus primarily on two of the prototype robots developed by the dutch namely, ”Baps” and ”Denise” since both can be considered a good representation of the simplicity principle.

1) Baps: Baps was one of the first robots developed by the dutch team. It used the principle of the simplest 2-D walker as defined by Garcia [6] with bisecting hip joint. The purpose of the prototype was to investigate changes to the robot's stability caused by active actuation of the hip joints by means of McKibben muscles. The robot did not have knee joints and was controlled using simple on-off sequences of signals to the valves controlling the robot. Performed experiments have confirmed positive influence of active actuation hip actuation of the hip on the overall stability of the robot. The prototype assumed the properties of the dynamic properties of MPA as described by (9). Robot required downward sloping flat surface and minimal actuation to walk and relied almost completely on the passive assistance of the gravity. Baps was however very prone to falling forward, backwards and to the sides, due to its very small tolerance to variation in its starting conditions.

2) Denise: Denise is Delft University's fourth attempt at constructing bipedal walking robot and includes significant improvements to its predecessor ”Baps”. The prototype includes among others active knee joints with magnetic latches preventing the joints from overextending, active hip and foot actuation along with significant upper body construction. An illustration of the robot is shown in figure 4. A common feature for both prototypes are their rounded feet. In case of Denise this feature was deliberately copied from previous designs in order to utilize the Lean-to-Yaw coupling, caused by side-to-side tipping. The dutch solved the problem of having the robot falling backwards, by making it continually fall forwards. Similarly they solved the problem of robot loosing its balance to excessive leaning by making it continually change direction, so that robot turns towards the direction of leaning and continues to fall forwards in that direction. This resulted in the robot walked by continually turning from side to side, however never leaving its stable gait basin of attraction.

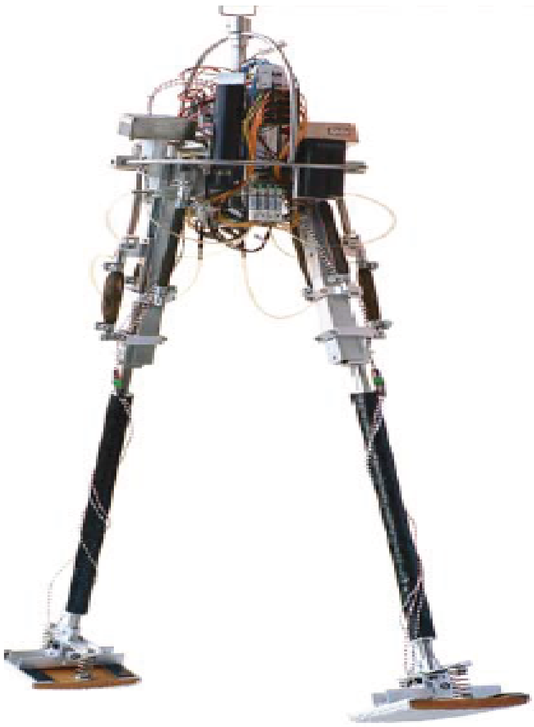

Fig. 3. Baps robot developed by Delft University of Technology [16]

In both studies the researches did no try to exploit more sophisticated methods of controlling the gait of the robots. such as zero-point-moment ZMP [8] or limit-cycles [14]. Therefore in the scope of this paper both are regarded as examples of simple dynamics models.

B. Complex Dynamics

This section provides information on two research papers regarding the use of McKibben muscles and advanced control schemes for the purpose of bipedal locomotion. Both studies propose principles on which the prototype robots can be constructed. First of the two ”Mowgli” [11] is an example in use of ZMP method, as adequate criteria for the stable

Fig. 4. Denise robot developed by Delft University of Technology [16]

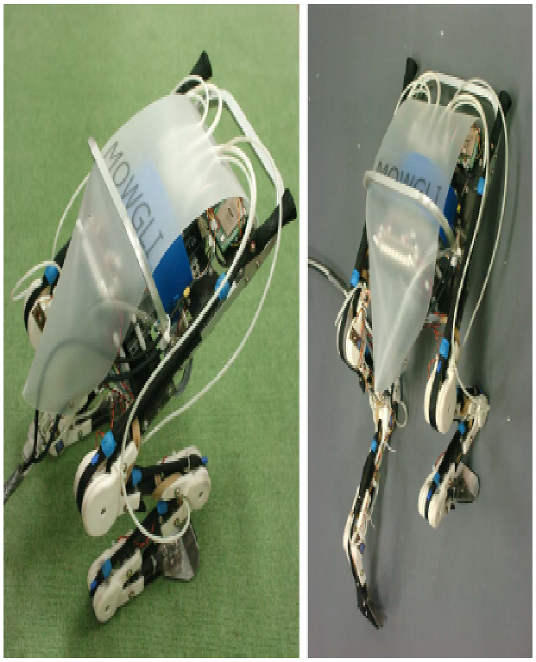

Fig. 5. Mowgli Robot developed by Niiyama, Nagakubo and Kuniyoshi [10]

robot gait. The skeletal construction of the robot serves as the basis for the prototype robot I hope to develop as the initial part of the masters thesis. The second robot ”Athlete Robot” [11] bases itself on the principles and results obtained from experiments performed using ”Mowgli” robot. Both robots and their appropriate research are presented in their respective subsections III-B1 and III-B2

1) Mowgli: Figure 5 illustrates the prototype robot ”Mowgli”. This robot and its construction served as the design basis for the leg joints developed as art of the IN5590 subject at University of Oslo. The primary purpose of the design was to implement a compliant skeletal structure allowing the robot to softly land and take-off. The robot was able to consistently jump approx. 50% of its body height and land softly. Research suggests that even when articulating all of the joints at the same time, the robot follows a proximo-distal sequence of joint extensions, due to its biologically designed structure. In other words the jumping and landing is possible due to effects of the musculoskeletal structure. This is promising as this implies that a well designed model is capable of stable movements caused just by its design.

Figure 6 shows the assembly of the Mowgli joint used as the reference in the design of the first prototype self-walking robot of my design. As shown the joints are fairly elaborate and allow for interchangeability of the parts. Simultaneously the parts are easy to manufacture and mass produce. The inner semi spherical part serving as the kneecap for the robot’s joint allows for smooth almost frictionless movement of the tendons. Although Mowgli’s control scheme is not that different from the previous examples, it’s complex design of the joints, careful muscle placement and use of tendons as part of the design, sets it apart from the ”Baps” and ”Denise”.

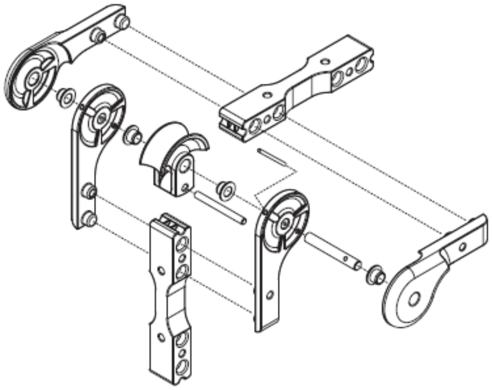

Fig. 6. Mowgli joint structure developed by Niiyama, Nagakubo and Kuniyoshi [10]

2) Athlete Robot: The robot is the natural progression of the Mowgli design. In its development the researches based the design on human anatomy, resulting in greater number of MPAs, as well as more complex construction. The robot shown in 7 uses antagonistic muscle placement principle, emulating human anatomy using MPAs to imitate such muscle groups as; GMAX: gluteus maximus muscle, IL: iliopsoas muscle, HAM: hamstrings, RF: rectus femoris, BF: short head of biceps femoris muscle, VAS: 3-component vastus muscles, GAS: gastrocnemius muscle, NULL: a muscle not exist in human, SOL: soleus, TA: tibialis anterior. Additionally the prototype uses air valves with proportional airflow characteristics, which are a significant improvement over on-off valves of all previous prototypes. Researchers based the construction of the robot on their novel concept of ”Maximum output force profile” [8] in order to maximize the robot’s compliance to the environment while both jumping and landing. Athlete Robot is considered as possible template design for later part of the Master’s Thesis.

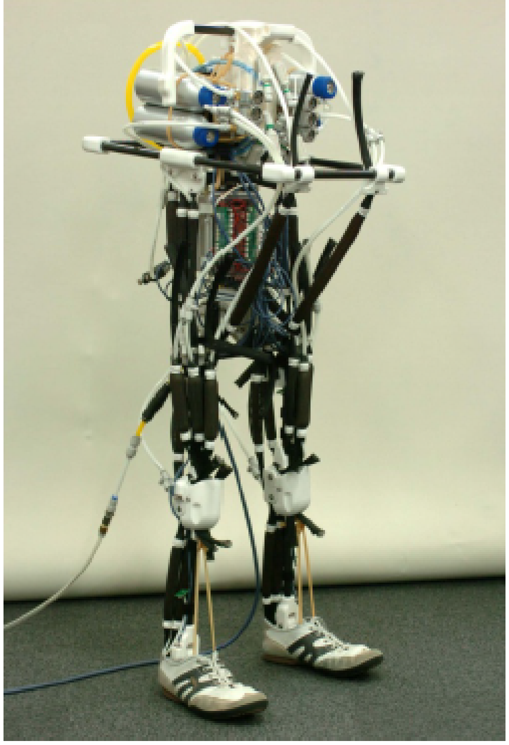

Fig. 7. Athlete Robot developed by Niiyama and Kuniyoshi [11]

IV. IN5590 PROJECT WORK

This section provides details about the prototype robot joint constructed as part of the IN5590 subject, considered for use in the Master’s Thesis. As mentioned the joint design shown in 8 is heavily inspired by the joint construction of ”Mowgli” robot, and serves as the initial prototype for testing; environment compliance, MPA force to pressure dynamics and implementation of different control schemes. The initial construction allows for comfortable placement of the McKibben muscle, utilizes polymer kneecap as the guiding groove for the nylon mesh tendon and has similar range of motion to that of a human knee-joint. During preliminary testing the the joint performed adequately to the expectations, allowing for smooth extension and contraction of the McKibben muscle. Figure 8 shows one of three muscles constructed for the purpose of the project. all three performed similarly with the exception of the repurposed muscle developed by last years student. The repurposed muscle separates itself from the two constructed in this semester, by its considerably lesser stiffness and lesser air pressure required for full expansion of the inner bladder. This year’s muscles require approx. 3bars of pressure for full expansion, whereas the last year’s muscle requires only 2 bars. The important characteristics of the muscles are briefly summarized in table I

Fig. 8. Prototype robot joint constructed as part of IN5590 subject

	Muscle 1	**Muscle 2**	**Muscle 3**
Contraction [%]	35	34	37
Strength	27,7	26,8	27.1
Diameter change [%]	200	198	189
Pressure [bar]	3	3	2

TABLE I

EXPERIMENT RESULTS FOR MCKIBBEN MUSCLES CONSTRUCTED FOR IN5590 SUBJECT.

The 3D rendering of all of the joint parts is shown in figure 9. The joint consists of a center kneecap, two inner acrylic side plates allowing for interchangeable construction, two outer PLA side plates and two PLA bone structures.

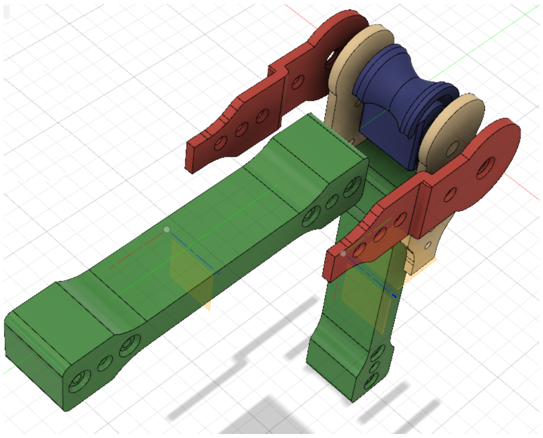

Fig. 9. 3D rendition of the robot joint

V. FUTURE WORK

Considering the research into the topic of use of McKibben muscles for bipedal walking robots, the next stage of the project will focus on research regarding use of machine learning and reinforcement learning. Another possible are of research for the project would be investigation into combining the results of developing jumping, walking and running robots into a signle multi-locomotion biped [1] using ZMP method [8] and limit cycles [2]

A. Conclusion

Construction of the robot joint shed some additional light on such challenges with the design as; the ratio between McKibben muscle length and length of the robot's bones, not completely inelastic properties of the nylon mesh, nylon mesh diameter not matching completely with outer bladder diameter, kneecap part swinging freely with no limits to its motion etc. These shall be revised in the coming weeks and improved upon. On of the biggest considerations is use of more durable polymer for synthetic joint parts.

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