# MACCEPA: the Actuator with adaptable compliance for dynamic walking bipeds.

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## Abstract

Walking robots can be divided into two categories: on one hand the fully actuated robots that don't use passive dynamics, and on the other hand the energy efficient passive walkers. For autonomous robots the energy storage is a problem, forecasting a bright future for passive walkers. At this moment the passive walkers are restricted to one walking speed due to the eigenfrequency, which is fixed by the mechanical constructions. Several actuators with adaptable compliant have been designed, but due to size, complexity or controllability these are difficult to implement in bipeds.

Another application of the use of adaptable compliance is safe robot-human interaction. Sometimes a robot has to be stiff, e.g. for pick and place operations, but when moving between humans, a robot is preferably compliant. Also for exoskeletons or rehabilitation devices this compliance can improve ergonomics and speed up the rehabilitation process.

The MACCEPA is a straightforward and easy to construct rotational actuator, of which the compliance can be controlled separately from the equilibrium position. The generated torque is a linear function of the compliance and of the angle between equilibrium position and actual position. This makes this actuator perfectly suitable for dynamic walking, human-robotic interfaces and robotic rehabilitation devices.

**Keywords**: Adjustable Compliance, Equilibrium Position, Actuators, Compliance control, Spring

## 1 Introduction

Humans, like most walking animals, are walking efficiently by using the kinetical energy and the potential energy of the lower limbs [1,2]. Human joints are actuated by at least 2 muscle groups, giving the possibility to change the stiffness of a joint and to control the equilibrium position. By controlling both the compliance and equilibrium position a variety of natural motions is possible, requiring a minimal energy input to the system.

One of the first realizations of a compliant actuator was the MIT Series Elastic Actuator [3], which has an inherent, but fixed compliance. For shock absorbance this is useful, but in order to use natural dynamics this approach is limited to one eigenfrequency since the spring constant is fixed. This is comparable to passive walkers [4], which are able to walk energy efficiently, although restricted to a single walking speed.

Different designs with adaptable compliance have been made: at Carnegie Mellon University the AMASC (Actuator with Mechanically Adjustable Series Compliance) [5], at the Vrije Universiteit Brussel the Robotics and Multibody Mechanics research group has developed the PPAM (Pleated Pneumatic Artificial Muscle) [6] used in the biped Lucy [7], at the University of Pisa, Italy, [8] the Variable Stiffness Actuator (VIA) is developed, at Georgia Institute of Technology, USA, a Biologically Inspired Joint Stiffness Control [9] is made. All these design work on the same principle: two antagonistic coupled non linear springs.

Adaptable compliance can be used in walking bipeds, but also in a number of other disciplines. The ultimate (lower)leg prostheses is an actuated system, which moves naturally as a human body would do. The knowledge acquired by developing walking bipeds is applicable in the field of leg prostheses, and so is the use of an actuator with adaptable compliance. Other possible applications are rehabilitation robots. Such devices are imposing gait-like motion patterns to, for instance, the legs of a patient. In the beginning of the rehabilitation process it is preferred to have a relatively high stiffness, which could be gradually lowered when a patient has regained a certain level of control over his/her legs. While classical industrial robots are built to be as stiff as possible, resulting in unsafe devices for humans, the new trend is to incorporate compliance to make it possible to have a safe human-robot interaction. For example [10], describing a soft robot arm which will assist the user to carry the load, while the operator only has to push gently on the load.

As is shown in the above examples a straightforward, easy to control actuator with adaptable compliance has a bright future.

## 2 Working principle

In **Fig. 1** the essential parts of a Maccepa (Mechanically Adjustable Compliance and Controllable Equilibrium Position Actuator) are drawn. As can be seen there are 3 bodies pivoting around a common rotation axis. To visualize the concept, the left body in **Fig. 1** can be seen as an upper leg, the right body as the lower leg and the rotation axis, which goes through the knee joint. Around this rotation axis, a lever arm is pivoting, depicted as a smaller body in **Fig. 1**. A spring is attached between a fixed point on the lever arm and a cable guided by a fixed point on the right body to a pretension mechanism.

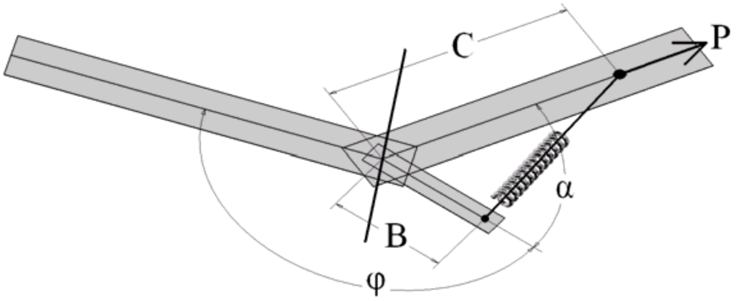

**Fig. 1.** Working principle of the Maccepa

The angle φ between the lever arm and the left body, is set by a classical actuator. When α, the angle between the lever arm and the right body, differs from zero, the force due to the elongation of the spring will generate a torque, which will try to line up the right body with the lever arm. When the angle α is zero—this is the equilibrium position—the spring will not generate any torque. The actuator, determining the angle φ actually sets the equilibrium position. A second actuator, which pulls on the cable connected to the spring, will set the pretension of the spring. This pretension will vary the torque for a certain angle α, thus controlling the spring constant of an equivalent torsion spring.

## 3 Calculation of the torque

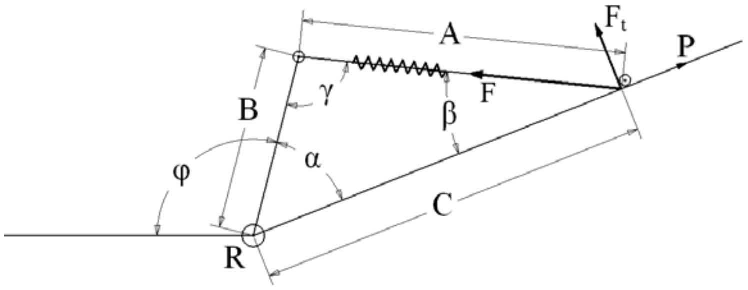

**Fig. 2.** Scheme of the Maccepa

R = Rotation point
T = Torque applied by Maccepa
F = Force due to extension of the spring
k = Spring constant, assume a linear spring
B = Lever arm motor, which controls equilibrium position
C = Distance between joint and spring tension mechanism
L = Length of the cable + restlenght of the spring – position of the pretensioner
P = Pretension of the spring, function of the position of the second actuator
α = Angle between lever arm and right body
φ = Angle between left body and lever arm, equilibrium position

$$T = k.B.C\sin\alpha.\left(1+\frac{P-L}{\sqrt{B^2+C^2-2BC\cos\alpha}}\right) \tag{1}$$

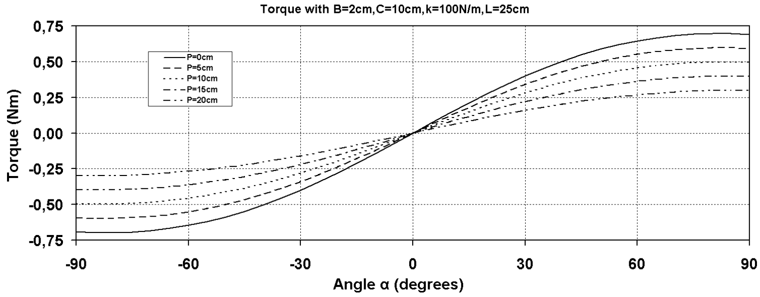

**Fig. 3.** Torque as a function on angle α when pretension (P) is altered

**Fig. 3** shows the torque generated by the Maccepa is symmetrical around the equilibrium position. The torque (see formula 1) is also independent from the angle φ, which means the compliance and equilibrium position can be controlled independently. For the linearity one can see that around the equilibrium position the plot is rather linear, but for larger angles the plots are not linear anymore.

Before talking about linearity, one should define the working range. As useful working range we assume -45° to 45°. It is worth mentioning, the range of the joint is not limited to 90° with this choice, since this range of -45° to 45° means the angle between actual position and the equilibrium position. The equilibrium position can vary over a range of 360° and even more. When using the joints for bipedal walking—either robots or prostheses—the choice of -45° to 45° is perfectly justifiable. So when looking at the linearity only the range between 0° and 45° will be studied because of the symmetrical torque characteristics.

## 4 Influence of design variables

The variables k, B and C are chosen during design and are fixed during normal operation. In this chapter the influence of these four variables will be shown in detail.

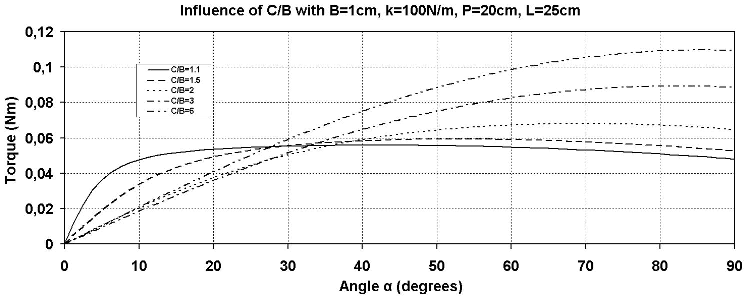

**Fig. 4.** Influence of C/B

In **Fig. 4** one can see that the C/B ratio determines the non-linearity of the curves. One can see the bigger the ratio C/B the more linear the curves. Note that looking at the formula of the torque one can see that B and C can be exchanged without changing the result, so C/B should be big enough or B/C should be big enough. Simulations showed that from a B/C or C/B ratio of a little above 5 the correlation coefficient is 0.99. This can be used as a guideline during design, when working with a range of -45° to 45°.

In **Fig. 5** the influence of the length of the lever arm, B is depicted. If the length of the lever arm is doubled, the torque is also approximately doubled. Since B and C can be exchanged, the influence of C is analogous.

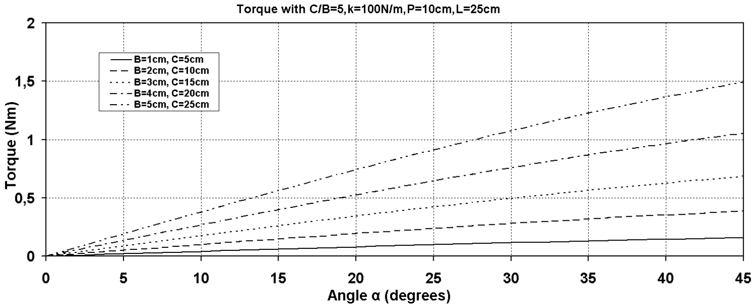

**Fig. 5.** Influence of the lever arm B (or C) on the torque with C/B = 5

The Influence of k is linear, looking at formula 1. As shown in **Fig. 3** the torque can be adjusted by controlling the pretension.

## 5 Experimental Setup

A first prototype was built. In **Fig. 6** a CAD drawing of the setup is depicted. On the left side the body with the pretension mechanism is shown, on the right side the body with the actuator, which controls the equilibrium position. The rotation axis between these bodies is equipped with 2 roller bearings. A potentiometer is placed on this axis to measure the angle between the two bodies, the actual angle of the joint. Actuation is done by servomotors, which are position controlled actuators with integrated position measurement and position controller.

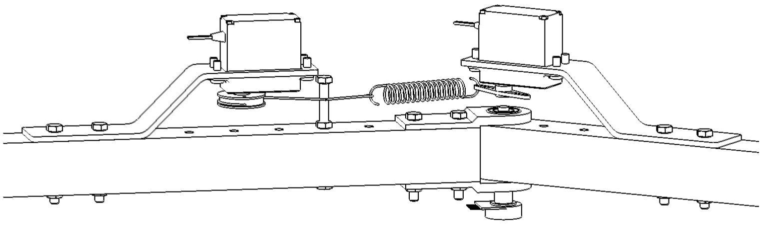

**Fig. 6.** CAD drawing of the first Maccepa prototype

In a first experiment the difference in natural movements with altered compliance was witnessed. The setup is placed so the rotation axis is vertical, as such gravity does not influence our experiment. During the experiment the equilibrium position is set to 0 degrees, defined as the position where both arms are aligned. In **Fig. 7** the joint, which is made stiff, is pulled manually out of the equilibrium position and released. As a result the joint starts oscillating around the equilibrium position with a certain frequency. After the joint stops oscillating (around 2 sec), the joint is made more compliant, and pulled again out of the equilibrium position (2.5 sec). Releasing the joint will result in a lower eigenfrequency.

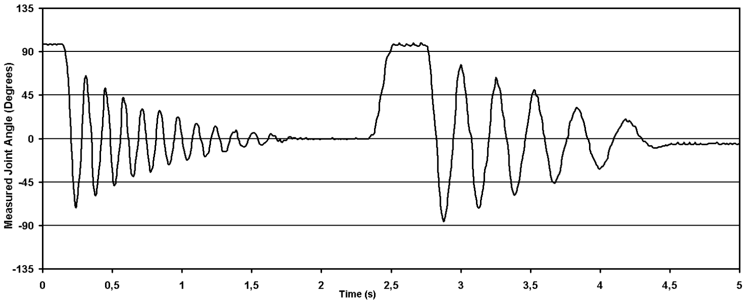

**Fig. 7.** Variation of the natural frequency for different settings of the compliance.

As can be seen from the experiment, the compliance can be controlled, by only changing the position of one of the actuators, which is not the case in other designs with adaptable compliance.

## 6 Conclusions

The Maccepa (Mechanically Adjustable Compliance and Controllable Equilibrium Position Actuator) is presented in detail. The design variables, limited in number, are explained and their influence on the torque characteristics is shown. Compared to other compliant mechanisms the Maccepa is straightforward and relatively inexpensive. The control of the equilibrium position and compliance is completely independent. Thus to control the one parameter it requires only the action of one of the two actuators, e.g. one servo motor. These advantages make it the ideal actuator for use in applications where adaptable compliance is required or useful, e.g. dynamic walking or any robotic application interacting with humans.

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