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Orthopaedic rehabilitation: A powered elbow orthosis using compliant actuation

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***Abstract*— This paper reports on the powered elbow orthosis for orthopaedic rehabilitation project and its main challenges. The mechanical design is briefly discussed. The actuator being used is the novel rotational actuator, MACCEPA or *Mechanically Adjustable Compliance and Controllable Equilibrium Position Actuator*. The schematic representation and working principle of this actuator are recapitulated in short before describing the mathematical model of the orthosis and the choices made to find a balance between simplicity, usefulness and correspondence with reality.**

I. INTRODUCTION

Down the road the social security systems as we know them in Western Europe will face some difficulties. Every year 15.200 patients suffer a spinal cord injury. Together with stroke, this is the most common cause for decreased mobility and functionality for both upper and lower extremities [1]. The post world war baby boom and the increasing life expectancy are driving up the age of our society. Combined with the growing number of patients and the cost of their treatment, this will put an additional strain on our social security systems [2]. A shortage of social workers and therapists is already to be expected in the near future.

The emerging field of rehabilitation robotics, assistive robotics as well as medical therapy robotics can bring a partial solution to this problem. They allow longer and more frequent training sessions, as the sessions are no longer conditioned by the physical endurance of the therapist. However, in no way can the use of medical therapy robots ever replace the therapists. They merely lessen their load and offer them new tools to asses and treat their patients. Robot-aided therapy also allows a degree of objectivity and repeatability that is much harder to achieve with manual therapy. The patient's efforts and progress can be more precisely monitored which will empower the therapist to tailor a training schedule to the needs of each particular patient.

Although more studies concerning the effectiveness of robot-aided therapy and their comparison with conventional therapy techniques should be performed to conclusively state that automated therapy outperforms the conventional methods in terms of clinical and biomechanical measures, the results available today are encouraging. Preliminary results indicate a significant enhancement of the rehabilitation process when robotics is applied [3].

In the subsequent sections of this paper first the powered elbow orthosis project and its specific challenges will be discussed. Before describing the mathematical model of the exoskeleton, the mechanical design of the orthosis will be briefly reviewed, as well as the working principle and main characteristics of the MACCEPA actuator.

II. THE POWERED ELBOW ORTHOSIS

The greater part of currently available rehabilitation robots (as well as the current research prototypes) focuses mainly on neurorehabilitation. This means the patients have no or limited control over their limbs, but their limbs themselves are not damaged. The injury is at the level of the central nervous system, e.g. in the brain (stroke) or the spinal cord. The muscles, bones and joints are intact. This paper however focuses on a different kind of rehabilitation: orthopaedic rehabilitation. Contrary to neurorehabilitation cases, the limb is damaged, i.e. either the bone is broken, the muscle is torn or there is some damage to the joint itself. While neurorehabilitation is primarily dedicated to mobilising the joint and training the central nervous system of the patient, orthopaedic rehabilitation requires both mobilising and immobilising of the joint. The posttraumatic elbow joint for example is only allowed small angle flexion/extension movements in the first phase of the rehabilitation. These movements have to be allowed and to certain degree even induced to counter the stiffening. Pronation, supination and large flexion/extension movement should be immobilised.

Although the elbow is a physiologically very complex joint, kinematically and for rehabilitation reasons, it can be seen as a simple 1 DOF hinge joint. A lesion of the elbow very often has a very particular rehabilitation issue: the joint tends to stiffen very rapidly [4]. Although the exact reasons for this stiffening of the joint are not yet fully comprehended, it is believed that tissue calcification plays an important role in this process. This posttraumatic elbow stiffness is a common problem that is often difficult to manage. The goal of the treatment is to at least restore a functional range of elbow motion (about 30° to 130°) [5]. In order to maximally restore the range of motion, it is imperative that rehabilitation treatment starts as soon as possible after the trauma to mobilise the joint and counter the stiffening. This very statement however also implies that the rehabilitation process should start out very apprehensively, in order to not further damage the already injured joint. Due to the specific nature of the elbow, a small excess force or a minor unnatural movement can have great consequence in the initial phase of the rehabilitation. Therefore, compliant actuation is not just an advantage, but an imperative in this kind of orthopaedic rehabilitation.

Concerning the elbow, there is an anatomical aspect that is often overlooked or neglected when developing an orthosis: The carrying angle (fig. 1).

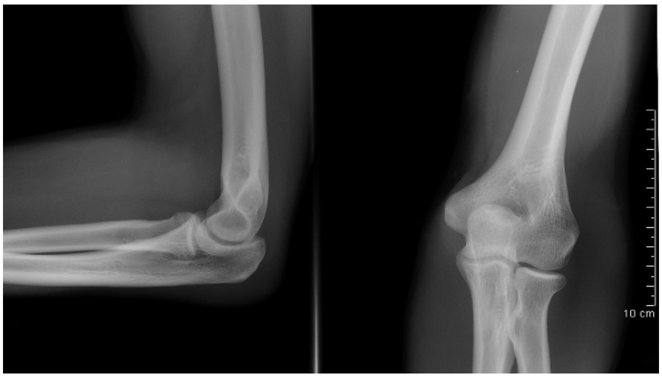


Fig. 1: The carrying angle of the fore arm

When the arm is extended, with the palm facing upward, the bones of the upper arm and the forearm are not perfectly aligned. This deviation gradually disappears with the flexing of the elbow. The deviation occurs in the direction of the thumb, and is generally larger for women then for men. This carrying angle permits the forearms to clear the hips in swinging movements during walking, hence the generally greater carrying angle for women. When using the orthotic approach for a neurorehabilitation device, this angular deviation is compensated by the yielding attachment of the orthosis to the limb and the soft tissue deformation of the forearm. The conventional non-actuated orthoses used to immobilise the elbow joint after trauma and surgery generally do not face this problem of increasing angle deviation when extending the elbow, partly because the elbow should not be fully extended in the brace. It is believed that in the case of an actuated orthosis the angle will also be sufficiently compensated by the soft tissue deformation of the forearm. Furthermore, the workspace of the orthosis will mainly be around 90° flexion of the elbow. Only at the more advanced stages of the rehabilitation will the allowed angular displacement grow closer to full extension of the elbow.

The above challenges in mind, a one dimensional powered elbow orthosis for orthopaedic rehabilitation is being developed to be used as soon as possible after the trauma to counter stiffening of the elbow joint. The orthosis will be actuated by MACCEPA's, *Mechanically Adjustable Compliance and Controllable Equilibrium Position Actuators* [6], thus ensuring compliance and safety.

The device will have three separate modes, one for each successive stage of the rehabilitation process: the passive, the active and the interactive mode.

The passive mode will mainly be used during early rehabilitation. The device will completely induce the movement and the patient will not have to exert any force, cfr. continuous passive motion machines (CPM's). The patient remains passive. During the interactive mode, the patient will try to complete a movement. The device is equipped with several rotational position sensors and therefore will register when a patients' movement deviates too far from the movement that should be induced, i.e. when the angle between the two bodies deviates too much from the angle between the left body and the lever arm. When it is registered that the patient needs some help, the device will assist. The active mode will mostly be used towards the end of the rehabilitation process to train muscle strength. In this mode, the device will counteract the movement the patient tries to make. In this mode, the device can be compared to a training tool that generates resistance which the patient has to overcome.

Due to the adaptable compliance of the MACCEPA and a force control strategy, an ideal force and/or resistance pattern can be applied. Both equilibrium position and compliance can be adjusted online.

Currently, orthopaedic rehabilitation of the elbow joint customarily consists of about one half hour of physiotherapy per day and immobilising the joint for the greater part of the day. Therapists are convinced that more frequent and longer training sessions will speed up the recovery process and more effectively counter the stiffening.

There are already commercial systems available that allow the patient to make small flexion/extension movements, however they sometimes lack effectiveness because patients are reluctant to exercise due to fear of the pain that might come with training.

A portable or even wearable powered elbow orthosis can be a solution to this problem. So far there are no actuated elbow orthoses commercially available.

III. Mechanical Design

The elbow orthosis was developed using the MACCEPA actuator (fig. 2) to ensure an inherent compliance as can only be found in naturally compliant actuators. The number of rehabilitation robots using intrinsic compliant actuation is rather limited, even though this soft actuation offers specific advantages compared to the conventional stiff actuators. The natural compliance of the actuators provides an inherent safety and allows the human-robot interaction to occur in a gentle and more comfortable manner [7].

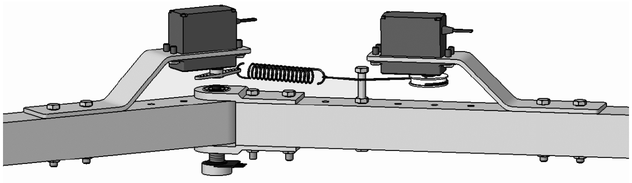


Fig. 2: CAD of a MACCEPA actuator

Safety is a major issue when designing rehabilitation robots. Whatever happens, the robot should never be able to harm the patient in any way. Besides using natural compliant actuators to ensure safety, an array of other measures were taken. The maximum torque to be applied to the human limb is limited, mechanical stops were added to avoid extending the elbow too far and the software will be implemented in a fail safe manner.

As stated earlier, it is beneficiary for the patient to increase the frequency and length of training sessions and therefore ideally the orthosis has to be portable, even wearable. The orthosis was developed to be lightweight and slim, thus allowing patients to take it home for training. Because the orthosis must fit an array of patients, all with different height and body weight, it must also be adjustable. Patients who suffer from a trauma at the elbow need a brace to fixate the joint. It is important that the joint can only perform certain small movements, and is protected from any excess force or large displacement. Therefore it's imperative that each patient gets his own personal brace, tailored to his specific physique and needs. This brace is totally independent of any robotic rehabilitation training that the patient might receive. Keeping this in mind, the second prototype will entail an easy click-on system, which will allow the actuator to be separated from the brace. The advantage of this approach lies in the fact that, although the braces are always custom-made, they can be produced in such a way that the actuator can always be attached to it, thus allowing one actuator to be used by multiple subsequent patients, simply by clicking it on.

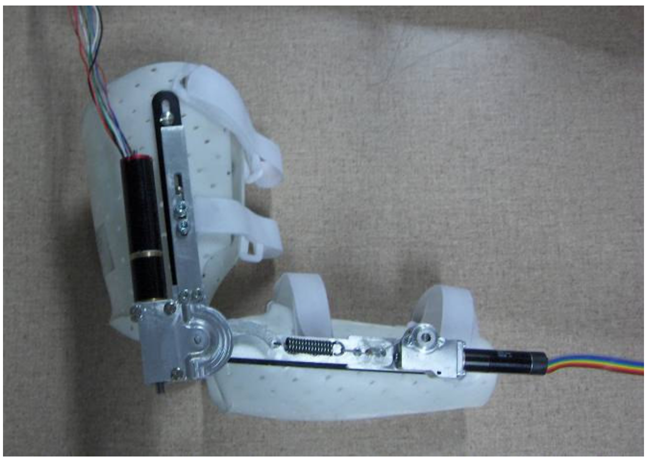


Fig. 3: The elbow orthosis prototype, side view

The MACCEPA actuator allows the separate drive of both equilibrium position and compliance. To accomplish this in an active manner, two (electric) drives are needed. The larger one, attached nearest to the joint allows the orthosis a maximum torque of 10Nm with a movement frequency of 0,5Hz. The high powered electric and gearbox drive weigh only 336g.

Fig. 4: The elbow orthosis prototype, top view

The smaller electric drive is part of the pretension mechanism, which will set a pretension on the spring, thus determine the compliance of the system. This compliance is adjustable through this electric drive which allows the full range of compliance to be reached within one second. The weight of this drive-gearbox combination is merely 139g.

The total weight of the prototype, excluding the electronics, is merely 1,1kg. This low weight is important to ensure wearability, but even more consequential towards impact on the injured limb and joint. The weight is barely over the weight of a conventional sophisticated elbow brace and is distributed over the entire upper limb, thus the impact on the injured joint should be minimal.

IV. The MACCEPA

Before going into the mathematical model and equation of motion of the robotic system, it is opportune to briefly elaborate on the working principle and main characteristics of the MACCEPA, as it is a fairly novel rotational actuator.

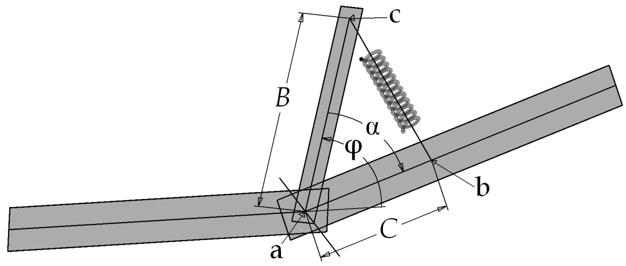
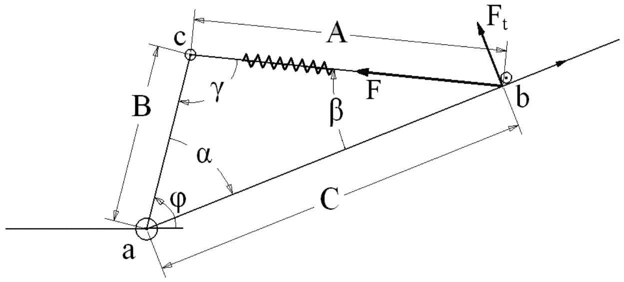


Fig. 5: Working principle of the MACCEPA

Figure 5 shows a schematic drawing of a MACCEPA. The actuator consists of three bodies or links which can all pivot round an axis perpendicular through point a. Consider the left link grounded. The smaller link is called the lever arm. The position of this lever arm (i.e. the angle φ) is set by a drive, e.g. an electric drive. The right link is connected to the lever arm by means of a cable with an elastic element (e.g. a spring). When the lever arm and the right link are not aligned, the spring is elongated and exerts a force between the two links. This generates a torque T round point a and pulls the right link towards the lever arm. It is clear that this force depends on the elongation of the spring and on the angle α. When the angle α is zero, the lever arm and the right



link are aligned and the force exerted by the spring is also in line with the links, thus not generating any torque round point *a*.

Fig. 6: Scheme of the MACCEPA

a = Rotation point
b = Fixed point on right body. The cable between the spring and the pre-tension mechanism is guided around this point.
c = Fixed point on lever arm, where the spring is attached
F = Force due to extension of the spring
F_t = Component of *F* orthogonal to line *ab*, that generates torque
k = Spring constant, assuming linear spring
P = Extension of the spring caused by pre-tensioning (equals the total extension of the spring when $\alpha = 0$)
α = Angle between lever arm and right body
φ = Angle between extension of left body and lever arm, equilibrium position

Because of the elastic element, this actuator has natural compliance. However, the MACCEPA has *mechanically adjustable compliance*. This is achieved by adding a second (electric) drive which can set the pretension of the spring. When the spring is pretensioned, the force exerted at the same angle α will be larger. Thus by changing the pretension of the spring, the compliance of the actuator is changed. Notice that both equilibrium position and compliance are completely decoupled and so can be set independently.

Figure 6 shows the MACCEPA schematically. The torque generated by the actuator is [6]:

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

This can be linearized for small angles:

$$T = \alpha.\mu.P$$

With $\mu = \dfrac{k.B.C}{|C - B|}$

It is worth mentioning that with an adequate choice of the geometrical parameters this linearization is valid for angles up to ±45°.

V. Mathematical model of the exoskeleton

Figure 7 gives a schematic representation of the orthosis shown in figures 4 and 5. *AB* is the first link (upper arm) and *BD* the second link (forearm). *BC* is the lever arm of the MACCEPA which is connected to point *D* by means of a cable and an elastic element, in this case a spring.

For this model we consider the upper arm, and thus the upper part of the exoskeleton as grounded (cfr. the left link of the MACCEPA). This means the patient would hold the upper arm and elbow next to his body, not moving it during the training session. More accurate might be to consider the shoulder (point A) also as a pivot point, instead of considering link *AB* (i.e. the upper arm) as grounded.

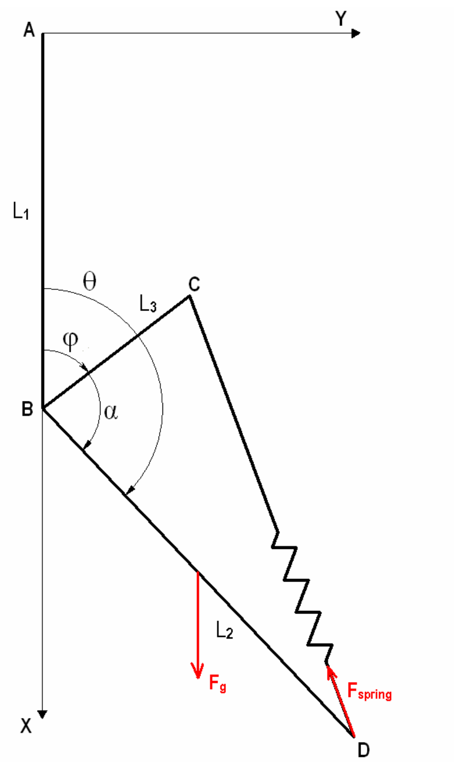


Fig. 7: Scheme of the elbow orthosis

With: θ = angle between the first link and the lever arm
φ = angle between the first link and the lever arm
α = angle between the lever arm and the second link
m = mass
g = gravitational constant

I = moment of inertia of the lower link
L_2 = length of the second link (forearm)
L_3 = length of the lever arm
k = spring constant
P = pretension
τ_e = torque of the elbow

In this model there are three components affecting the motion of the system. First, there is the gravitational component F_g. Both the mass of the lower part of the exoskeleton and the mass of the fore arm (calculated as a percentage of body weight) are modelled as a point mass in the centre of gravity. Notice that the upper part of the system does not contribute as we have considered it fixed in space. The second component is a torque exerted by the actuator. As the lever arm misaligns with the lower link, the spring will be elongated and thus a force F_{spring} will exist between the lever arm and the lower link, resulting in a torque trying to align the both. The third component which is not shown in the scheme is a torque due to the elbow joint itself, τ_e. As mentioned before, after trauma, the elbow stiffens very rapidly. This stiffening occurs in the flexed position. This means that there will be a torque exerted by the elbow joint, trying to bring the elbow in complete flexion.

Putting the above in mathematical form, leads to the equation of motion of the system:

$$I.\ddot{\theta} = m.g.\frac{L_2}{2}.\sin(\theta) + \overline{BD} \times \overline{F_v} + \tau_e$$

Considering that

$$\overline{F_v} = k.\left[\left|\overline{DC}\right| - (L_2 - L_3) + P\right].\overline{1_{DC}}$$

The equation of motion of the system becomes:

$$\ddot{\theta} = \frac{m.g.L_2}{I} \cdot \sin(\theta) - \frac{k.L_2.L_3.\sin(\theta - \phi)}{I} \cdot \left(1 - \frac{L_2 - L_3 - P}{\sqrt{L_2^2 + L_3^2 - 2.L_2.L_3.\cos(\theta - \phi)}}\right) + \tau_e$$

This model still has some serious simplifications, so it does not fully comply with reality. Figure 8 gives a graphical representation of the solution of the equation of motion of the system.

As can be expected, the system oscillates round the equilibrium position of the actuator. In reality, mechanical friction will act as damping and the system will go to the equilibrium position. Mechanical friction was deliberately not included in the model. This mathematical model will be used for further simulation to develop a suitable control. Damping may stabilize an otherwise unstable controller. A controller which is able to adequately control a frictionless model will perform even better in reality.

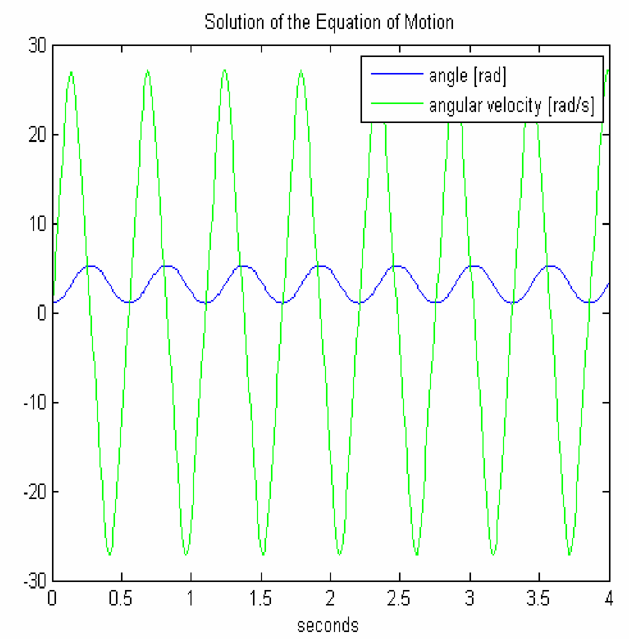


Fig. 8: A solution for the Equation of Motion

VI. Conclusions and Future Work

The emerging field of rehabilitation robotics, assistive robotics as well as medical therapy robotics can help to lighten the load of our social security in the future and therefore should be pursued wholeheartedly.

The mathematical model of the elbow orthosis has three major components:

$$I.\ddot{\theta} = m.g.\frac{L_2}{2}.\sin(\theta) + \overline{BD} \times \overline{F_v} + \tau_e$$

a gravitational component, a component due to the actuator and a component as a result of the stiffness of a post-traumatic elbow joint. Mechanical stiffness (and the damping that comes with it) was not considered in the model to avoid that in future simulation, unstable controllers may seem stable.

In the near future, the mathematical model of the orthosis will be adjusted to include motion of the upper arm and a mathematical model for the electrical drive for the position of the MACCEPA will be implemented. Further simulations will be done to develop an adequate control for the orthosis. This control poses interesting problems. Both the safety of the patient, as the compliance of the actuator will render the control of the orthosis quite challenging.

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