Minimizing Energy Consumption through Optimal Mechanical Design and Stiffness Regulation

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I. INTRODUCTION

HUMANOID robots and exoskeletons should not follow the rule 'stiffer is better' as they are physically interacting with humans [1]. In order to guarantee safety, they need to be compliant. Also for those which are autonomous, energy efficiency is an important issue. Elastic elements, e.g. springs play an important role in compliant robotic joints. They decouple inertia of the motor which normally has a large value from inertia of the link and so decrease the stiffness of the joint contributing to safety in case of a collision. They also can absorb kinetic energy, store it as potential energy and then release it again as kinetic energy. By setting stiffness with respect to desired trajectory and suitably design the mechanism, this ability of recovering a part of energy can help minimizing energy consumption in periodic motions, however in this case the mechanism should be able to adapt its stiffness. Since walking is a limit cycle motion [2] it can be considered as a periodic motion. Currently, using these types of robotic joints in walking robots, for instance bipeds or exoskeletons, is gaining interest due to energy efficiency and safety. A common problem in these types of joints is that both actuators are directly dealing with spring's deflection. Therefore, the energy required for adjusting the stiffness while tracking a desired trajectory is considerably high. In order to cope with this problem a new Actuator with Adjustable Stiffness (AwAS) is proposed in this paper. The main idea is to make the force generated by the springs perpendicular to the displacement needed to change the stiffness. This makes the energy consumption to control the stiffness low and a small motor can be used to control this parameter. This paper presents the design of this new actuator.

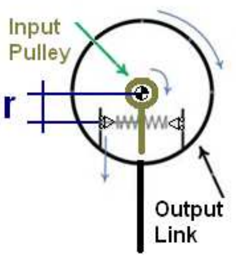

Fig 1: Principle of operation

II. PRINCIPLE OF OPERATION

A. Principle of Operation

A guiding mechanism allows the control of length of the lever arm *r* by moving the two springs down (to increase stiffness) and up (to reduce stiffness). The sum of the lengths of the two springs is always a constant, so the pretension does not change when controlling the stiffness. When the output link is in its equilibrium position (the angular position where zero torque is generated, so when the extension of both springs is equal), the force generated by the springs is perpendicular to the displacement needed to change the stiffness. This has the important consequence that in principle no energy is needed to change the stiffness. In different designs the force required to compress the springs in order to change the stiffness is acting always parallel to the springs requiring a strong motor and sufficient amount of energy to regulate the stiffness. In reality, the presence of friction has to be overcome. In addition, if the joint is not in the equilibrium position, the force generated by the spring has a component parallel to the displacement and a small amount of energy is needed. However due to this property the motor controlling the stiffness can be considerable smaller than other designs of variable stiffness actuators. An additional advantage of this design is that it does not require the use of non-linear springs or mechanisms to provide the nonlinear force/displacement profile which is necessary for the stiffness regulation. According to the categorization made in [3] this novel actuator belongs to the "Mechanically Controlled Stiffness Actuators" because the stiffness adjustment is done by varying the points where a compliant element is attached to the structure.

III Mechanical Design of the Joint

In this section, the mechanical design of the proposed actuator is presented. Figures 2 and 3 show the CAD design and a prototype of the assembled actuator, respectively. The actuator attached to the base link (1), consists of two motors. The first motor M1 (2), which controls the equilibrium position, is a frameless Emoteq BLDC motor (HT 02300) in series with a harmonic drive (CSD-25) (3) having a reduction ratio of 50:1. The second motor M2 (4), which tunes the stiffness, is a Faulhaber DC (2.25W) motor in series with planetary gearbox providing a gear ratio of 20:1. The output of the harmonic drive is directly attached to an intermediate link component (5). The output link of the unit (6) is coupled to this intermediate link component by means of two antagonistically connected compression springs (7). This elastic coupling permits the relative rotation of the output link with the respect to the intermediate link (5) and therefore decouples the output link from the harmonic drive.

The two springs used in the prototype have a stiffness of 300N/mm and a free length of 32mm. When being installed, the springs experience a pre-compression of 5mm, this is half of the maximum compression permitted by the springs. The motor which is responsible for the stiffness regulation is fixed on the intermediate link component. A guiding mechanism implemented by a ball screw driver is connected at the output of this motor to allow the adjustment of the lever arm r as demonstrated in Figure 1. The rotational stiffness of the output link is related to the length of the lever arm by the following expression [4]

$$K = 2K_s(r^2 + \frac{r_s^2}{3})(2cos^2\alpha - 1) \qquad (1)$$

Where K, K_s, r_s , α and r are rotational stiffness of the output link, the stiffness of the spring, external radius of the spring, angular difference between output link and input pulley and the length of the lever arm, respectively.

In this prototype the lever arm can be adjusted from 9mm to 33mm, resulting in a rotational stiffness range from 60 to 650Nm/rad.

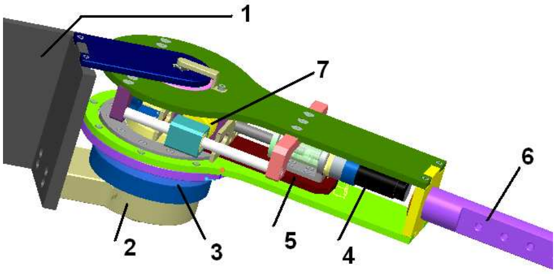

Fig. 2. CAD view of the proposed variable stiffness actuator

Fig. 3. Actuator prototype

Figure 4 shows rotary stiffness versus different values of the lever arm and different angular difference between input pulley and output link.

Two encoders measure the position of each motor shaft and another encoder measures the position of the output link. A torque sensor installed between the intermediate link and the harmonic drive measures the applied torque.

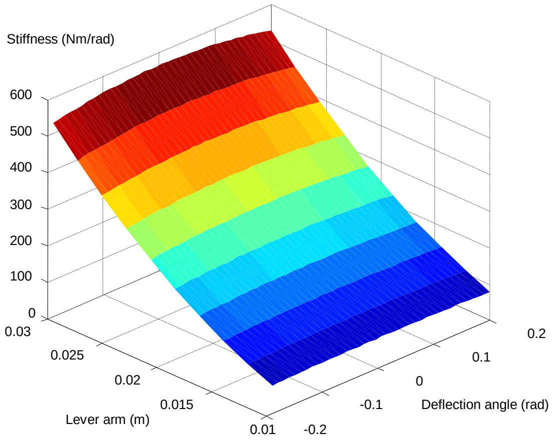

Fig. 4. Stiffness regulation versus the lever arm and angular deflection of the output link

III. CONCLUSION

This paper describes the design and development of a new actuator with adjustable stiffness which can be used in robots physically interacting with humans, e.g. humanoids and exoskeletons. The actuator can independently control the equilibrium position and stiffness using two motors. Compared to existing prototypes, an important novelty in the proposed design is that the displacement needed to change the stiffness is perpendicular to the forces generated by the springs used to provide the compliance. As a result the energy required for the stiffness adjustment is minimal. The ability of the actuator to change its stiffness allows energy consumption to be minimized while tracking a desired trajectory.

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