A BENCH-TOP PROTOTYPE OF A VARIABLE STIFFNESS PROSTHESIS

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ABSTRACT

A prototype of a variable stiffness prosthetic joint has been constructed and tested. The joint is based on two actuator subsystems arranged in an antagonistic configuration. Each actuator subsystem is composed of a small, high-speed electric motor, a single stage, worm-gear based transmission and a nonlinear stiffness element. Each nonlinear stiffness element is composed of a set of short sections of elastic tube that was chosen based on its stiffness characteristics. The system is powered by batteries and can be controlled in a number of ways. The paper will present the basis used for selecting the nonlinear stiffness elements, the details of the design as constructed and a comparison of the actual performance of the prototype to predictions based on design calculations and simulations. The prototype has performance that is comparable to commercially available prostheses and showed good correspondence between simulation and prototype. The prototype was able to lift a 2 kg load through 135 degrees in 1.42 seconds and to vary its stiffness from 14 to 24 Nm/rad.

INTRODUCTION

A variable stiffness elbow prosthesis should look and feel more natural and allow the amputee to perform constrained or contact movements with the arm at a low stiffness, and fast, precision movements at a high stiffness. Previous research suggests that it should simplify control issues, provide increased dexterity and allow greatly improved energy efficiency when interacting with the environment [1, 2, 3, 4, 5]. Antagonistic nonlinear compliant actuators acting about the joint provide stiffness variation capabilities. A nonbackdrivable transmission allows external forces to be statically supported without using the motors.

A variable stiffness prosthetic arm bench top prototype was designed, constructed, mathematically modelled and tested. The configuration consists of two actuators arranged antagonistically around the elbow joint. Each actuator is made up of a dc motor, gearhead, nonbackdrivable transmission, nonlinear spring and two pulleys. Figures 1 and 2 show the resulting prototype.

Figure 1: Bench top prototype
DESIGN DETAILS

Using design criteria based on currently available upper arm prostheses [6, 7], the components were chosen. A Maxon RE35 dc brush motor with a 4.8:1 gearhead was chosen for its torque and speed capabilities. A worm and worm gear set from Boston Gear makes up the transmission. A single-start, hardened steel worm and 30 tooth, bronze worm gear with a diametral pitch of 12 met the strength and wear criteria for the chosen motor running at its thermal torque limit.

There are two types of nonlinear springs. A hardening spring is a spring in which the stiffness (derivative of spring force with respect to displacement) increases with displacement and a softening spring has a stiffness which decreases with displacement [3, 8, 9]. It has been shown [10] that an antagonistic pair of hardening springs can create either a linear, hardening or softening joint depending on the spring’s curvature. This is also true for a softening spring. Therefore, either a hardening spring or a softening spring can be used in this design.

The two main springs studied were the belleville washer and rubber tubing. Both of these act as softening springs that produce a hardening joint. It was determined that although the belleville washers have ideal spring force and stiffness characteristics, there is too much friction between the washers, creating a much higher spring force than originally calculated. This causes problems with the motor’s ability to deflect the spring. The rubber tubing was chosen and rather than one very thick tube, ten 5 cm lengths of blue Thera-Band tubing are used to create an arm stiffness within the required range.

The radii of the two remaining pulleys were determined to create the desired total gear ratio required to move the arm through 135° in 1.2 s. The elbow pulley radius is 0.035 m while the worm gear pulley radius is 0.0144 m. The system is powered by a 14.4 V, 4500 mAh NiMH rechargable battery.

Figure 2: Bench top prototype - motor, transmission and spring
PROTOTYPE PERFORMANCE

Testing has shown that the prototype works as expected and agrees with the Matlab simulations. Notable differences are higher current and friction which caused the simulation to be optimistic with arm speeds. The differences can also be attributed to inconsistencies in spring length, motor parameters, unmodelled electrical connections and drive friction.

The arm’s performance when lifting the 2 kg load was 1.42 s for the full range of flexion. This is very close to the design goal of 1.2 s. The test speed was slower than the simulation for the stiffness change. The motors could not handle the load of the springs at the fully stretched length and gradually slowed to a stop. A spring with a lower overall force would solve this problem.

Both the simulation and the tests showed a relatively constant stiffness can be maintained during a position change. The stiffness increased a small amount during the task due to the spring force and a speed difference was evident between the two uncontrolled motors. This happened because a higher spring force (which occurs at a lower stiffness) puts more torque on the motor. In the agonist motor’s case, this causes it to slow down. For the antagonist motor, however, the force pulls the same direction as the motor is turning, which decreases the work required by the motor, decreases friction in the transmission and allows the motor to turn faster. Upon reaching a new equilibrium, the arm stiffness is slightly higher because, overall, both springs have a decreased deflection value. This increase is higher for a lower initial arm stiffness, which gives a higher internal spring force.
CONCLUSIONS AND RECOMMENDATIONS

The performance of the resulting prototype agrees with a mathematically modeled simulation and also is comparable to currently available upper arm prostheses. This prototype will be used as a bench model to test new actuators and springs as well as different control methods. The size and weight must also be reduced to create a wearable prosthesis.

REFERENCES


Figure 4: Stiffness change simulation results