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PROGRESS TOWARDS A BIOMIMETIC PROSTHETIC ARM

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ABSTRACT

Detailed design of a prototype prosthetic limb based on biomimetic principles has been completed. This paper will update the progress that has been made toward the creation of a new, high-performance limb. The limb uses antagonistic actuators with low and variable stiffness to create dynamics and interaction properties similar to those of a healthy arm. Theoretical examination of the mechanical design has yielded several interesting results and an accurate estimate of the performance and improved efficiency levels of the limb. The results have been used to understand several fundamental issues regarding the design of such a limb. Prototype construction is underway and reflects overcoming several design challenges by careful use of standard components.

BACKGROUND

Biomimetic design of a prosthetic limb involves the use of natural limb properties to inspire the configuration and design of the prosthesis. One of the major long term hypotheses to be tested with this design approach is that both ease of use and ease of training will be greatly improved due to the inherent similarities between a biomimetic prosthesis and a natural limb.

The basic concept [1,2] behind this design is to use to antagonistic, low and variable stiffness actuators in the prosthetic limb (See Figure 1). Once built, the limb is to be controlled using myoelectric inputs from two antagonistic muscles, nominally, the biceps and triceps muscles. However, many challenges concerning the mechanical design of the limb have been discovered. This paper summarizes a number of these challenges and their solution.

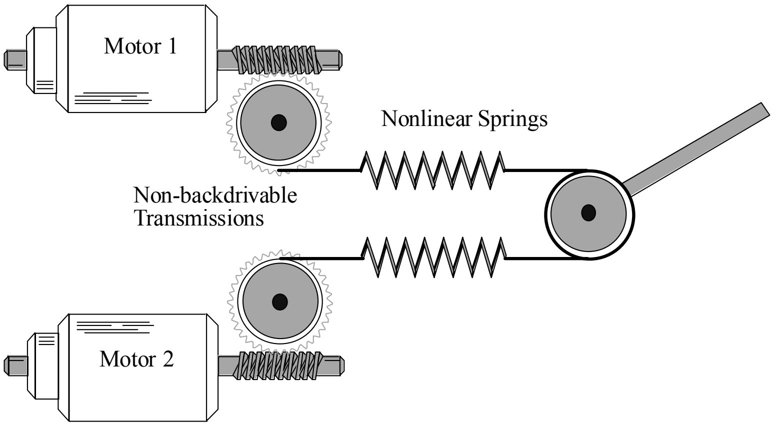

Figure 1. Limb Configuration

Basic Function

Before describing the details of the design issues, a basic description of the operation of the limb is in order. To flex the limb, both motors move so that the limb rotates and that the lengths of the springs remain unchanged. The springs allow the limb to absorb impacts. Static loads

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can be supported without energy input since when the motors are not active the gears cannot turn (non-backdrivable). Any load applied to the limb in this situation causes the limb to move from its equilibrium position by an amount dependent on the total joint stiffness. To change the net stiffness of the limb, the actuators both turn in a direction that lengthens or shortens both springs without changing the equilibrium position of the limb.

ACTUATOR SYSTEM DESIGN ISSUES

Motor/ Gear Selection

As this design approach makes use of a self-locking or non-backdrivable transmission, new techniques are required to understand and optimize the efficiency of the motor and transmission. A graphical technique has been developed [3] that not only allows a clear description of the motor dynamics when the transmission is locked or unlocked but also clarifies the transition between these two states.

The main limitation on the selection of the motor is shown on the figure as the Maximum Thermal Current Range. Also clearly shown is the operating condition of the motor, that is, whether it is performing as a motor (delivering power) or as a generator (absorbing power).

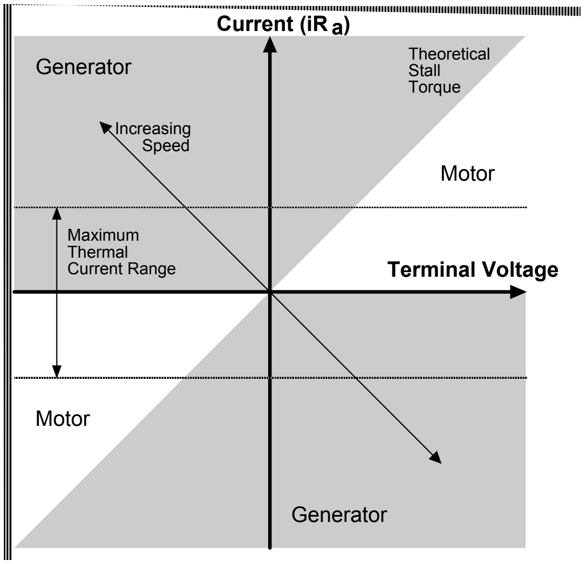

Figure 2: Motor / Transmission Selection

Efficiency

In previous work [3] rough estimates of improvements in efficiency that result from allowing the amputee to choose a stiffness that allows improved interaction with constraints were found to approximately 20 fold in extreme cases. In recent work [4,5] a figure of merit has been developed to clarify certain tradeoffs that appear when a non-backdrivable transmission is used. The principle tradeoff arises from the fact that non-backdrivability arises from increased friction in the gear train. This means that there are more losses during movement despite the improvements in supporting a static load. The figure of merit (Equation 1) is the ratio of the time spent in performing static tasks to the time spent in dynamic movements.

$$\frac{\Delta t_s}{\Delta t_k} = \frac{\omega_w K_t^2 g_h^2 G e_w\big|_{Static}^2}{\tau_G R_a}\left(\frac{1}{e_w} - 1\right) \qquad (1)$$

In this equation, R_a is the resistance in the moor armature, $\square_G$ is the torque required to support the load, K_t is the motor torque constant, g_h is the motor gearhead ratio, G is the gear ratio of the worm and gear set, $e_w|_{static}$ is the static efficiency of the gear set and defined based on the gear tooth geometry and the coefficient of static friction between the gear teeth, e_w is the dynamic efficiency of the gear set and w_w is the speed of the worm gear.

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For the design under consideration and typical working conditions, □$_W$ ~ 275 rad/s, K_t = 0.0075 Nm/A, g_h = 5.75, G = 20, R_a = 0.19 □e□|$_{Static}$ = 0.4193 and e□= 0.4911, this ratio is

$$\frac{\Delta t_s}{\Delta t_k} = 1.93 \tag{2}$$

Therefore in this analysis, if the arm spends 1.93 times more time in static load support than in motion, the non-backdrivable approach, and other energetic issues are not considered (such as the ability to efficiently interact with constraints) the non-backdrivable approach should be used.

CONTROLLER ISSUES

Stiffness Description

The ability to specify the stiffness of the limb assumes that the behaviour of the stiffness is well understood. [6,7] In a biomimetic design the input signals are assumed to be as they would have been for a healthy limb. Figure 3 shows a schematic, simplified representation of the stiffnesses present in such a limb. We have developed techniques to assess the impact of the missing two-joint muscles in that are missing after an above elbow amputation. Techniques for describing the limitations due to this absence are developed and various possibilities of compensating for the missing stiffness are being investigated. One important impact of the missing stiffness is the change in stiffness that occurs during interaction with a constraint.

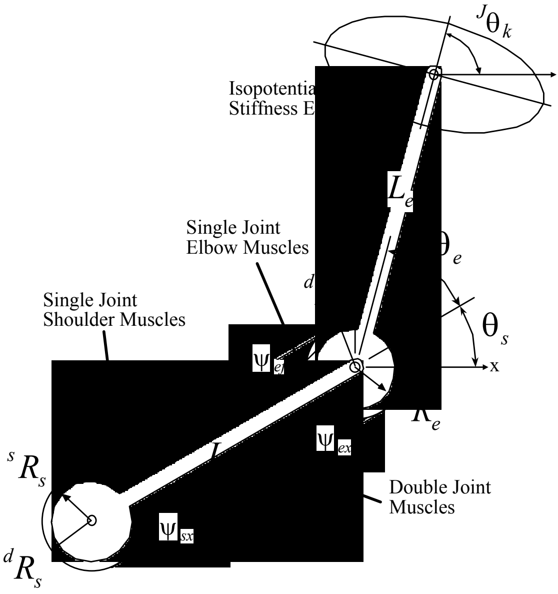

Figure 3. Stiffness Relationships

CONCLUSIONS – REMAINING WORK

A prototype is being designed and constructed based on the techniques and approaches outlined in this paper. Several control schemes are under consideration and on completion of the prototype it will be possible to assess the impact of this design on issues such as ease of interaction, the benefits of controlling stiffness and simplified training and ease of use requirements.

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