Presented at the IEEE Biomedical Circuits and Systems Conference (BIOCAS), 2008, Baltimore, MD.

Robotic Biarticulate Muscle Leg Model

M. Anthony Lewis and Theresa J. Klein
Department of Electrical and Computer Engineering
University of Arizona
Tucson, USA
malewis@ece.arizona.edu

***Abstract*—The construction of a new robot model of the human lower limb system. The robot features biarticulate muscle-actuators, or actuators that span more than one joint. The transfer of power from proximal to distal segments is demonstrated. The timing between biarticulate muscles and monoarticulate muscles appears critical in maximizing peak power output.**

I. INTRODUCTION

How does the nervous system coordinate the control of the many muscles of the human body? The human body has about 244 kinematic degrees of freedom (DOF) controlled by a minimum of 630 muscles [1]. This large degree of freedom system if complicated by the fact that many muscles are *biarticulate*, that is, they act on more than one joint simultaneously. Biomechanically, these muscles have been ascribed a function of transferring energy from proximal to distal limb lower limb segment and to shock absorbency. Further, the control problem is ill-posed an infinite number of muscle activations could give rise to the same movements.

We have begun the construction of a neurorobotic simulation of he lower limb systems of humans in order study the relationship between neuronal networks responsible for control of movement and the complex musculo-skeletal system.

This article report on initial progress in the construction of this system. Some of the material presented here has appeared previously[2].

II. BIARTIULATE MUSCLES

Many muscles in the human body are biarticulate. The Gastrocnemius muscle attaches to the femur (the thigh bone) and the back of the heel as one of the muscles acting on the ankle joint. See Fig. 1. Thus, the GA spans two joints, the knee and the ankle. The GA muscle is assisted by the soleus (SO) and is opposed by the tibialis anterior (TA), both acting around the ankle alone. The ankle has one more major muscle than is needed in pitch.

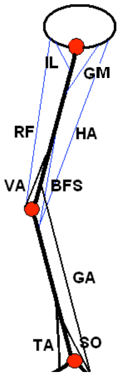

Figure 1. Model of the human leg. TA is tibialis anterior, SO is soleus, GA is gastrocnemius, VA is Vatus lateralus, RF is rectus femoris, BFS is short head of biceps femoris, HA is two-joint hamstrings, GM is gluteus maximus, and IL is iliacus. Redrawn from [*1*].

The GA assists in transmitting power from the thigh to the ankle. As the knee is rotated, the GA can allow the muscles acting on the knee to do work on the ankle. The knee is extended by the muscles including the rectus femoris (RF), itself a biarticulate muscle anchored to the hip and knee and the vatus lateralis (VL) acting on the femur and knee. Finally, the Gluteus Maximus (GM), assists in extended the hip femur. This leads to chain of energy transfer: **Gluteus Maximus->Rectus Femoris-> Gastrocnemius-> Ankle.**

Power transmission and shock absorption via biarticulate muscles has been documented in humans [3]. While these properties are remarkable, biarticulate muscles are not used in walking machines, with at least one exception [4, 5].

III. MAMMALIAN LEG MUSCLE ARCHITECTURE

The human leg can be modeled as a system of three parallel joints (hip, knee, and ankle) and nine muscle actuators (See Figure 1.) The muscles include three biarticulate muscles: the GA, which spans the knee and ankle, the RF, and the HA, which both span the hip and knee. The leg uses an agonist/antagonist, or flexor/extensor design with regard to monoarticulate muscles. Extensor muscles are used to support the body weight of the robot against gravity. Flexor muscles are used to lift the limb. The flexor muscles are generally much smaller than the extensor muscles.

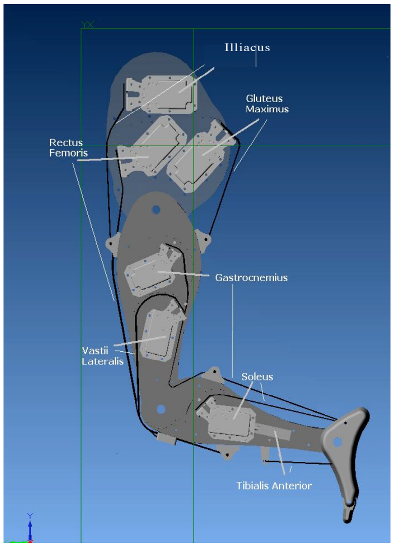

Figure 2. Actuator architecture of robot leg. Shown above is a cut away view of the robot limb. High performance modular motors pull on Kevlar straps to activate the joints. Biarticulate actuators are: Gastrocnemius and Rectus Femoris. Hamstrings are not implemented here.

Monoarticulate muscles on the ankle include the TA, which flexes the foot, and the SO, which in conjunction with the GA, extends the foot. The knee is extended by the VA, while the BFS helps flex the knee. The GM holds the hip upright, while the Illiacus (IL) flexes the hip.

In human beings it has been demonstrated that knee extensors generated significantly more force than the knee flexor [8]. An even more dramatic example is of the ankle flexor versus extensor.

In humans, the cross sectional area (CSA) of various muscles have been measured. While the particular configuration of the muscle (e.g. Pennation angle) can affect the force generating capability of muscle, we note that muscles such as the VL and SO have a much greater CSA than muscles such as biarticulate GA and RF [9]. This implies that the monoarticulate extensor muscles must produce more force. Moreover it suggests that implementation of a robot based on human leg muscle architecture can be done using smaller motors for the flexor and biarticulate muscles, thus reducing the weight penalty for using multiple motors for each joint.

IV. IMPLEMENTATION OF DESIGN CONCEPTS

We implemented these ideas in an human-like leg, with pin joints at the hips, knees and ankles. Each joint is actuated by a combination of actuators designed to mimic the mechanics of muscles. The following muscles were modeled: GA, TA, SO, VA, RF, IL and GM (the HA and BFS were not modeled).

The toe was modeled as a passive joint. An elastic cord is used to straighten the toe. The use of a toe proves the robot with the ability to 'stand on tip-toes.' The distances and proportions of the limb segments were based on human anthropometric data [9].

A. Actuators

The actuators were composed of stiff Kevlar strap connected to a motor. The straps were affixed to a mounting bracket that pulls and releases the strap in one direction. We have selected Robotis RX-28 motors for the combination of force and compactness for the GA, SO and VA muscles and a Futaba S3150 for the TA muscle. Robotis RX-64 are used for the HS, RF and IL.

We used an agonist/antagonist muscle configuration. This type of actuation allows the motor to pull but not push, similar to muscle action. As an example, we modeled the TA with one motor placed in the calf and connected by a Kevlar flat strap from it to the front of the foot. The SO was modeled by connecting a flat strap between the rear of the foot and the calf. The dual strap also permit joints to be "stiffened" by applying force to both sides, which assists in leg stabilization during foot touch down.

Figure 2 shows a 3D CAD drawing of the leg design, including motor positions and Kevlar straps running down the front and back of the leg. Figure 3 shows photos of the completed leg as constructed.

B. Sensors

Angle sensing pots (Murata SV01A103) are used to measure joint angles of the foot, knee and hip. Each sensor was calibrated in radians by comparing the voltage output versus a known angular reference. We found the pots to be highly linear. At the attachment point of the straps with the motors, we designed a custom made force sensor. This sensor is based on a Futek FSH01463 Force gage. The assembly was mounted between the motor bracket and the strap. As force is exerted by the strap, this force is measured by the gage. Finally, we used a load cell to measure tension at the Achilles' tendon (both the SO and GA act on the ankle via the Achilles' tendon). The model number of the Achilles' tendon load cell was unknown.

V. WORK AND PEAK POWER AT THE ROBOT ANKLE

A. Work Transfer

Work produced by a rotational torque can be written in time-discrete form as:

$$W = \sum \vec{\tau} * \Delta\vec{\theta}$$

The torque at the ankle is given by:

$$\tau_{Ankle} = -\tau_{TA} - \tau_{GN} - \tau_{SO}$$

$\tau_{TA}, \tau_{GN}, \tau_{SO}$ are torques produced by the TA,GN and SO respectively. Multiplying by the angular displacement, in radians, of the joint we have the net work at the ankle:

$$W_{Ankle} = \Delta\theta_{Ankle}\tau_{Ankle} = -\Delta\theta_{Ankle}\tau_{TA} + \Delta\theta_{Ankle}\tau_{GN} + \Delta\theta_{Ankle}\tau_{SO}$$

$$W_{Ankle} = -W_{TA} + W_{SO} + W_{GN}$$

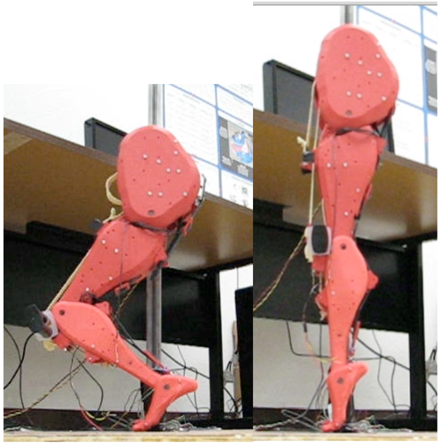

Figure 3. Bent knee squat. This configuration was used to measure the contribution of SO and GA to the ankle power as well as to analyze the effect of SO and GA activation timing on peak power production.

where W_{TA}, W_{SO}, W_{GN} is the work contribution by the TA,SO and GN respectively.

Likewise, for the knee:

$$W_{Knee} = W_{VL} + W_{RF} - W_{GN} - W_{BFS} - W_{HA}$$

In the simplified case of activating the extensors alone:

$$W_{Ankle} = W_{GN} + W_{SO}$$

$$W_{GN} = W_{VL} + W_{RF} - W_{Knee}$$

Substituting:

$$W_{Ankle} = W_{SO} + W_{VL} + W_{RF} - W_{Knee}$$

Because muscles pull, but cannot push we note $W_{SO} \geq 0$, $W_{GN} \geq 0$ and thus $W_{VL} + W_{RF} - W_{Knee} \geq 0$. Hence the work contribution of the upper leg and the lower limb sum together when the GA is active; the work done on the ankle is greater than just the SO alone. We conclude that the work done at the ankle on the environment is assisted by the RF and the VL.

Note, it is critical that an actuator be cable of pulling and not pushing. If the GA could push, it would be possible for the upper leg to take energy away from the ankle. Thus, a stiff rod connection between actuator and joint cannot be used, for example, if we are to adhere to biological principles.

VI. METHODS

During the following experiments, the robot was commanded to do a weight lifter's 'squat.' The timing of the SO versus GN was varied as was the activation of the SO or GN. Simultaneous measurements were made of the potentiometer and the force gage using a PICO Scope (Model 5203). The sampling rate was 100K Hz.

Next the change in distance at the ankle attachment point was computed using the following formula: $\Delta x = r * \Delta\theta$ where r is the moment arm from the ankle rotation axis to the ankle attachment point of the Achilles' tendon in units meters (0.0023 meters) and θ is the angular measurement of the ankle in radians.

Combining the displacement in meters and force in Newtons we can integrate the measurement to compute work. Power is the time derivative of work. We can compute the instantaneous power at the ankle by: $P = {}^{\Delta x}\!/_{\Delta T} * F$.

VII. EXPERIMENTS

In the following experiments, the robot was constrained by a vertical rod to control balance. We confirmed that measurement of the work done at the ankle reflected the actual work. This was done by calculating total work in two ways: (1) By the ankle torque method described above and by calculation of the work done by elevating the center of mass of the robot during a calf-raise movement. In particular, we calculated work done at the ankle as 0.433 Joules and the work done by elevating the center of mass as 0.41 joules, the difference being about 4%.

A. *Contributions of SO and GA to ankle work and power*

In experiment 1 examined the work and power output of the ankle from a bent knee squat. The starting configuration of the robot was toes directly under the hip (Fig. 3a). The robot was then command to extend fully from a squat (Fig 3b). We varied the following conditions: (1) SO activation, GA relaxed, (2) GA activation, SO relaxed, (3) Both activated together. We then computed both work versus time and power versus time.

In Figure 4 we see that more work is done in the ankle when both SO and GA are activated versus when either SO or GA is activated alone. Further, we note that the GA delivers more power to the ankle than the SO. In this particular experiment, we use a delay between the GA activation and SO activation of 300 ms.

B. *Variation in Timing of SO Activation and GA activation*

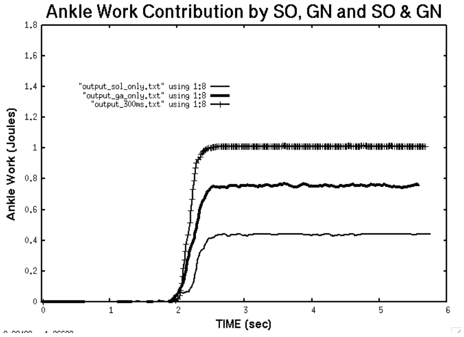

Figure 4. Ankle work done by SO, GA and both SO and GA together during return from squat.

The relative timing of the SO and GA activation in humans has been measured and it was found that the GA activation preceded SO activation [9, 10]. We compared the case of both SO and GA activation with SO activation at the following delays: 0ms, 50ms, 100ms, 150ms, 200ms, 250ms, 300ms 350ms 450ms.

Similar to experiment 1, we computed the work and power done at the hip. We summarize these results be showing the peak work and peak power versus GA-SO delay.

Figure 5 shows the results. As can be seen, at no delay, the peak power output is 3.4 watts. At 350ms the peak output rises to 6.1 watts an 80% increase in power.

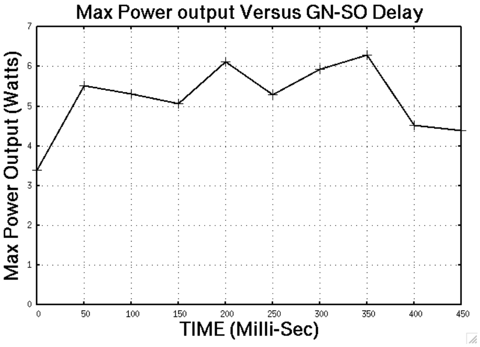

Figure 5. Max power at ankle versus delay between GA activation and SO activation.

We also analyzed the total work done under each delay. We found that variation seemed insignificant. The peak work may have declined about (approximately 10%) at greater delays. In future work we will try to determine if this effect is meaningful.

Redundant biarticulate muscles are an essential part of biological walking systems. We have presented preliminary work in the construction of a lower limb that exploits the use of biarticulate muscles. We showed that the upper leg should contribute to ankle work and peak power. Through experimentation we confirmed this results. We also observed that in humans, the activation of the SO is significantly delayed from the activation of the GA. We found in our robot that a delay of 350 ms yielded a higher peak power output. Finally, we demonstrated analytically

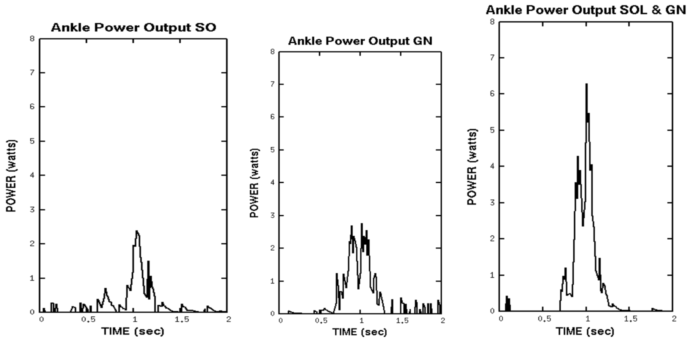

Figure 6. Power versus time at ankle during return from squat. (A) SO alone, (B) GA alone (C) Sol and GA.

References

[1] B. I. Prilutsky and V. M. Zatsiorsky, "Optimization-Based Models of Muscle Coordination," *Exercise and Sport Sciences Reviews,* vol. 1, pp. 32-8, 2002.

[2] T. J. Klein, T. M. Pham, and M. A. Lewis, "On the design of walking machines using biarticulate actuators," in *CLAWAR*, 2008.

[3] B. I. Prilutsky and V. M. Zatsiorsky, "Tendon Action of Two-Joint Muscles: Transfer of Mechanical Energy Between Joints during Jumping, Landing, and Running," *J. Biomechanics,* vol. 27, pp. 25-34, 1994.

[4] A. Arampatzis, A. Knicker, V. Metzler, and G.-P. Brüggemann, "Mechanical Power in Running: A Comparison of Different Approaches," *J. of Biomechanics,* vol. 33, pp. 457-463, 2000.

[5] R. Jacobs, "Biologically-Inspired multi-segmented robot," USPTO, Ed. USA: Intelligent Inference Systems corporation, 2003.

[6] Y. Sakagami, R. Watanabe, C. Aoyama, S. Matsunaga, N. Higaki, and K. Fujimura, "The intelligent ASIMO: System overview and integration," in *IEEE/RSJ International Conference on Intelligent Robots and Systems*, Lausanne, Switzerland, 2002.

[7] Y. Nakanishi, Y. Namiki, J. Urata, I. Mizuuchi, and M. Inaba, "Design of Tendon Driven Humanoid's Lower Body Equipped with Redundant and High-Powered Actuators," in *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)* San Diego: 2007.

[8] M. V. Narici, G. S. Roi, and L. Landoni, " Force of knee extensor an flexor muscles and cross-sectional area determined by nuclear magnetic resonance imaging," *European journal of applied physiology and occupational physiology,* vol. 57, 1988.

[9] D. A. Winter, *Biomechanics and Motor Control of Human Movement.* New York: John Wiley & Sons, Inc., 1990.

[10] Y. Ivanenko, R. Poppele, and F. Lacquaniti, "Five basic muscle activation patterns account for muscle activity during human locomotion " The Journal Of Physiology, vol. 87, pp. 3070-3089, 2004.