From Swimming to Walking: Examples of How Biology is helping us Design Better Machines

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Abstract: Three biomimetic machines are presented: an external knee prosthesis, a bipedal robot, and a robotic fish. Here we demonstrate how models of biological movement and actuators that perform like muscle can enhance machine stability, efficiency and dynamic cosmesis. Ideas addressed in the paper include the use of muscle tissue for machine actuation, and how biological models can serve as virtual control elements for the stabilization of bipedal walking machines.

1 Introduction

A long standing goal in engineering is to exploit the unique designs of biological systems to guide the development of autonomous biomimetic machines that exhibit agility, strength and speed in a variety of natural environments. Most critical to this effort is the development of actuator technologies that behave like muscle and control methodologies that exploit principles of animal movement. In this paper, three autonomous biomimetic machines are discussed. First, an external knee prosthesis used by trans-femoral (above-knee) amputees is presented in which biological data are used as desired targets in an auto-adaptive control scheme. Using only local mechanical sensing, the prosthesis automatically adjusts knee damping levels for each phase of walking without any parameter tuning required by a prosthetist. Computer controlled prosthetic knees currently on the market, such as the Otto Bock C-LEG, are not patient adaptive and therefore require a prosthetist to define knee damping levels (Dietl and Bargehr, 1997; Kastner et al., 1998). In a second biomimetic machine, biological models used to characterize human walking are employed as virtual control elements in the Virtual Model Control Language for legged machine stabilization (Pratt et al., 1997). This overall strategy is comparable to that developed by Raibert for quadrupedal running in which a virtual compliant leg dictates the movements of a physical quadrupedal machine (Raibert, 1985). Lastly, a third biomimetic machine is presented in which animal-derived muscle tissue is used to power swimming motions in a robotic fish. Here loop electrodes are used to depolarize the muscle actuators and to control swimming undulations, and chemical, electromechanical and genetic interventions are employed to enhance muscle contractility and robustness *in vitro*.

2 An Auto-Adaptive Knee Prosthesis

In order for a trans-femoral amputee to walk in a variety of circumstances, a prosthetic knee must provide stance control to limit buckling when weight is applied to the prosthesis. In addition, it must provide aerial swing control so that the knee reaches full extension just before heel strike in a smooth but timely manner. Unlike a biological knee, an autonomous prosthetic knee must accomplish both stance and swing control without direct knowledge of its user's intent or of the environment. Rather, such a prosthetic knee must infer whether its user desires stance or swing behavior and predict when future stance/swing transitions should occur. The knee must also determine when dramatic changes occur in the environment, as for example, when an amputee decides to lift a suitcase or walk down a slope.

A prosthetic knee must not only be safe to use, but should also help the patient walk in a smooth and non-pathological manner. Conventional prosthetic knees often force the amputee to walk with an awkward gait. As an example many prosthetic knees lock up during ground contact, not allowing the amputee to go through normal knee flexion and extension motions found in early stance (Gard, 1999). The amputee is therefore forced to roll over a perfectly straight leg, resulting in large vertical fluctuations in the amputee's center of mass and diminished shock absorption.

Using state-of-the-art prosthetic knee technology, a prosthetist must pre-program knee damping levels until a knee is comfortable, moves naturally, and is safe (Dietl and Bargehr, 1997; Kastner et al., 1998). However, these adjustments are not guided by biological gait data, and therefore, knee damping may not be set to ideal values, resulting in the possibility of undesirable gait movements. Still further, in such a system knee damping levels may not adapt properly in response to environmental disturbances. The knee prosthesis presented here automatically adapts to the amputee, accounting for variations in both forward speed and body size, without pre-programmed information of any kind from either amputee or prosthetist. With this technology, knee damping is modulated about a single rotary axis using a combination of magnetorheological and frictional effects, and only local mechanical sensing of axial force, sagittal plane torque, and knee position are employed as control inputs. With every step, the controller, using axial force information, automatically adjusts early stance damping. When an amputee lifts a suitcase or carries a backpack, damping levels are

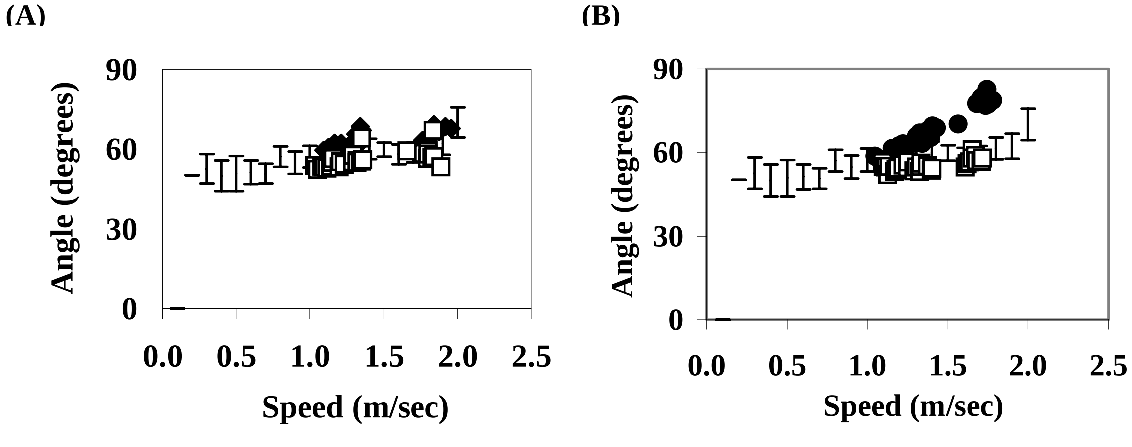

Fig. 1: Peak flexion angle during the swing phase versus walking speed is shown for one subject using the auto-adaptive knee (plot A, filled triangles) and a mechanical knee (plot B, filled circles). In (A) and (B), the subject’s sound side leg is shown (open squares), along with reference data from unimpaired walkers of comparable height and body size (error bars). In (A), peak flexion angle is consistent with biological data, but in (B) the peak angle increases with increasing speed.

increased to compensate for the added load on the prosthesis. With measurements of foot contact time, the controller also estimates forward speed and modulates swing phase flexion and extension damping profiles to achieve dynamic cosmesis throughout each walking swing phase. Overall, the adaptation scheme successfully controls early stance damping, swing phase peak flexion angle (Fig. 1) and extension damping, suggesting that local sensing and computation are all that is required for an amputee to walk in a safe, comfortable and natural manner.

3 Models of animal movement applied to bipedal walking machines

Despite a vast literature on legged locomotion, it is not fully understood how human walking is controlled or how robots can be made to achieve humanlike walking. Here our broad aims are (a) to test biological models of limb mechanics and control, and (b) to use these models to develop robust control schemes for walking robots and rehabilitation devices such as orthotic and prosthetic leg systems. In addition to technological innovation, such an integrative approach may lead to a better understanding of the control mechanisms that determine gait performance. In this paper, we report progress toward our goal of a control system for bipedal walking that learns from human demonstration.

The control described here is derived from motion data captured at Spaulding Rehabilitation gait laboratory in Boston, Massachusetts. To support this investigation, we have developed a 3-D, 12-degree-of-freedom model representing the legs and lower torso of a human. The model structure closely resembles the morphology of the human subjects from which motion data were collected. Thus, the motion data can be applied to the model to obtain forces via inverse dynamics. The model can also be run in forward-dynamics mode to test the control system. The control is described in terms of virtual model components (Pratt et al., 1996). These components provide a high-level means of translating desired forces on parts of the model into commanded joint torques. It has been shown that a simple configuration of such components can achieve 2-D walking in a bipedal robot (Pratt et al., 1997). In this investigation, various virtual element architectures are evaluated in terms of their biological plausibility and their ability to produce humanlike walking. For example, the model's legs can be made to act as compliant spokes of a spinning wheel. In this scheme, which has similarities to those used recently for quadrupedal animal simulations (Herr and McMahon, 2000) and a hexapod robot (Saranli et al., 2000), the important control parameters are the mechanical impedances, tangential velocities, and swing periods of the legs. The motion data are analyzed to provide biological estimates of these parameters. For parameter tuning, a supervised learning architecture is employed. Inverse virtual components can convert joint-torque data from the motion capture into high-level force specifications corresponding to a reduced-order model. Supervised learning is used to learn the characteristics of this reduced-order model and thereby to achieve a form of learning from demonstration (Schaal, 1999), where the demonstration consists of the captured motion data.

The significance of this work is twofold. First, the model provides a framework for testing the roles of specific control mechanisms in the generation of walking behaviors, unlike previous models of walking mechanics (Cavagna, 1977; Mochon and McMahon, 1980). Second, a robust control based on demonstration may prove useful for the control of biologically realistic robots such as the 3-D humanoid walking robot M2 developed in the Leg Laboratory at MIT.

4 Toward the future: actin-myosin machines

Muscle is employed almost exclusively by animals for actuation, from sub-millimeter organisms to blue whales. Using muscle to power movement has certain advantages. Muscle generates force quietly, allowing predators to move within close proximity of prey. Muscle is also adaptive and responds to varying work loads by modulating its structure to meet specific task demands. Still further, muscle is efficient. Working aerobically, muscle can generate up to 4000kJ of work from just 1 Kg of glucose (Woledge, 1985). And for its size, muscle can generate a large isometric force, enabling the extremities of organisms to be lightweight but strong.

Although important research has been conducted to advance actuator function, engineering science has not yet produced an effective artificial muscle in terms of quietness, adaptiveness, robustness, power density, transduction efficiency, and bandwidth. As an example, polymer gels provide stresses and displacements comparable to muscle, but their contractile velocity is often too slow for many applications (Tatara, 1987; Suzuki, 1991). Here we investigate the feasibility of using animal-derived muscle as an actuator for robotic applications in the millimeter to centimeter size scale.

Perhaps researchers in the past did not consider muscle a viable actuator because of tissue robustness problems. It is true that native whole muscle, once extracted from an animal, only retains contractility for several days using standard organ culture techniques (Harris and Miledi, 1972; McDonagh, 1984). However, recent advances in biology suggest that enhancing tissue robustness *in vitro* may now be an achievable goal. Preliminary experiments by Rosenthal and collaborators at Massachusetts General Hospital suggest that IGF-I genetic interventions (Fig. 2) may improve muscle contractility and robustness. IGF-I genetic manipulations have been shown to enhance the tetanic force of native wildtype muscle by as much as 25 percent (Barton et. al, 1998). There is also preliminary evidence that these interventions promote cell differentiation and robustness in cultured tissues grown from transgenic mice.

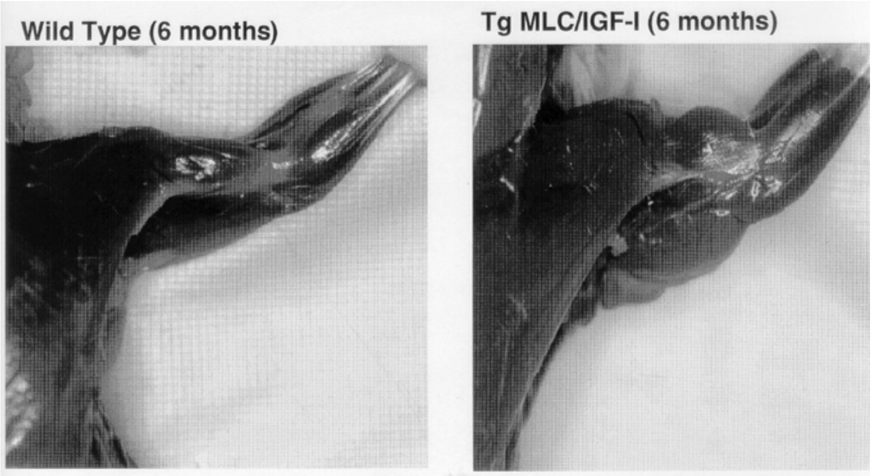

Fig. 2: The forelimb of a wildtype mouse (left) and a genetically-modified mouse (right) are shown. The pronounced muscular hypertrophy in the transgenic animal is the result of locally-acting IGF-I.

In addition to IGF-I, we are also investigating chemical, electromechanical and temperature interventions that promote tissue robustness *in vitro*. In this investigation, two types of muscle are being examined: native and cultured tissues from genetically-modified mice (Fig.2) and native whole muscle from non-mammalian sources such as marine invertebrates.

Once engineered, the contractility and robustness of these tissues are characterized and comparisons are made to current artificial muscle technologies.

Hybrid robotic fish, part synthetic and part living tissue, are also being developed to investigate control and sensing strategies for muscle actuators. These robots, or actin-myosin machines, are fueled by glucose. To elicit contractions, a small battery and stimulation system is used to depolarize each muscle membrane. With these robots simple control actions are possible, such as forward linear swimming and rudimentary turning movements.

A muscle actuator may offer certain advantages over contemporary motor technologies. As with real muscle, an engineered muscle could offer a transduction efficiency far superior to that of electric motors, or shape memory alloys, powered by battery or fuel cell. Although high efficiencies can be achieved from gasoline engines, stealth quietness cannot; gas powered autonomous robots are noisy and produce environmentally unfriendly biproducts. In distinction, engineered muscle generates force quietly with biodegradable biproducts. Finally, there remains the possibility of manufacturing engineered muscle at low cost. Starting from the cells of an animal, it may be possible to grow hundreds of actuators.

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