Bio-Inspired Tendon-driven Robotic Limbs

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1 Why build tendon-driven limbs?

Biorobotics has a two-fold goal: (i) to create versatile bio-inspired robots and (ii) to shed light on the neuromechanical properties of animals that grant them their enviable mechanical performance. In contrast to traditional'torque driven' robotics, the book *Fundamentals of Neuromechanics* [1] discusses the function of tendon driven robots which are simultaneously (i) *redundant* (i.e. n+1 actuators, n.- degrees of freedom) and (ii) *over-determined* (i.e. vertebrate limbs use sensorized backdriveable linear actuators that resist stretch in a context-dependent way). We emphasize the construction of tendon-driven robotic limbs to exploit these neuromechanical properties for robots and advance neuroscience research. Here we present two examples.

2 Model-1 robotic leg/finger

Model-1 has been used in isolation for locomotion in hardware ([2] Figure 1-A,B) and simulation [3], as an ensemble on a quadrupedal structure (Figure 1-C) and for hand manipulation [4]. Its design is useful to mimic the mechanical function of musculoskeletal systems who's movements depend on muscles contracting and relaxing to allow joints to flex and extend. As per [1], this design has the minimal number of actuators $(n+1)$ that, when well-routed, can control n kinematic degrees-of-freedom (DoFs). This robotic leg is controllable (i.e, versatile) since it can generate forces with its foot in all directions in its workspace (i.e., its feasible force set expands to all directions on the plane of movement, regardless of the posture) (Figure 1-A). We use the term feasible "force" set, instead of feasible "wrench" set, since this is a representation case of a planar force (f) only containing fx and fy, no torque components. The feasible wrench set and space are respectively calculated as follows:

$$H = [J^{-T}RF_0] \quad (1)$$

$$w = Ha \quad (2)$$

Where J is the limb Jacobian, R is the moment arm matrix, F_0 is the maximum force matrix that motors (i.e. muscles) can generate. In Equation 2, a is the neural activation space, this equation helps researchers explore the path between the neural input a and mechanical output H (Details in [1]). When mounted on a body, model-1 leg is a 2–DoF mechanism whose joints are distally actuated by three DC gearless motors pulling on stiff strings (i.e., backdrivable motors pulling on artificial tendons). Backdrivability allows the motors to move because of both: electrical and mechanical stimulation; the later due to interaction with the environment or action from other motors. Matching the high speed and accelerations of gearless backdrivable motors is a big challenge for control systems, making the position control of this model not simple, specially when compared to cases where motors with coupled encoders and reduction gearheads are used (e.g. servo motors). The bioinspired properties of this leg help on the production of the hybrid, intermittent dynamics of locomotion, as shown in [2, 3].

3 Model-2 robotic leg

Instead of having only active actuators, we are currently focusing on the design of a redundant backdrivable leg that also incorporates passive parallel and series elastic elements (e.g., [5–8])(Figure 2). While limb contraction is handled by a motor, extension happens thanks to a spring which will also work as a passive element that absorbs/releases energy. By reducing the number of actuators, processor resources will be freed for other tasks, like reading a high number of sensors. In contrast to the design of model-1 (Figure 1) which includes single actuators affecting more than one joint, model-2 design (Figure 2) has only one joint per actuator. This will enable us to apply and test (i) learning algorithms (e.g., G2P [2]) and/or (ii) control techniques like Hybrid Zero Dynamics which consider one actuator per degree of freedom [9]. For this design, we keep the motors close to the Center of Mass, keeping inertia low as for model-1 case. This model includes backdriveable Maxon DCX16S-GPX16 motors in spite of their 21:1 reduction ratio gearhead. Overall, the geared motors help us reduce motor rpm, increase torque, and keep backdrivability; all this pointing to a more stable and stronger robot.

4 Conclusions

Even though the model-1 leg/finger has been successfully used for locomotion and grasping experiments, the model-2 leg opens the possibility of scaling up a tendon-driven robotic system without greatly compromising weight, power and computational resources. Besides allowing motors to work at lower RPM and higher torques, model-2 in-

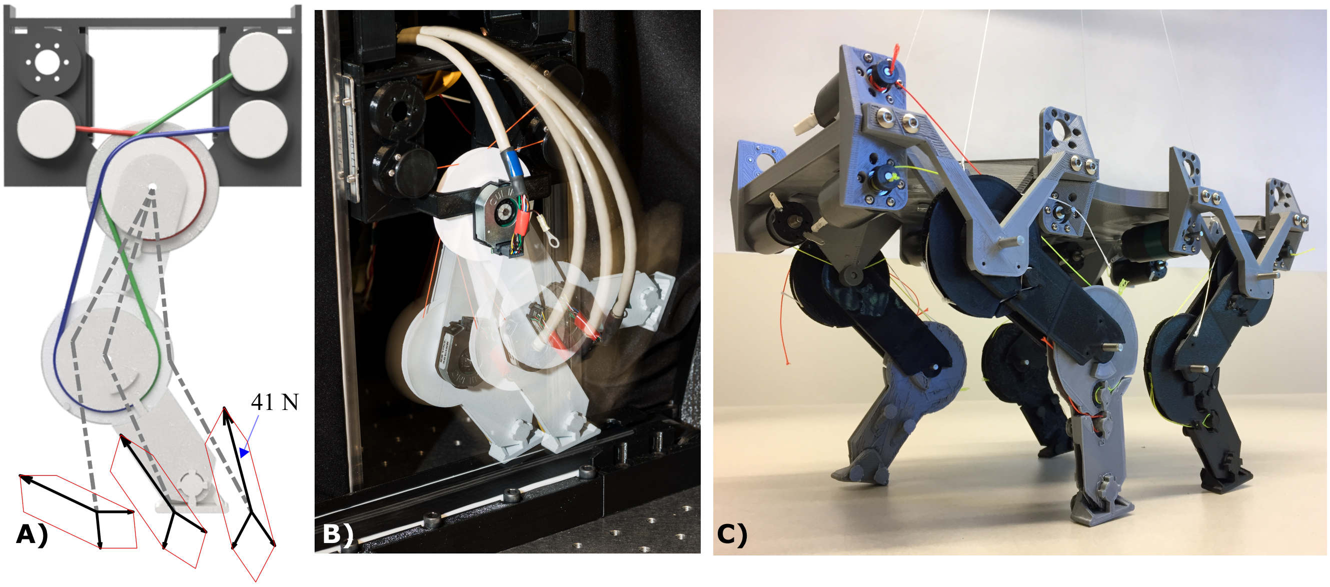

Figure 1: Model-1 of the robotic backdrivable tendon driven leg: **A)** Leg render with tendons shown in red, green and blue. Dotted line shows three different leg positions with red polygons showing the feasible force set of the leg in such positions. **B)** Leg performing cyclical movement to propel a treadmill [2]. **C)** Quadruped.

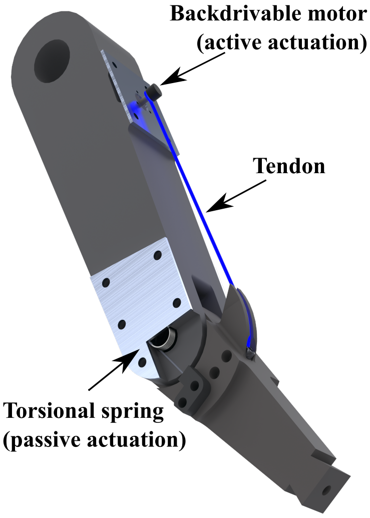

Figure 2: Model-2 of the robotic backdrivable tendon driven leg. It includes both: active (i.e. flexion) and passive (i.e. extension) actuation of the knee join.

cludes elastic passive elements that will help absorb mechanical energy intrinsic of the interaction with the environment. Both models are backdrivable and tendon driven, providing researchers with a tool to understand robotic and biological tendon-driven systems.

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