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Passively Stable Hopping of an Articulated Leg with a Tendon-Coupled Ankle

Paul J. Csonka, Alexander D. Perkins, and Kenneth J. Waldron

Abstract— **Dynamic maneuvers have been successfully implemented on many prismatic legged robots. Systems with articulated legs of significant relative mass pose more of a challenge in part due to the physics of thrusting with rotating limbs, which results in undesired non-vertical impulses, and in part due to the control problem of synchronizing ankle and knee joints. Presented here is an experimental articulated leg system that simplifies the control of an articulated monopod through the use of a joint-coupling tendon. The ankle is coupled to the thigh with an inelastic tendon, which causes automatic horizontal impulse compensation on liftoff for varying knee thrusts. Using a tendon-coupled ankle, stable sustained hopping is achieved for a fixed-torso monopod with a very simple control strategy, and with minimal hip actuator effort, while hopping in place is achieved for short time periods with a bipedal robot with freely pitching torso.**

I. Introduction

In medium and large legged biologic organisms capable of dynamic maneuvers, there is often a high degree of mechanical coupling between joints ([9]). This connection is achieved through tendons (sinews), which couple muscles in one location with joints in others. As an example, the *Gastrocnemius* muscle ([1]), and its associated tendon, spans from above the knee to the heel of a typical mammal.

Tendons have several purposes. First, they allow power transmission from the location of the muscle to the location of the joint. This is particularly useful in animals optimized for running, as it allows muscle mass to be stored closer to the hip joints, thereby lowering the effective inertia of the legs, allowing for faster leg swing and a lower energetic cost to running. Tendons are also elastic, with up to 10% strains ([1]), allowing for energy storage during a ground contact phases while running.

Finally, if a tendon spans more than one joint, it provides mechanical coupling between multiple joints, with the type of coupling depending on the routing of that tendon. This can simplify active control by offering more complex desired kinematic configurations with minimal control effort. The resulting phenomena is easily seen in humans: when the knee joint is straightened, it feels natural to point the toe, because a tendon stretches from the buttocks (*gluteus maximus*) to the ankle (*talocrural joint*) through a passage under the knee (*gyena*). When the knee is straightened, this tendon is placed under tension, causing the toe to point. This coupling is convenient for running, as it causes extension of all of the leg joints to occur somewhat automatically, making the required spring-off from the toe natural. These effects are perhaps most pronounced in the ostrich, which has nearly all of its muscle mass concentrated in its torso, and uses tendons to transmit force to the knee, ankle, and metatarso-phalangeal joints.

In the field of legged robotics, tendons have been incorporated on robots largely for their energy storage abilities ([2], [5]). One of the most difficult problems in achieving dynamic maneuvering in legged robots is delivering large amounts of controlled energy over the short stance time. By employing elastic tendons, a portion of the impact energy can be captured and redirected toward thrusting. However, to the authors' knowledge, inelastic tendons have not been employed to effect mechanical coupling between leg joints in dynamic robots. In this work, an inelastic tendon is used to couple the knee and ankle joints of a monopod hopper. As a result of this coupling, control of dynamic maneuvers is significantly simplified. Hardware experiments, backed by simulation, produce stable hopping along a two dimensional plane, using a control strategy that only controls the thrust timing, and does not need to control leg angle to remain stable.

II. Robotic System

A. Geometry

For the work presented here, the robotic system being studied is a single planar articulated leg, as shown in Fig. 1.

The leg is comprised of three segments: a thigh, a shank, and a foot. These segments are connected via co-axial revolute joints at the knee and ankle. The thigh is attached to a torso at the hip. This torso is free to translate in the vertical plane perpendicular to the joint axes, but cannot rotate. The leg is constructed with revolute joints rather than prismatic joints because revolute joints allow greater travel, a more compact retracted state, and are much less susceptible to binding ([6]).

B. Actuation

As with any robotic system, the actuation of the joints is as important as the geometry of the links. For a dynamic legged robotic system, there are two primary considerations for actuators: location and energy delivery rate. Location is important because actuators that are placed lower on the leg add significantly to the inertia of the leg, which in turn can reduce dynamic performance. To minimize leg inertia,

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P. Csonka and A. Perkins are with the Department of Mechanical Engineering, Stanford University, Stanford, CA 94403, USA pcsonka@stanford.edu

K. Waldron is with the Department of Mechanical Engineering, Stanford University, Stanford, CA 94403, USA, and the School of Electrical, Mechanical, and Mechatronic Systems, University of Technology Sydney, Sydney, NSW 2007, Australia

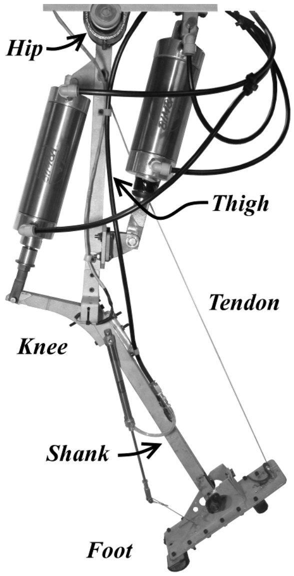

Fig. 1. The monopod hopper. A boom arm constrains the torso to the vertical plane.

all actuators should be placed in the torso, similar to how most of an ostrich's muscle mass is located in its torso. This results in a very low inertia leg, allowing the leg to be moved quickly with relatively little actuation effort. However, placing all of the actuation in the torso leads to complicated power transmission requirements; biologic systems are able to effectively actuate their knee, ankle, and metatarso-phalangeal joints via a complex array of tendons. While such sophistication is widely seen in nature, it is difficult to reproduce robustly via mechanical means. Thus, in a legged robotic system a compromise must be struck between leg inertia and power transmission complexity.

Additionally, actuator energy delivery rate is important in a legged robot, given that dynamic maneuvers require large amounts of energy to execute, all of which must be delivered during a stance period which often only lasts tens of milliseconds. Fortunately, given that running involves the exchange between kinetic and potential energy ([4]), there is also a large amount of impact energy which can be potentially captured to lower the demands on the actuators. Thus, when selecting actuators for a dynamic legged robot, consideration should be made toward high rate energy release and capabilities for energy capture.

1) Hip and Knee Actuation: The effect of the knee and hip actuators on leg inertia taken about the hip is much less pronounced than for the ankle actuator, since moment of inertia is a function of distance squared. Therefore, for the leg design presented here it is more important to simplify power transmission to the hip and the knee - and reduce the associated losses - at the expense of increasing the leg inertia. This leads to the design shown in Fig. 1, with the actuators for both the hip and the knee located such that they can immediately act on the members on either side of their respective joints. Previous simulation studies of articulated hopping have indicated that a large actuator at the knee is sufficient for all requisite energy addition ([7]). Therefore the primary thrusting actuator is used to drive the knee and a smaller secondary actuator is used to drive the hip.

Energy capture can easily achieved through the use of an elastic element. However, with added elasticity comes a loss of high precision control, which is often required for static maneuvers ([3]). In an effort to compromise between elasticity and controllability, pneumatic cylinders are used to actuate both the hip and the knee, as shown in Fig. 1.

2) Ankle Actuation: Any actuator collocated with the ankle will be quite distal from the torso, greatly increasing the leg inertia. Therefore, it is more important to relocate or eliminate the ankle actuator at the expense of complicated power transmission. However, the ankle is vital for stability ([7]), and as such pure passivity is less desirable. In order to eliminate the ankle actuator without leaving the ankle unactuated, and to create desirable passive stability, a tendon connects the heel of the foot to the thigh, thereby causing the toe to "point" as the knee straightens, as in does it humans. A tension spring is attached to the toe of the foot and the shank, preventing the toe from pointing except when forced by the tendon. In this configuration, ankle extension is affected by the knee cylinder, and flexion is affected by the tension spring. An overview of the tendon system is shown in Fig. 2.

If the tendon length is properly selected, this configuration has the advantage of creating a passively stabilized system, where perturbations of the leg in the forward or backward direction causes the leg to hop back to the center position. This passive stability is the real strength of the tendon-coupled knee and ankle.

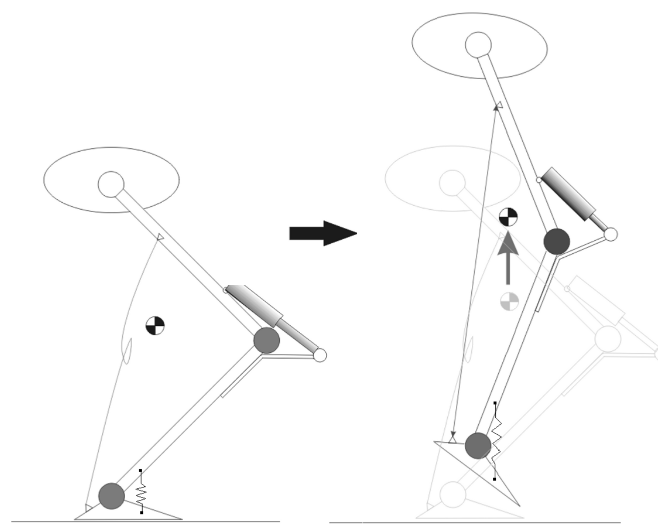

Fig. 2. Progression of the leg through a jump cycle. At the start of thrust, the tendon is still slack as in (a). If the tendon length is selected properly, at some point during the thrust phase the tendon will engage, and after leaving the ground the leg will jump vertically only as seen in (b).

C. Specifications

The robotic system being used in this work consists of a small torso and a leg with a thigh, shank, and foot. The hip is constrained to move in a vertical plane by means of a $3.5\,m$ aluminum boom. The total mass of the experimental system is $17\,kg$, and consists of the mass of the hopper, and the constraining boom arm. Approximately 50% of the system mass is in the legs. The majority of components are machined from aluminum of various grades. The primary structural elements of the legs are $45\,cm$ long square cross-section hollow tubing with $3.2\,mm$ wall thickness and $25\,mm$ width. To test the wider applicability of the tendon-actuated ankle, hopping was also tested on a 25 kg bipedal robot constrained to planar motion via the same boom, but which allowed torso pitch as well. As the biped is not the focus of this study, its specifications will not be elaborated upon.

All compressed air supplying the valves is at 0.83 MPa, and is oil and particle filtered down to $2\,\mu m$. All cylinders are controlled with high-speed ($12\,ms$), high flow ($1400\,\frac{L}{min}$) proportional five-port valves (Festo Corporation MPYE-5-1/4-010-B). The hip cylinder is a $76\,mm$ bore, $100\,mm$ stroke (Bimba 704-DXP) with $1.75\,kg$ mass, while the knee joint is driven by a cylinder with $64\,mm$ bore, $125\,mm$ stroke (Bimba 505-DXPBF) with $1.1\,kg$ mass. All pneumatic tubing has $6\,mm$ ID.

The tendon is comprised of a cable and turnbuckle. The tendon is $600\,mm$ in length, $1.5\,mm$ diameter, $200\,kg$ test pull Kevlar. The turnbuckle allows an additional $150\,mm$ manual adjustment of the tendon length.

The foot contact points are compliant, energy-absorbing rubber (Noserex) at all four corners of the foot, in order to insure a minimally elastic contact with the $5\,mm$ thick rubber surface of the ground. The use of rubber contact points and ground surface minimizes slippage as well.

A preemptive multitasking microcontroller (Elba Corporation Zx-1280n) is used to control the robot; three multitasking threads run at $300\,Hz$. One task controls all the joints to target positions via PID, and the remaining two tasks determine the knee target positions based on the phase of the hop cycle, and maintains the hip angle.

III. Control Theory

The control of prismatic legs is well understood and relatively straightforward ([8]). For this reason, the role of the tendon is to allow a thrusting articulated leg with revolute joints to behave more closely to a thrusting prismatic leg, where hip torques are not necessary to keep the foot under the hip when jumping directly upward. Additionally, observing the behavior of a constrained single-leg system allows isolation of the passive stabilization phenomena the tendon creates, whereby the hp angle need not be controlled for perturbation rejection. This is unlike Raibert's hoppers, which require active control of the hip angle to remain stable.

An articulated leg requires different control considerations than a prismatic leg due to its dynamics. Without hip torque, there is difficulty in keeping the foot of an articulated leg beneath the hip when thrusting. Consider the simple planar articulated legged system where there is only a thigh and shank, but no foot. Both the hip and knee joints are actuated. While thrusting, an undesirably large hip torque is generated by the moment of effective force of the thigh and shank as they extend toward a straight leg, since the center of mass of this two-link system is accelerating backwards when the knee points forward. This impulse causes the leg to swing backward after loosing contact with the ground on liftoff.

A hip actuator must provide compensation for this impulse ("impulse compensation") precisely, otherwise the leg will swing backwards undesirably if the angular impulse is too small or concludes too soon, or swing forward if the impulse is too large or concludes too late. Without impulse compensation of any kind, the leg would swing backward immediately on flight.

Now consider a nearly identical system, but with a foot attached via a revolute ankle joint. If the ankle provides torque to further extend the leg while thrusting, the required impulse compensation can arise from the foot's motion. Since a leg near the end of its thrust phase is essentially a long rod, relatively small forces at the foot can cause large moments about the hip, and create the necessary impulse to halt or reverse the backward swinging motion fo the leg (assuming non-sliding feet).

When the torso has a sufficient counter torque via a counter-swinging leg, or is prevented from rotating (essentially leading to the same result), forward impulses which arise from ankle liftoff compensate correctly for backwards impulses of the thigh and shank's CoM that naturally arise from thrusting.

With tendon coupling, varying degrees of impulse compensation automatically occurs with varying knee thrusts, as long as the tendon length is correctly set. This was tested by increasing the flow to the knee cylinder by $100\,\frac{L}{min}$ with each hop, beginning at $200\,\frac{L}{min}$, and up to the maximum $1400\,\frac{L}{min}$. No notable difference in stability was observed, although hop heights were reduced for the lower flow rates.

The ankle need not be powered with its own actuator for this strategy to work. A tendon can rotate the ankle while the knee joint rotates. A tendon that is properly tuned to have the optimal length and is connected with the appropriate angular coupling (both will be discussed shortly), the ankle can provide automatic impulse compensation via the knee actuator. For stable hopping of a perturbed articulated leg system, the knee joint simply thrusts, and impulse compensation occurs automatically regardless of thrust levels or foot placement relative to the hip (within reason). The system is therefore robust to perturbations, and control of the articulated leg is greatly simplified.

IV. Experimental Results

A. Procedure

To verify the efficacy of impulse compensation via a tendon coupled ankle, tests were run with a monopod hopper. At the start of a hopping test, the monopod was initially suspended approximately $30\,cm$ from the ground. Joint encoder data is captured at $300\,Hz$ by a separate microcontroller

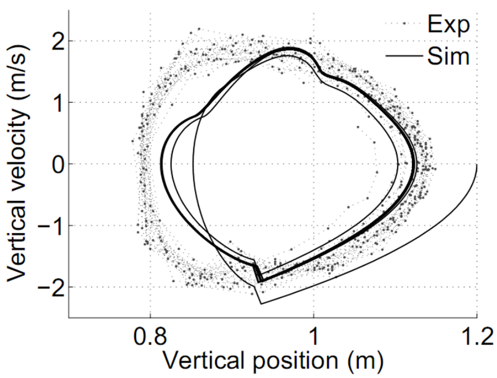

Fig. 3. Vertical phase plot of the hip for both experimental (light color) and simulated (dark color) results.

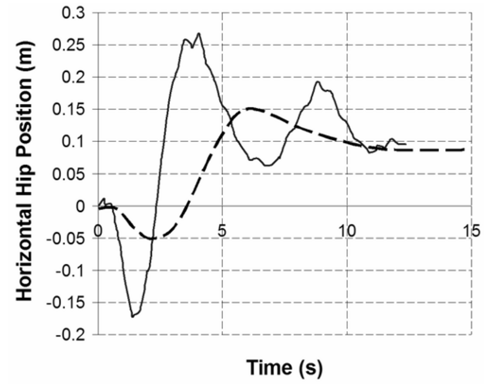

Fig. 4. Experimental horizontal hip motion over time. The solid line is the actual data, while the segmented line shows the running average.

(Oakmicros ZX1281ae). Data collection begins immediately before impact, and continues for about fifteen jump cycles. After a test completes, the host computer receives the data serially for conversion and processing in Matlab.

B. Results

The exact parameters for the control law were determined empirically in hardware, since only four parameters were needed to be found: the initial hip angle α_{nom}, the initial knee angle β_{nom}, the angle deviation $\Delta\beta_{\text{thrust}}$ at which thrusting occurred, and the tendon length ℓ_{tendon}. Finding these parameters was a simple procedure, as there are numerous combinations of parameters which yield passively stable hopping. One combination that worked well was $\alpha_{\text{nom}} = 23^o$, $\beta_{\text{nom}} = 50^o$, $\Delta\beta_{\text{thrust}} = 75^o$, and $\ell_{\text{tendon}} nom = 773\,mm$. (A validation of the simple heuristics required for tendon-coupled hopping arises from the fact that similar parameters were obtained despite working independently in hardware and a simulation).

In hardware experiments (with simulation closely agreeing as verification), hopping seems to be stable in the vertical direction upon the first hop, leading to repeatable vertical hip velocities decoupled from horizontal position as seen in Fig. 3. However, the convergence is slower in the horizontal direction as seen in Fig. 4, with the leg hopping backwards about $10-15\,cm$ before reaching a stable horizontal location after about eight thrust cycles. This may be caused by the initial drop conditions that were not carefully determined.

With single-leg hops of a bipedal system, which includes a freely pitching torso, the first six hops were within $2\,cm$ of the initial drop position. Body pitch was bounded within 5^o of the initial drop angle, until the seventh destabilizing hop that occurred due to parameters that have yet to be properly tuned for the free torso. Bipedal hopping with a free torso is still under investigation.

The greatest strength of a tendon-coupled ankle involves stability in the presence of perturbations of the body or leg: the tendon-coupled ankle creates a passively stable system. If the foot lands in front of the hip, the tendon will engage later in the thrust cycle and for a shorter time, causing the leg to swing backwards, and *vice versa*. The result is a stable hop which tends toward an upright configuration, and which requires no additional control to compensate for anterior or posterior disturbances. The monopod is therefore also stable to perturbations of the torso position, as it is the foot's horizontal position relative to the hip that is stabilized. This stability to perturbations was tested by physically pushing or pulling the monopod near the hip with approximately $5\,kgf$ applied by hand for $0.3\,s$ to the thigh cylinder during the flight phase. The torso moved $11\,cm$ in the direction of the force, but hopping was stable and in place immediately after the disturbance. This test was repeated several times in both directions, with similar results: at most, hopping in place was reached by the third hop, depending on the impulse of the disturbing force.

V. Discussion

Dynamically stable control of articulated legged systems with large leg to body mass ratios is more complex than for systems with prismatic legs, in part due to the backwards impulses of the leg segments during thrusting. For our robot, whose leg is 50% of the total system mass, this backwards impulse is significant, and compensation requires a hip torque beyond what reasonable hip actuators are capable of providing. Additionally, even if the actuator were sufficient, a small degree of desychronization of the hip torque may still cause large undesired leg rotations about the hip. Fortunetely, when a tendon-coupled ankle is driven during the thrust sequence of the knee joint, the ankle is synchronized with the knee, resulting in a significantly lower required hip actuator effort to maintain a horizontal torso. Beyond coordinating the knee thrust to trigger at a certain knee angle, no control of the monopod is required. Similarly, for a bipedal robot with a freely rotating body, a counter-swinging leg presents the thrusting leg with a sufficiently stiff body for a small hip actuator to allow for jumping straight up and down with a tendon. Given that the amount of compensation is directly determined by the thrust due to the coupling, impulse compensation is correct for varying thrusts as well without returning the tendon.

Considering this automatic position correction of the foot relative to the hip, it is possible to control the forward or backward motion of the hopper by varying the tendon length by several millimeters in either direction from the optimal length that leads to upright hopping, with the distance between ground contact on consecutive hops changing proportional to the tendon length. For example, if the tendon is significantly longer than $\ell_{\text{tendon}} nom$, the horizontal hop distance will be longer than if the tendon is only slightly longer. This behavior can be used to control the leg to hop forward or backward as well.

A fixed-length tendon limits the maneuvers possible on a robot. For example, static motions such as stepping require a tendon several centimeters longer for the most robust stepping with that system, in order to allow the center of mass to reside over the foot while the heel touches the ground in a stable stance. This is not unlike biological systems, where muscles can contract and reposition tendons. A separate actuator could be used to vary the tendon length by small amounts to allow static and dynamic maneuvers. The advantage of an actuated tendon system, when compared to an actuator directly powering the ankle, is that the tendon actuator need only be varied occasionally, and the actuator can be conveniently located at the thigh end of the tendon, close to the hip. An actuated tendon would allow switching between dynamic and static maneuvers and forward or backward excursions during hopping without varying β_{nom}.

VI. Conclusion

An articulated, fixed-torso monopod hopper was built and tested in hardware to verify the effectiveness of a tendon-coupled ankle. Additionally, an articulated bipedal hopper with freely pitching torso was tested with the same leg configuration. In both systems, the ankle and knee joints were coupled via an inelastic tendon between the foot and the thigh. In both hardware experiments and simulation of the monopod, stable vertical hopping was achieved under a simple heuristic control algorithm, while the biped achieved a limited number of hops in place. The tendon specifically allowed a lower leg inertia by replacing the ankle actuator and a simpler control algorithm by eliminating an active degree of freedom. The use of a tendon-coupled ankle greatly simplifies control of hopping for a dynamic, articulated legged robot.

VII. Acknowledgments

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