Bipedal Running:
When Leg Architecture Influences Speed, Efficiency and Robustness.

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1 Introduction

Building a bipedal robot is a very challenging task. Many of these challenges arise due to technical constraints, which is compounded by the inherent complexity of the biological systems upon which these designs are based. The traditional design process of making a robot is the result of a succession of steps: mechanical design in CAD software, assembly, identification, simulation of the designed robot and development of control algorithms. While this design process has been successful to some extent, it does not allow for investigating easily new design features and will limit the overall robot performance to its initially designed capabilities even with a great controller. To build the FastRunner, a fast, efficient and robust bipedal robot, we chose the reverse approach. By first modeling the robot in simulation, we have been able to investigate and evaluate many design features previously identified by the biomechanics community in running animals. To date, a planar simulation of the FastRunner has achieved running up to 50 kph (31 mph) while being inherently stable and relatively energy efficient (Lowest cost of transport recorded was 0.5 at 32 kph). Based on these simulation results, this paper summarizes some insights on how the mechanical architecture of a legged system can influence its speed, energy efficiency and robustness.

Figure 1 shows the current Fastunner leg architecture. Each leg is made of six joints (labeled with lower-case letters), six links (numbers) and a number of elastic elements (upper-case letter). While the leg architecture is detailed in [1], the next sections discuss the contribution of the main design features to the FastRunner performance.

2 Velocity Amplification

Several architectural elements contribute to the FastRunner's high speed running capabilities. First, the Achilles linkage (7) acts as an angular velocity amplifier by creating a coupling between the knee and the ankle joints. Changing this transmission ratio, will change the velocity of the foot and consequently affects the performance of the robot. We tested a large range of transmission ratios and the most effective was 1:2, really close to what is observed on ostriches. Second, the length of the leg is not fixed. Instead, it varies between a minimal length occurring during the full retraction at mid-swing to a maximal length occurring at the full extension of the leg at the end of the swing phase, increasing the leg end point velocity. The cyclic motion created by a succession of retraction and extension is the result of the combined effects of the leg inertia and the elastic elements.

3 Springs

A fundamental observation made in the biomechanics literature is that fluctuations of the kinetic and gravitational potential energy during running occur in phase with each other. This observation leads to the conclusion that efficient running requires energy to be stored and released during each step. One of the simplest way to implement this feature is to use mechanical springs. Use of springs in legged locomotion is largely supported by spring-mass models, since they are capable of describing data gathered from human running experiments quite well. In addition to saving energy, springs also add compliance to the leg, reducing impulsive loading due to ground impacts. Another observation, true

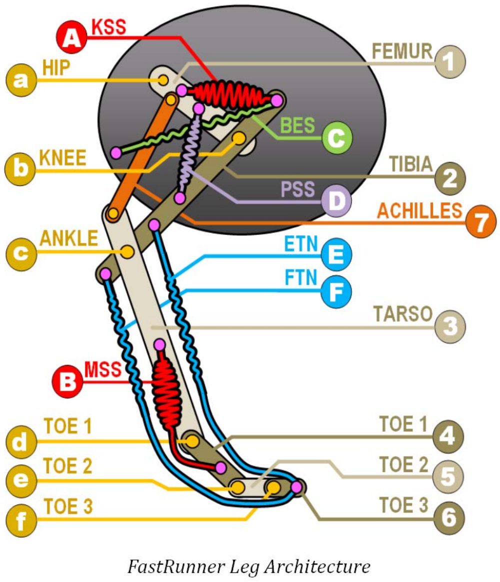

Figure 1: FastRunner Schematic: Joints, Springs and Links.

across a large range of species, is that leg stiffness increases with speed, suggesting that springs must exhibit a non-linear profile (stiffness increases non-linearly with deflection). We verified these observations by implementing a large number of non-linear springs in the FastRunner leg architecture. Instead of trying to replicate the full functionality of an ostrich's muscles, we identified the primary functions of each of the ostrich's major muscle groups that contribute to the essential aspects of running, in order to create a simplified yet functional planar model of the leg. This model emulates the same essential planar functionality without requiring the full multiplicity of elements. All the springs are using a non-linear profile and have been tuned to provide the exact amount of force necessary to counteract the gravity effect in the rest position. Non-linear profiles of the elastic elements are also tuned to take advantage of the natural leg's inertia, not to fight it, over the whole range of achieved speeds. As such, adverse motion dynamics are reduced while passive motion dynamics are enhanced. With the architecture presented Figure 1, FastRunner successfully reached 50 kph in a planar simulation. The non-linear profiles used in the springs are mainly responsible for steady running over its whole range of speeds, while simple linear profiles provided steady running for a limited range of speeds. By analyzing the FastRunner's energy expenditure versus running speed curve, Figure 2, we observed that the FastRunner has a preferred running speed, similarly to legged animals. More specifically, we have been able to change the efficiency point on this curve by tuning the elastic elements and hip trajectory.

4 Energy recycling

While in the FastRunner architecture several springs are enhancing passive motion dynamics and storing energy, we noticed that most of the energy produced by the actuator was still lost. Since running and more specifically joint motions during running are periodic events, it makes sense to try to recycle the energy produced by the actuator. The FastRunner uses only one actuator per leg that applies torque about the hip joint which varies sinusoidally in time. By implementing a spring (H) in parallel to the actuator and having this spring working in phase with actuator (requires adequate spring profile), we succeeded to decrease the cost of transport by 30%, down to 0.5 when running at 32 kph.

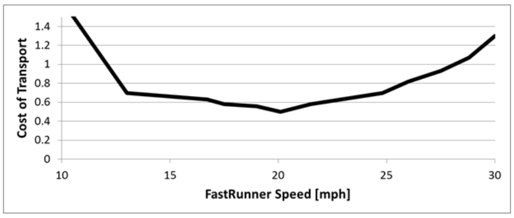

Figure 2: Mechanical cost of transport observed in the FastRunner planar simulation.

5 Curved toes

Contrary to classical legged robots that use point feet or flat feet, the FastRunner utilizes a foot architecture made of three toe segments. Toes are important in running because they allow the feet to roll as they push off at the end of the stance phase, resulting in a smoother trajectory of the center of mass. This rolling motion also eliminates the need for active ankle torque to move the center of mass in front of the stance foot, an approach often used in conventional legged robots.

6 Hybrid dynamics

For legged animals, a specific set of muscles is active during each phase of the gait cycle. This results in a hybrid system made of several dynamic modes where each mode is optimized for a specific duty. Previously, legged robots have not had such capabilities and, consequently, relied on a single dynamic mode to achieve their behavior. By implementing a mechanism to engage or disengage the knee suspension (A) according to the phase of the gait, the FastRunner benefits from having two dynamic modes. In the first mode, the knee suspension is active during stance, supporting the body weight and storing potential energy. Some of this energy is then kinematically converted into forward thrust during the energy release phase thanks to the four-bar mechanism coupling the knee and the ankle. In the second mode, the knee suspension is inactive during swing, allowing for a full radial contraction of the leg which increases the ground clearance. With the leg retracted, the leg moment of inertia is reduced as the leg pulls in, reducing the amount of energy required to swing the leg forward.

7 Dicussion

Previous research in the field of legged robots has shown that it is difficult to find a good balance between speed, energy efficiency and stability. However, nature has proven in numerous ways that this balance does exist, thus robots should be able to replicate, or at least approach, the capabilities of animals. We implemented several features observed in legged animals into the FastRunner architecture and have proven in simulation that these features really influence running performances and are capable of producing efficient running gaits that are self-stabilizing over a range of forward speeds.

References

[1] S. Cotton, I. Olaru, M. Bellman, T. van der Ven, J. Godowski and J. Pratt, "FastRunner: A Fast, Efficient and Robust Bipedal Robot. Concept and Planar Simulation." In Proceedings of the International conference on Robotics and Automation, May 2012.