Softer legs allow a modular hexapod to run faster

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We describe a bioinspired hexpedal robot that uses only 7 motors and is built from CKBot modular robot modules. The robot has elastic 2-DOF legs whose stiffness falls in the biologically relevant range, allowing it to run dynamically. We used gradient search to optimize the running gait parameters on two sets of legs with different stiffness. Surprisingly, the softer legs run 16% faster at a gait frequency 11% lower – contradicting the simple design intuition that more rigid legs and higher gait frequencies are key to faster running.

Keywords: Gait optimization; leg stiffness; modular robots

1. Introduction

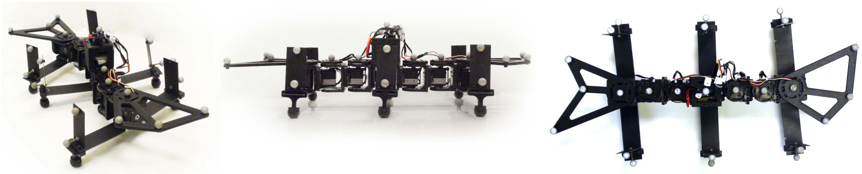
In the last decade we have witnessed an enormous increase in the interest in legged robots, primarily centering around the ability of legged platforms to traverse terrain that is difficult or impossible for wheeled vehicles. For quasi-static legged systems, the governing mechanics are well understood[1]. The situation is starkly different for dynamically moving legged robots, where the combination of hybrid transitions, surface interaction and robot deformation often proves challenging to analyze.

Modular robots offer the chance to quickly prototype and explore the parameter space of a given robot design. Such an approach has been the subject of ongoing work, primarily with a bio-inspired focus[2]. Our work on rapidly prototyping robots with the CKBot platform[3], lead us to explore the possibility of dynamical locomotion with these modules[4].

Motivation for our design — Among the fastest autonomously powered legged robots are the Sprawl[5] and the RHex[6] robot families. Both are bioinspired, applying design principles and parameter ranges obtained from studies of cockroach (*Blaberus sp.* and *Periplaneta sp.*) locomotion. We present a robot of the same overall type – a hexapod with elastic legs, whose mass lies in between that of the largest Sprawl and smallest RHex[4].

This robot was designed with the goal of achieving dynamic running using a modular robot platform.

2. Robot design

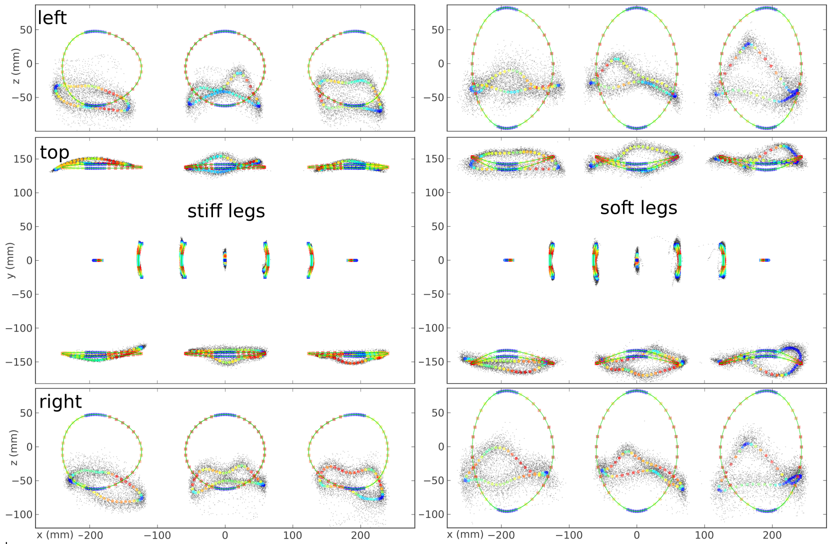


Unlike the cockroach inspired robots whose leg motions are primarily in the saggital plane, our robot also borrowed from the body-plan of centipedes (*Scolopendridae sp*) by having a laterally bendable body and laterally projecting legs, each of which was a fiberglass cantilever plate mounted on a servo allowing its roll angle relative to the body to be controlled. We attached a "foot" (a normally offset rubber pad) on each side of the leg cantilever. The design achieves an effective 2-DOF motion for each of its 6 feet with only 7 motors. We ran the robot in a motion tracking arena (Vicon, 16 cameras, 100fps) while tracking the rigidly attached markers.

Gait optimization — The gait parameters we optimized were frequency, leg roll amplitude, leg yaw amplitude (achieved via body bending), sweep angle and duty cycle (relative duration) of the stance period. These were tuned by a Nelder-Mead simplex based gradient search using a python program that ran the robot back and forth in the 5m x 5m tracking arena. The robot was kept on track by a human operator using a joystick. Pressing a button would start and end a trial. The optimization attempted to minimize time divided by distance between robot position at start and end of each trial by changing the gait parameters.

Data analysis — After optimization we collected tracking data of all markers while running the robot back and forth. A total of 52 trials were conducted with an average of 372 frames and an average distance of 3.0m (minimum of 303 frames and 2.1m). From one end to the other end of the arena counts as one trial. Trials were segmented by thresholding velocity of the robot. We removed marker association errors using a combination of manual and automated tools. An average of 1.4% of markers were occluded in a trial and were linearly interpolated. We used the fore-aft motions of the legs to reconstruct the dynamical phase of the gait limit cycle using the Phaser algorithm[7], allowing us to reinterpret our data as a function of phase and to construct Fourier series models of the marker trajectories superior to those that can be achieved with footfall based phase estimates.

3. Results



Plots show trajectories of body and leg corner markers, with colors indicating speed in 3D space (red faster, blue slower). We plot the positions predicted by a rigid body model (square color markers on solid green line), the observed positions (point cloud of black points) and a Fourier series model of the observed positions (round color markers).

Our optimizations terminated with the following gait parameters results

Leg	Freq. Hz	Roll deg	Yaw deg	Sweep deg	Duty %	Speed cm/s	K_{tri} N/m	L mm	H mm
Soft	3.1	33	11	22	19	78	331	152	68
Stiff	3.5	22	12	20	18	67	1950	137	43

We observed that soft legs give 16% higher speed with a 11% lower gait frequency. This difference cannot be accounted for by either frequency-length scaling, which predicts soft legs would be slower, or by estimating ground speed of the feet, which predicts soft legs should be much faster than observed in practice.

3.1. *Biomechanical approach*

Biomechanists[8,9] have developed methods to compare animal gaits despite large variability in scale and body structure. A key observation is the presence of dynamic similarity between running in various organisms, which expresses itself in the existence of a common parameter, the "Froude Number" $\mathfrak{f}$, governing the transition between running and walking ([9] fig 1).

We argue that for our robots, the appropriate leg length to use is not the unloaded hip-height [8], because very substantial compression occurs even when standing still. Since our robot runs in an alternating tripod gait, we use as our vertical length l the equilibrium height of the body when standing on a single tripod of legs. At a weight of $15.7\,N$, this implies $l = 21\,mm$ and $\mathfrak{f} = 3.0$ with soft legs; $l = 35\,mm$, $\mathfrak{f} = 1.3$ with stiff legs. We conclude that with the soft legs, the robot achieves a running gait dynamicaly similar to animal running ([9] fig 1), while with the stiff legs, the robot is (dynamically speaking) merely executing a rapid walk.

4. Discussion

Our results suggest that in the biologically relevant parameter range of leg stiffness, the performance of dynamically running robots is difficult to anticipate from first principle arguments, or at least those arguments that rely on rigid body models and no-slip contact conditions. That the results are counter-intuitive in laboratory conditions on a flat and uniform floor, speaks to the baffling complexity that must appear as we attempt to design robots to run in uncontrolled environments. The combination of simplicity and flexibility provided by using a modular plaform affords us the opportunity to explore performance optimization through careful empirical study – at least until such a time when we have better theory to guide our designs.

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