

Evaluation of Grasshopper Inspired Spring Actuation Model for Tensegrity Robot Locomotion

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June 12, 2018

Abstract

Tensegrities are popular structures for soft robots due to their robust properties but are also difficult to move in meaningful ways. Looking at movement methods in grasshoppers, which are able to move many times their body length in short intervals, may lead to discovering more effective movement patterns for tensegrity structures. Much of the grasshopper's effective locomotion is due to the the spring-like structures in its hind legs which store and release energy needed for movement. Tensegrities also have spring structures which can be contracted to produce movement. Spring stiffness varies in grasshoppers between species and stages of development. By Hooke's law of spring dynamics, $F = kx$, altering the spring stiffness should increase the force production linearly. We explore the effects of changing spring stiffness on distance traveled in a tensegrity robot in simulation within Open Dynamics Environment. Six of the Twenty Four springs within the tensegrity robot were chosen to be actuated. The spring stiffnesses of these six springs were either changed uniformly or individually to determine if novel tensegrity movement would be produced. Spring stiffness values were optimized using the Covariance Matrix Adaptation Evolution Strategy. Unlike grasshoppers which have increased jump performance with greater spring stiffness, the resulting displacement values of the tensegrity did not follow a linear trend with changes in spring stiffnesses. They did not converge as expected by Hooke's law to the greatest possible value. This suggests that altering the spring stiffnesses in tensegrities could lead to more diverse patterns of locomotion which may also not follow a linear trend with increasing spring stiffness.

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1 Introduction

Soft robots such as tensegrities are being developed by entities such as NASA for their ability to traverse difficult and unknown terrain with limited damage to themselves and the environment. Tensegrities are popular structure for soft robots. However, tensegrities are also known to be difficult to model and move in meaningful ways.

Tensegrities are structures which maintain their stability through two types of elements: elements that are always tensioned (cables) and elements that are always compressed (struts). This creates a pre-equilibrated state, in which the internal forces (compression and tension) stabilize the structure. Tensegrities have useful qualities such as a high strength to weight ratio, compressibility and robustness [1]. Tensegrities can be moved in a number of ways, including contracting the cables or through attached resonating motors. A tensegrity robot which could move in efficient, predictable ways would have many practical uses such as exploration in unknown environments and difficult terrain.

Often technological advancements occur through biological inspiration. Tensegrity structures are inspired from biological systems in which they were seen to provide structural stability through tensioned forces [2][3]. Looking through the lens of biology again to methods of movement in organisms may lead to discovering more efficient movement patterns for tensegrity structures. For example, frogs, kangaroos and grasshoppers rely on jumping as their primary means of locomotion. These organisms have incredibly effective locomotion as they are able to jump many times their body length. Much of this ability in locomotion is due to the physical structure of the animal. For grasshoppers this appears in the large hind legs and musculature which have evolved specifically for greater jumping ability. In addition, they have a specialized cuticle in the hind legs to store energy for jumps. It would be difficult to mimic the locomotion pattern of the grasshopper without these corresponding supporting structures.

A tensegrity robot and a grasshopper have fundamentally different mechanical designs. Tensegrities can vary in number of struts and springs, with the simplest being three struts and potentially no maximum complexity. The tension of the spring, length of the strut and material of both the spring and strut can be changed but remain constant, except for damage through use and time. However, these attributes are constant during simulation. In contrast to the simplistic structure of tensegrities, grasshoppers are complex biological entities. Grasshoppers contain many parts that are not part of the function of locomotion. They jump by contracting their muscles and storing energy in their tendons and cuticle. The grasshopper then releases the energy to move, similarly to a catapult [4]. However, a common feature between tensegrities and grasshoppers are the spring structures. In tensegrities, the spring structure is the cable which distributes the force and can be actuated to contract. In grasshoppers the analogous spring structure is the cuticle of the extensor apodeme and

semilunar process which store and release energy needed for movement [5]. Modifying the spring behavior in a tensegrity could lead to more efficient and diverse patterns of locomotion.

The traditional model of spring behavior is Hooke's law which is $F = kx$ where F is the force produced, k is the spring stiffness and x is the displacement of the spring from its equilibrium position. In Hooke's law k is a constant. The k constant is determined by the slope of a stress-strain curve. When this holds, the behavior is said to be linear. If shown on a graph, the line should show a direct variation. Hooke's law says that stress is directly proportional to strain. Once the strain is increased past the permanent deformation point, the spring no longer returns to its equilibrium point and no longer obeys Hooke's law. However, many biological materials such as the semilunar processes in grasshoppers do not have a linear stress-strain curve [5]. Semilunar processes vary in spring stiffness across species and between individuals in a species [6]. They also vary in stiffness across the same individual's developmental lifespan [7]

The common method of moving tensegrity robots through contracting the cables involves changing the length of the cable through an attached rotating motor [1]. This causes the robot to topple over. The tensegrity in this example is the canonical six strut icosahedron formation. The spherical like shape of the tensegrity combined with the toppling motion creates a locomotion pattern of rolling. This pattern of locomotion relies on the firing pattern and timing of the contraction of cables to move. However, in this example, as in most tensegrities, the cables have the same spring stiffness. This limitation of parameters lends to a limitation in movement patterns. Thus the question is *to what extent does a non uniform spring stiffness model produce novel tensegrity movement?*

2 Related Work in Bioinspired Locomotion in Robots

2.1 Structurally bioinspired robots

Another approach to grasshopper inspired locomotion is to fully mimic the structure of the organism. This approach was seen in a study where a jumping robot was constructed based on the grasshopper leg structure [8]. Grasshoppers have a pause and leap jump whereby the jumps are separated by long time intervals. Grasshoppers move through sudden energy release and it is difficult to accurately control the jumping destination, stability after takeoff, and safe landing. The physical prototype created was successful in mimicking the grasshopper path and range as the robot jump path paralleled the images of the grasshopper jump path. The prototype could jump over obstacles of about 14 times its body height and had a jumping distance of about 20 times its body length at the takeoff angle of approximately 60 degrees. However, the prototype could not maintain the same stability of the grasshopper and could not make a stable landing. The robot they created

was very much a mechanical version of the lower body of a grasshopper. Their work shows that grasshopper musculature and movement pattern can be replicated but control of the movement is more difficult. While this muscle model of movement cannot be replicated in a tensegrity robot model due to the vastly different structural components, due to its robust, transformable nature, a tensegrity robot would not need to worry about making a stable landing since it could absorb the shock and regain its shape quickly.

2.2 Other biologically based locomotion in tensegrity robots

Tensegrities have also been used to model musculature such as the mechanism of an actin stress fiber [9]. Loua et al. modeled the stress fibers using a generic, planar tensegrity mast composed of multiple similar structural modules. The model incorporated multiple linear filaments oriented in parallel along its main axis, with many lateral structural links that would correspond to actin-associated molecules. From this research they suggest that tensegrity models may provide a useful link between molecular and cellular scale mechanical behaviors and could be used in multi-scale modeling of living materials.

Tensegrities have also been used to model animal locomotion, specifically in relation to caterpillars [10]. Rieffel et al. explored how the *manduca sexta* caterpillar could be used as a model species for soft robotics as they are completely soft-bodied and lack any rigid elements such as a skeleton. Locomotion is performed by the co-ordination of their abdominal segments. They suggested that the the dynamics of the caterpillar's system are responsible for control tasks and not necessarily neural circuits. They applied this to tensegrity robots, in their Open Dynmaics Engine (ODE) model they do not use explicit intermodular but rather they have every strut be able to sense and affect the tension on a single cable. Using this model they evolved dynamic gaits in simulation. They created a prototype of the soft robot inspired by the caterpillar but did not test their locomotion model on the prototype.

Orki et al. conducted further research on the modeling of caterpillar locomotion using a tensegrity model [11]. They represented caterpillar segments using a 2D Assur tensegrity structure called a triad. An interesting shared characteristic between the model and live caterpillars is that their internal pressure is not a function of its size. In a caterpillar during growth, body mass is increased 10000-fold, while internal pressure remains constant. The model is similarly able to maintain near constant internal forces regardless of size. Another interesting point in this research is that the control algorithm used for the model is also inspired by biological caterpillar. There is a low level control that is inspired by the mechanics of the caterpillar and a high level control that is inspired by the nervous system of the caterpillar. The model had many characteristics that were similar to a biological caterpillar and it generated some novel insight into caterpillar mechanics, thus this research showed that tensegrities could be used to accurately model a biological entity and provide novel

biological insight into that entity.

3 Related work in Grasshopper Spring Stiffness Models

3.1 Stress strain and deformation in grasshopper semilunar processes

The concept of the grasshopper muscle as a two-part spring (semilunar process and extensor apodeme) which strains at a rate dependent on stress was discussed by Bennet-Clark [5]. The force produced by the straining of the paired semilunar processes had a curve that did not follow the linear behavior of hookean springs. The points also fluctuated within 3 newtons for the same distance strained between individuals of the same species. The extensor apodeme was also seen to vary in fracture points in individuals when stressed over 16 newtons. The grasshoppers also did not exhibit visible plastic deformation in the cuticle from the stress, only full fractures. This differs from traditional spring models which have a period of plastic deformation before fracture. This difference is explained by the other musculature in the grasshopper leg which contribute to supporting the strain.

3.2 Stiffness of cuticle over developmental lifespan of grasshoppers

The distribution and stiffness of cuticle material in the legs of grasshoppers varies throughout their lives [12]. Katz and Gosline had previously found that scaling of the mechanical behavior (increased jump ability) does not translate to the scaling of external dimensions (increase in tibial length and diameter) [7]. Katz and Gosline explained this discrepancy in scaling through the alteration of the stiffness of the cuticular material which produced the observed scaling of flexural stiffness [12].

3.3 Femoral Stiffness Effects on Jump Performance

In contrast to Katz and Gosline, Scott and Hepburn state that femoral stiffness does not have a significant effect on jumping force [6]. They concluded this by straining the cuticle of various developmental stages and species with different jump performances. While they acknowledge the positive correlation between exoskeleton cuticular stiffness and jump performance, they state it is due to other elements within the extensor system. They also state that the jump performance of larvae and adults are similar if mass is taken into account.

3.4 Modeling Muscle-Spring Dynamics

A muscle-spring interaction model where spring stiffness and loading time were parameters and elastic energy storage was the desired output was created by Rosario [13]. This model also used the Hookean spring model and equation. However the muscle actuator was the dynamic part of this model. The Hookean spring served as a passive tendon. The spring was attached to the muscle and served to show storage of the energy generated by the actuated muscle. They used the model to explore the relationship between spring stiffness and energy storage in biological springs with varied loading times such as the bullfrog and grasshopper.

They found that muscles of organisms that load for longer time intervals, such as grasshoppers, benefited from high stiffness springs. This is because stiffer springs can store greater elastic energy, as would be expected from Hooke's equation when k is increased. However, they found that muscles that load for shorter time intervals, such as bullfrogs benefited from less stiff springs. Even though less stiff springs could not store as much energy, they required less activation energy, thus allowing the spring to stretch more for a given amount of force [13]. From this model, there is uncertainty as to whether stiffer springs would produce greater energy storage for any given muscle system in an organism, as loading time dynamics differ greatly between organisms. This brings up further questions whether a tensegrity robot would benefit from stiffer or less stiff springs and if its performance would be affected by the firing timing of the springs.

4 Methods

In order to determine if a non uniform spring stiffness model produces novel tensegrity movement, two treatments of uniform and non uniform spring stiffness changes were used. These treatments consisted of short or extended evaluations of either 400 or 8000 time steps.

4.1 Simulation setup and creation

The model of tensegrity robot locomotion was created within Open Dynamics Engine (ODE), a physics engine for simulating rigid body dynamics. The tensegrity formation used for this experiment was the six bar, spherical icosahedron formation. Twenty four spring elements connected the six bars. The spring dynamics were originally based on Hooke's law and were modified to actuate on changes in spring stiffness, this change being the spring stiffness multiplier. The value of spring stiffness multiplier was multiplied by the k constant in Hooke's law equation $F = kx$ to actuate the spring to increase force and thereby produce movement during simulation. This meaning that the actuation of springs occurred not by directly changing spring length, as one

would in a typical physical structure but rather by changing the value of the spring stiffness. This allowed for more direct assessment of the effects of changing spring stiffness on fitness. Fitness was measured by the horizontal displacement of the center of mass of the tensegrity from its starting position in a non actuated, non moving state. Vertical displacement was not used in determining fitness value. Center of mass was used as the point to determine displacement as to prevent changes in rotation and position effecting the fitness value. The two intervals of measurement were 400 and 8000 time steps, which is roughly equivalent to 20 seconds and 400 seconds. The displacement value from an evaluation is represented by difference in tensegrity location from the first time step to the last time step. A displacement of 1 would be the length of one strut or stable tensegrity length, a displacement of .25 would represent displacement of 25 percent of one tensegrity length.

4.2 Determination of firing pattern of springs

When springs contract they do so over a length of time, an instantaneous motion would not produce the desired production of force from the release of the spring. In particular, loading time has significant impact on biological spring force production [13]. In addition, repeated extended loading and without sufficient time to release the force is also not conducive to force production. Thus determination of a firing pattern that would allow the springs to produce movement in the tensegrity from actuation is key to evaluating the changes produced by altering spring stiffness. The firing pattern takes a period, phase, duty cycle and time step. The time step is the step within the simulation which is necessary to decide if the muscle is active or passive during that time step (determines force applied to spring/ if contracting or relaxing). The period, phase, duty cycle parameters are used to simulate biological parameters within a jump. The firing pattern used for the simulation was $timestep \% period \geq phase \&\& timestep \% period < (phase + (duty cycle * period))$ where timestep was the simulation loop count, period was the interval, phase was the offset and duty cycle was the percentage of how long the interval was spent in active contraction. These parameters define how long the muscle will be firing for and what part of the interval it should be firing for.

4.3 Determination and initialization of parameters

Initially, random value optimization trials for the parameters of period, phase and duty cycle where spring stiffness was fixed at 2 were used to determine the baseline parameters for later trials in which the spring stiffness would be altered. The period, phase and duty cycle parameters were held constant at 8, 6, 6 for the trials in which spring stiffness as optimized.

Six springs of the twenty four springs were changed using the spring stiffness multiplier during simulation. These six springs were chosen from early qualitative analysis where different configurations were used and

the movement of the tensegrity was visualized in simulation. The springs are relatively close to each other in simulation because this configuration produced forward movement using the initial parameters. Fewer springs actuated or actuation of springs spread across the tensegrity produced less forward movement. In several instances of more than six springs the tensegrity seemed to deform inwards during actuation of the springs.

The spring stiffness multiplier either changed uniformly or non uniformly across the tensegrity. In the case of uniform change of spring stiffness multipliers, all multipliers were changed together for a given evaluation. In the case of non uniform change, all six spring multipliers were mutated and optimized individually for a given evaluation. No spring stiffness was changed within an evaluation.

The default starting spring stiffness of all twenty four springs in the tensegrity model was 2. The values of all spring stiffness multipliers were initially 2 and were artificially bounded between the values of 1 and 6. The values of the multiplier of spring stiffness of the six springs were altered and optimized using Covariance Matrix Adaptation Evolution Strategy (CMA-ES) with elitism enabled.

4.4 Optimization using Covariance Matrix Adaptation Evolution Strategy (CMA-ES)

In order to optimize for spring stiffness, the Covariance Matrix Adaptation Evolution Strategy (CMA-ES) was utilized. CMA-ES is an evolutionary algorithm which is based off of the biological principle of evolution through variation and selection. Each new generation of candidate solutions are generated by variation through recombination and mutation. These candidates are evaluated using a fitness function which produces a fitness value for them. This continues with each generation getting candidates with better fitness values. If elitism is also used in the selection then only the best candidates are reintroduced from the previous generation to the next. The libcmaes package created by Nikolaus Hansen was utilized in order to perform the optimizations.

5 Results

The evaluations of one trial for uniform spring stiffness multipliers across six springs in a tensegrity, with an evaluation being 400 time steps is seen in figure 1. The highest fitness value for this optimization trial was determined to be 0.17 and was attained after 37 function evaluations. The optimum value of the six springs was determined to be 2.27 in this trial.

The evaluations of one trial for non uniform spring stiffness multipliers across six springs in a tensegrity, with an evaluation being 400 time steps is seen in figure 2. The highest fitness value for this optimization

trial was determined to be 0.17 and was attained after 217 function evaluations. The optimum values of the multipliers of the six springs was determined to be 2.46, 2.18, 4.88, 3.91, 2.87, and 2.27 in this trial.

Trials for uniform and non uniform spring stiffness multipliers were repeated and the output of the median of the fitness values over the first 200 evaluations of 400 time steps is shown in figure 3. Fitness values contained within the 1st and 3rd quartile varied less than .01 from the median value of the function evaluation for uniform spring stiffness multipliers. Fitness values contained within the 1st and 3rd quartile varied up to .05 from the median value of the function evaluation for non uniform spring stiffness multipliers. Distribution of the fitness values at convergence for these trials is seen in figure 4. The p-value for difference between data sets was less than .0001.

The evaluations of one trial for uniform spring stiffness multipliers across six springs in a tensegrity, with an evaluation being 8000 time steps is seen in figure 5. The highest fitness value for this optimization trial was determined to be 0.97 and was attained after 123 function evaluations. The optimum value of the six springs was determined to be 2.08 in this trial.

The evaluations of one trial for non uniform spring stiffness multipliers across six springs in a tensegrity, with an evaluation being 8000 time steps is seen in figure 6. The highest fitness value for this optimization trial was determined to be 1.27 and was attained after 127 function evaluations. The optimum values of the multipliers of the six springs was determined to be 2.46, 2.18, 4.88, 3.91, 2.87, and 2.27 in this trial.

Trials for uniform and non uniform spring stiffness multipliers were repeated and the output of the median of the fitness values over the first 400 evaluations of 8000 time steps is shown in Figure 7. This interval of evaluations, rather than the 200 evaluations for 400 time steps, was needed to show convergence of fitness values for non uniform spring stiffness multipliers. Fitness values contained within the 1st and 3rd quartile varied around 0.15 from the median value of the function evaluation for both uniform and non uniform spring stiffness multipliers. Distribution of the fitness values at convergence for these trials is seen in figure 8. The p-value for difference between data sets was .013.

6 Discussion

6.1 Tensegrity Robot Locomotion

Through Hooke's law $F = kx$ it is predicted that higher spring stiffness will lead to higher force production. Thus it would be expected in simulation that higher spring stiffnesses would lead to higher force production and thus greater distance traveled by the tensegrity. While there were often one or two springs out of the six that would converge to values close to the upper bound of 6 in various trials, the majority of non uniform

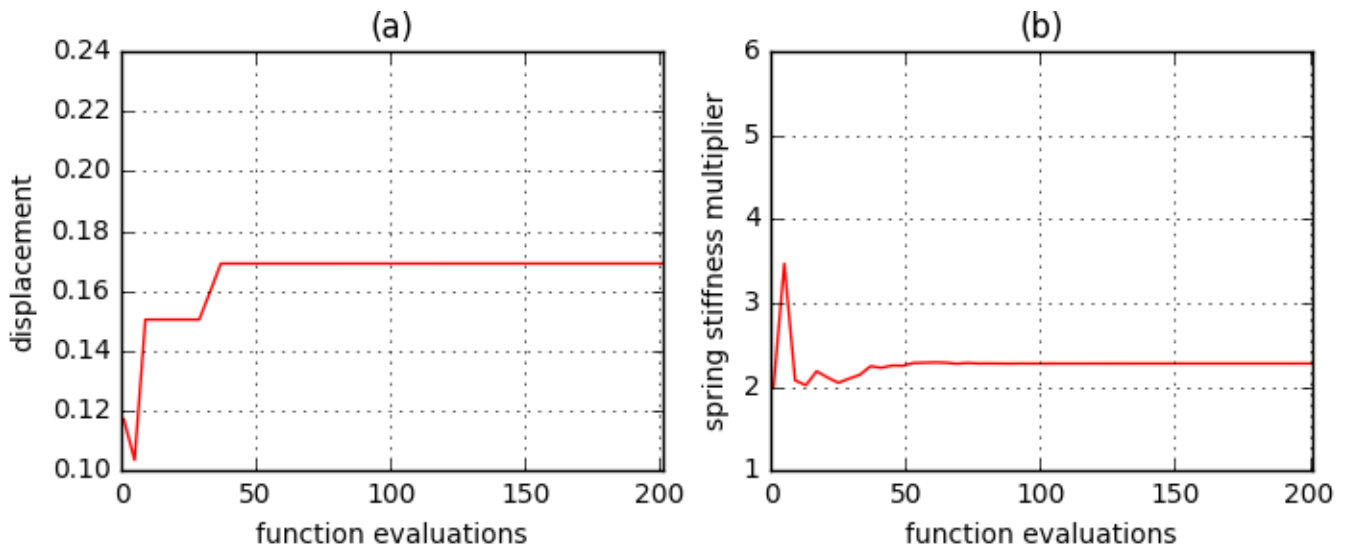


Figure 1: One optimization trial of uniform spring stiffness of six springs using CMA-ES elitism over 200 evaluations, each evaluation being 400 time steps in simulation. (a) Fitness value of 0.17 displacement attained after 37 evaluations. (b) Optimum value of the uniform spring stiffness multiplier determined to be 2.27 from evaluations.

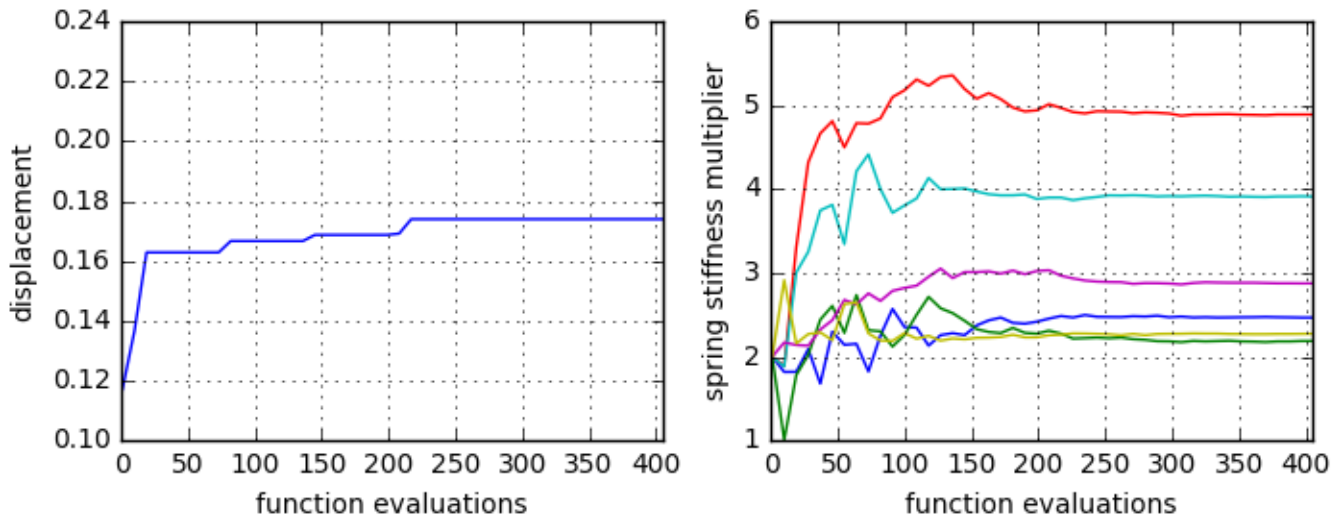


Figure 2: One optimization trial of nonuniform spring stiffness of six springs using CMA-ES elitism over 400 evaluations, each evaluation being 400 time steps in simulation. (a) Fitness value of 0.17 displacement attained after 217 evaluations. (b) Optimum values of nonuniform spring stiffness multiplier of six springs determined to be 2.46, 2.18, 4.88, 3.91, 2.87, and 2.27 from evaluations.

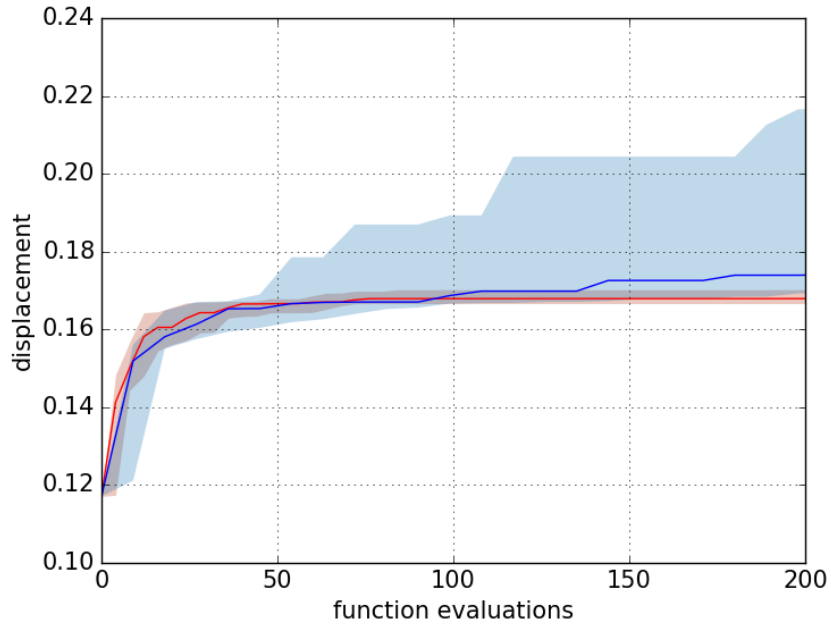


Figure 3: Median, first and third quartiles shown of tensegrity displacement fitness values of repeated trials of 200 evaluations, each evaluation being 400 time steps in simulation using CMA-ES elitism. Red represents uniform spring stiffness. Blue is nonuniform spring stiffness.

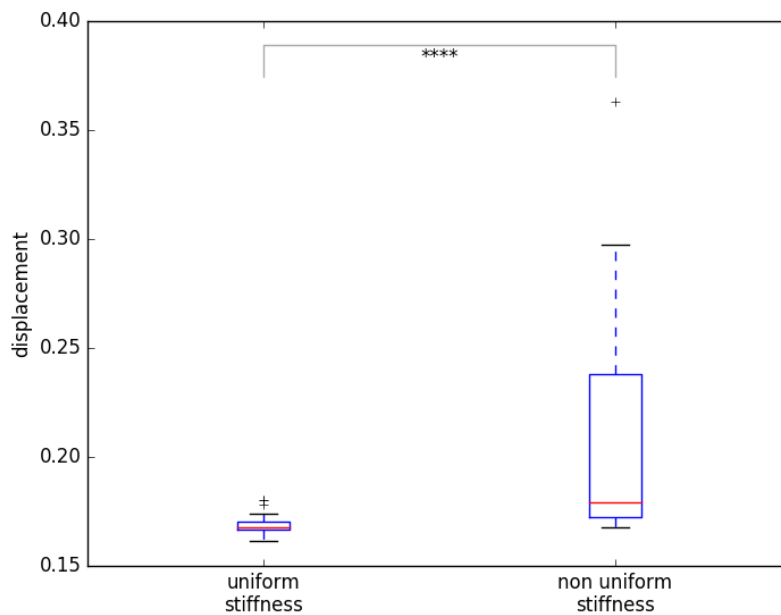


Figure 4: Median, first and third quartiles shown of tensegrity displacement fitness values at convergence for uniform and non uniform stiffness multiplier optimizations, each evaluation being 400 time steps. P-value represented of difference between data sets is $5.35049526923e-07$

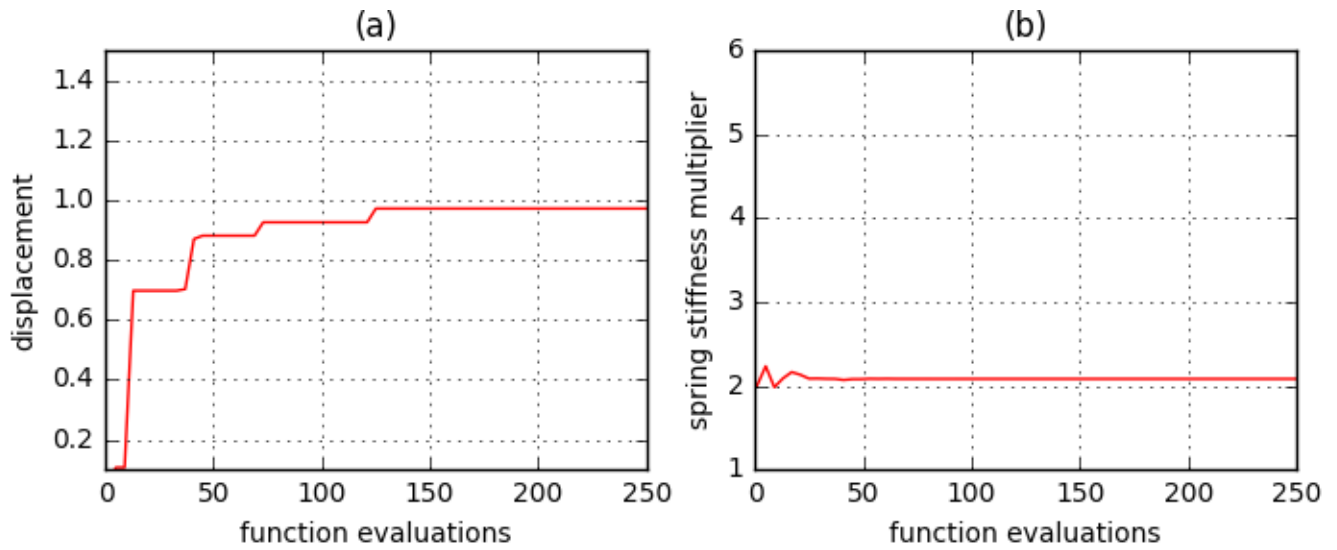


Figure 5: One optimization trial of uniform spring stiffness of six springs using CMA-ES elitism over 200 evaluations, each evaluation being 8000 time steps in simulation. (a) Fitness value of 0.97 displacement attained after 123 evaluations. (b) Optimum value of the uniform spring stiffness multiplier determined to be 2.08 from evaluations.

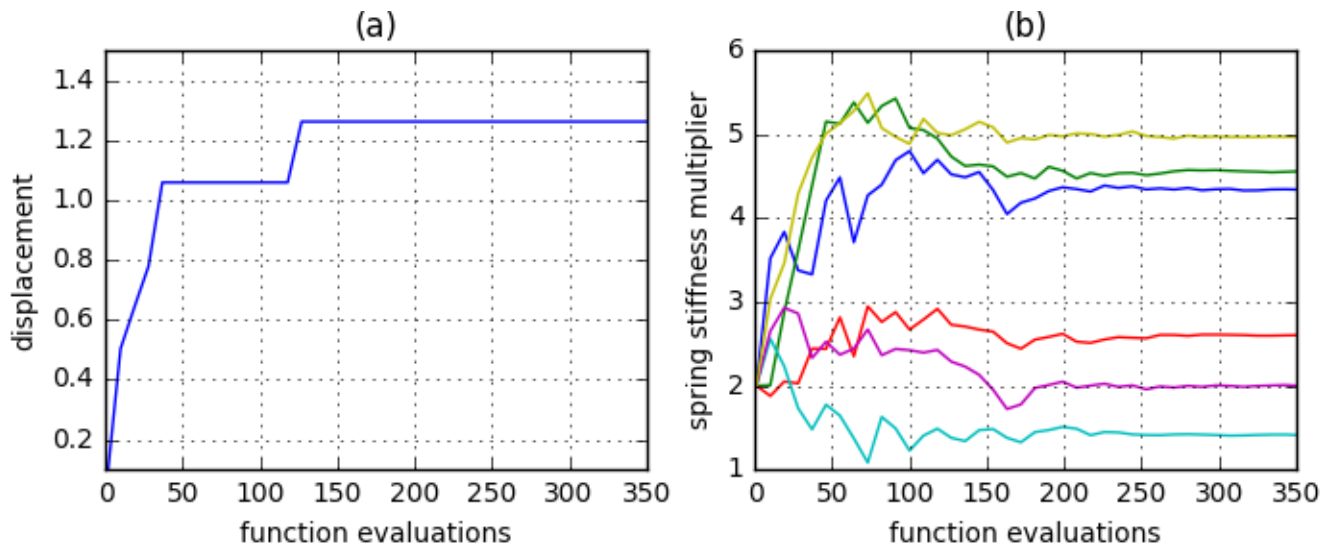


Figure 6: One optimization trial of spring stiffness of six springs using CMA-ES elitism over 400 evaluations. (a) Fitness value of 1.27 displacement attained after 127 evaluations. (b) Optimum values of the spring stiffness multiplier of 6 springs determined to be 4.35, 4.54, 2.60, 1.41, 2.00, and 4.97 from evaluations.

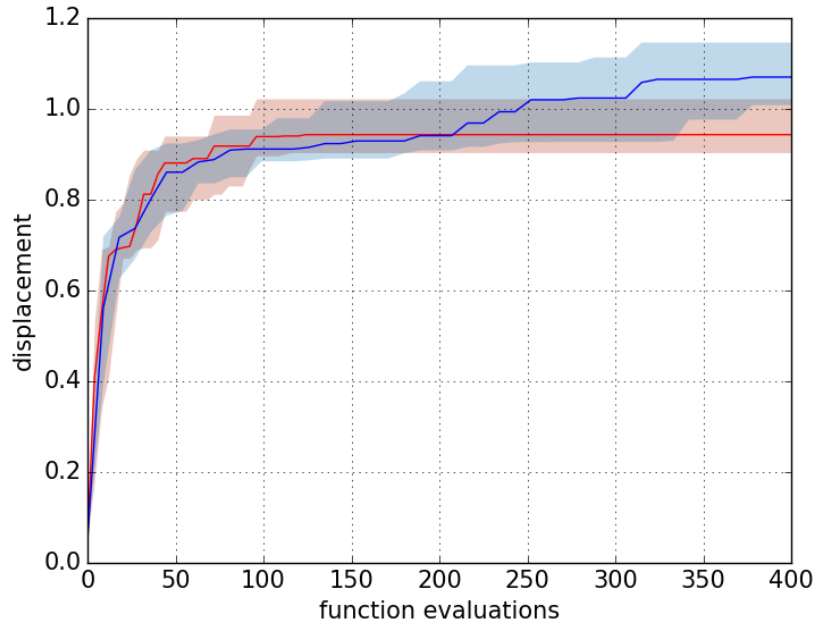


Figure 7: Median, first and third quartiles shown of tensegrity displacement fitness values of repeated trials of 400 evaluations, each evaluation being 8000 time steps in simulation using CMA-ES elitism. Red represents uniform spring stiffness. Blue is nonuniform spring stiffness.

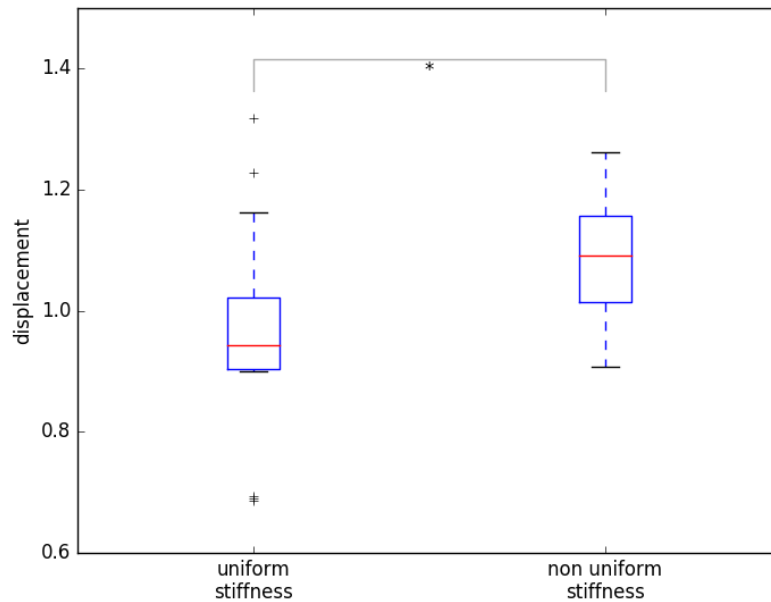


Figure 8: Median, first and third quartiles shown of tensegrity displacement fitness values at convergence for uniform and non uniform stiffness multiplier optimizations, each evaluation being 8000 time steps. P-value represented of difference between data sets is 0.013350786562.

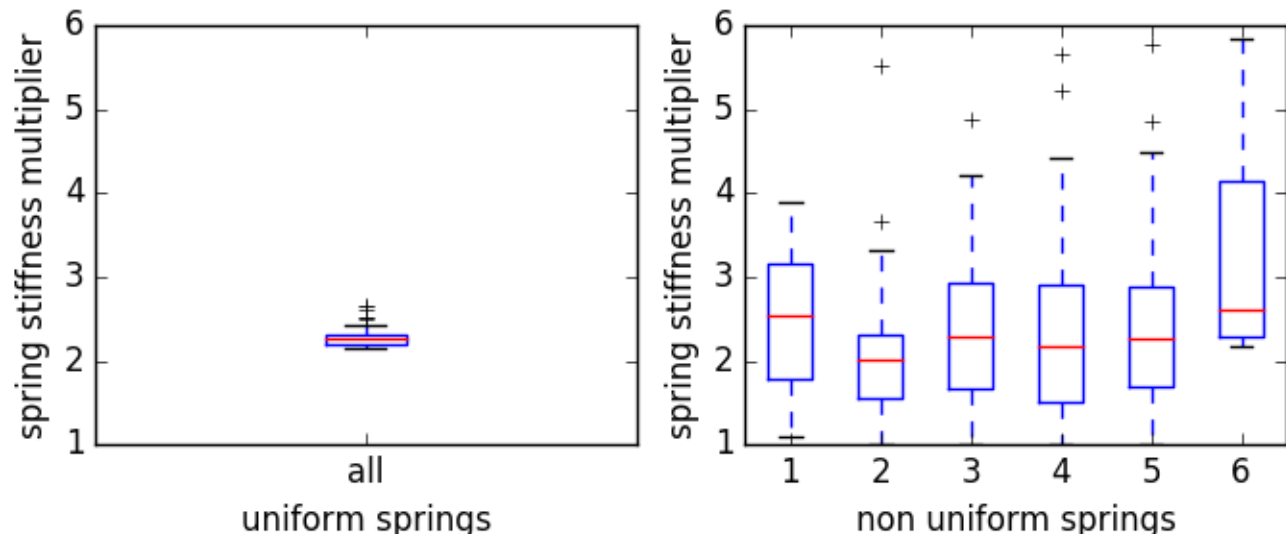


Figure 9: Spread of spring stiffness multiplier values at convergence for evaluations of 400 time steps

spring stiffness multipliers remained between 2 and 4 (Figure 2). The spring stiffness multipliers did not all converge to high values as would be predicted by looking at the hookean equation alone. In addition, the spring stiffness multipliers did not converge to a single best value, instead a spread of values was seen (Figure 9).

The data shows that altering the spring stiffness multiplier between springs produces a range of displacement values and greater displacement values than having a uniform spring stiffness multiplier for the given set of six springs for shorter time intervals of 400 time steps (Figure 3, 4). A similar trend of greater displacement values for non uniform spring stiffness multipliers is seen for the longer evaluations of 8000 time steps (Figure 7). However, the difference in displacement values between uniform and non uniform stiffness multipliers is not as large and may not be considered as significant (Figure 8).

It is interesting to note that trials with uniform spring stiffness not only had a more limited range of fitness values for both intervals (Figure 4, 8), but also displayed a limited a limited range of values of stiffness multipliers (Figure 1b, 5b). The best multiplier stiffness values at convergence rarely strayed from the starting 2.0 value. In these cases the best stiffness multipliers for the six springs was determined to be 2.27 (Figure 1b) and 2.08 (Figure 5b). This limitation in variation was not due to a limitation on mutation or generation size in the optimization. The original starting value of stiffness multipliers was 2 and was kept the same between all trials of uniform and non uniform spring stiffness. The initial sigma values (step size or error guess of best value) were kept the same between all trials. Lambda values (offspring between generations) were also kept at default values. Yet within the best offspring from the evaluations, the stiffness multipliers did not go below 2 or above 4. Trends early in the optimization may have effected the range of values tested. The increase in

uniform spring multiplier stiffness in the early evaluations (Figure 1b) is also responsible for the decrease in the fitness value of displacement (Figure 1a). This may have effected the optimization algorithm which have chosen to test values further away from the start point that seemed to decrease the fitness value. However, as seen in the non uniform trials, the relationship between fitness value and spring stiffness multiplier is not necessarily linear.

Overall this data suggests that having tensegrities with a range of spring stiffnesses could lead to greater displacement through locomotion. The displacement values did not follow a linear trend with changes in spring stiffnesses. This contributed to the diversity in displacement values during the optimization of the non uniform spring stiffness multipliers. This also suggests that altering the spring stiffnesses could lead to more diverse patterns of locomotion which may also not follow a linear trend with increasing spring stiffness.

6.2 Biological Grasshopper Spring Comparisons

In comparison to a grasshopper, our tensegrity did not move effectively. In short intervals, the body length to distance traveled ratio between a grasshopper and a tensegrity is not comparable. An adult grasshopper is able to jump 20x its body length in a single jump, however, our tensegrity, after optimization of stiffness, only averaged 1.1x of its body length in displacement after 8000 simulation steps. Even in repeated jumps, the average jump length of the adult American locust during a 20 minute interval was found to be approximately 10 body lengths and the locust jumped for 37% of that time [14]. This is over 1000 body lengths for a locust in this period. If we were to compare this value to our average values of .17 tensegrity body lengths for 400 time steps where a time step is .05 seconds in simulation and extrapolate the values then 20 minutes would be 240,000 time steps and the total body lengths moved by a tensegrity would be about 100. However, by this same scaling, a time interval of 8000 time steps with the same parameter optimization should have produced 3.3 body lengths. Yet, the body lengths were closer to 1.1. This is due to the tensegrity not moving in a straight line from spring actuation. Juvenile grasshoppers have even better endurance and can jump 4x as many body lengths as an adult in 20 minutes [14]. Even though a tensegrity robot does not show fatigue as an adult grasshopper would, the grasshopper still has a greater net distance traveled over extended intervals.

A change in grasshopper size does not correspond to an equivalent change in grasshopper force production or distance traveled as cuticle stiffness changes throughout their development [12]. In the tensegrity model, if the spring stiffness is held constant, scaling is not expected to change the force mechanisms. Thus the tensegrity would be expected to produce an equivalent change in force production and distance traveled with respect to body length.

In addition, the changes seen in grasshopper force production during development are different from

spring stiffness changes in tensegrities as their relationships between spring stiffnesses and distances differ. In grasshoppers there is a general increasing trend of increased cuticle stiffness and jump performance [7]. However, the relationship between spring stiffness and displacement in the tensegrity model did not have an increasing linear trend. This was seen clearly as higher spring stiffness values did not produce greater movement forward and the spring stiffness multipliers did not converge to the highest values possible.

We did not directly compare force production of a grasshopper versus the tensegrity robot due to the different means of force production and energy release. The tensegrity has multiple springs actuating and the position of the springs leads to much of the energy being dispersed throughout the body. In addition, the tensegrity actuates its springs several times before it produces movement that moves it forward and increases its distance traveled. In contrast, the grasshopper pushes down directly at the end of its tibia with the energy stored in its springs.

7 Future Work

Spring loading affects the optimal spring stiffness for energy storage [13]. Spring loading is comparable to the amount of time the springs of the tensegrity are actuated via the firing pattern. In the trials done within our study, the firing pattern and parameters were kept constant. The optimal firing pattern parameters were only found once for the spring stiffness multiplier of 2. These parameters were then kept constant for the remainder of the trials. The parameters and spring stiffness were optimized separately due to time constraints in running the simulation, as adding more parameters to optimize exponentially increases the run time when using the CMA-ES algorithm. In future work, running optimizations for firing patterns parameters and spring stiffness multipliers together might produce interesting results. These trials could be accomplished either by allocating more time to running simulations or using an optimization algorithm that requires less time.

Morphology plays a large role in locomotion effectiveness and patterns. This is seen by the differences in locomotion ability between structurally different organisms. It would be interesting to modify the configuration of the tensegrity, by adding more struts or modifying it such that it does not have the spherical icosahedron shape and then run optimizations of spring stiffness on the new configuration. Different configurations may produce more variations in locomotion through altering the spring stiffnesses. In the current setup, 6 out of 24 of the springs are being actively actuated. Different configurations of tensegrity structures may require less springs actuated to produce movement, thus requiring less energy to move. Also, these configurations may be more conducive to movement through altering spring stiffness, thus producing greater displacement values than the current setup.

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