Periodicity Emerges from Evolved Energy-Efficient and Long-Range Brachiation

Richard W. Timm, Hod Lipson

Mechanical and Aerospace Engineering, Cornell University
Ithaca, NY 14853, USA

[RWT7|HL274]@cornell.edu

Abstract. This paper examines the emergence of periodic motion as consequence of evolutionary pressure for energy-efficient partially-passive dynamic brachiation. Brachiation was simulated for gibbon-like creatures in a realistic physics environment. The morphologies of the brachiators were identical to each other and consisted of a simple 3-bodied system - two arms and a torso. Brachiator performance was controlled by their genome, which contained their initial position at $t=0$ and torque functions which were applied to the shoulder for $t>0$. Performance for each brachiator was measured by total distance traveled and energy-efficiency of locomotion. Brachiators found in the first two Pareto-optimum curves were selected for reproduction. It was found that energy-efficient long-range motion resulted in periodic motion in the brachiators.

1 Introduction

Brachiation is the hand-over-hand locomotion used by various primates to move about. The type of brachiation simulated in this research is called a continuous contact brachiating gate, because at least one arm is in contact with the environment at all times. The results of this research show that periodicity emerges from energy-efficient long-range brachiation of simulated gibbon-like creatures.

In this work we investigate the hypothesis that periodic brachiation is an emergent property of energy-efficient and long-range brachiation. In previous studies, periodic motion was a condition externally imposed on the system.

Ape brachiation was first compared to the swing of a pendulum by Tuttle [3]. Fleagle made the same comparison in more detail in 1974, but he studied the kinematics using video recordings of brachiation, and used mechanics to understand continuous contact brachiation [4]. Fukuda et al. used brachiating systems to test under-actuated systems with the goal of measuring the efficacy of various control algorithms [5]. Nishamura and Funaki designed, simulated, and built a three-link brachiating robot [6,7]. Control was performed via final-state control with error learning.

Gomes showed that solutions exist for a number of brachiation models: a point-mass model with a massless pivot arm, a single rigid body, and a two-link model. Ricochetal motions were also shown to exist for a three-link model and a five-link model [1]. However, periodicity in all of these models was forced, which makes the method outlined in this paper novel.

2 Brachiator Model

The morphology of the brachiator was chosen to best satisfy two objectives: to best mimic the functional shape of a natural brachiator, and to make the brachiator simple. Among the variables considered were the number of rigid bodies and the number of control motors to include in the system. The final model chosen consisted of 3 rigid bodies and 2 torque control functions. The bodies are connected at a common shoulder by a pin joint. Alternative morphologies that were considered include a 5-body model and a 2-body model. However, the 2-body model did not appear close enough to a natural brachiator to prove interesting, and a 5-body model would have taken too long to evolve due to complexity. Fig. 1 is a diagram of the selected morphology.

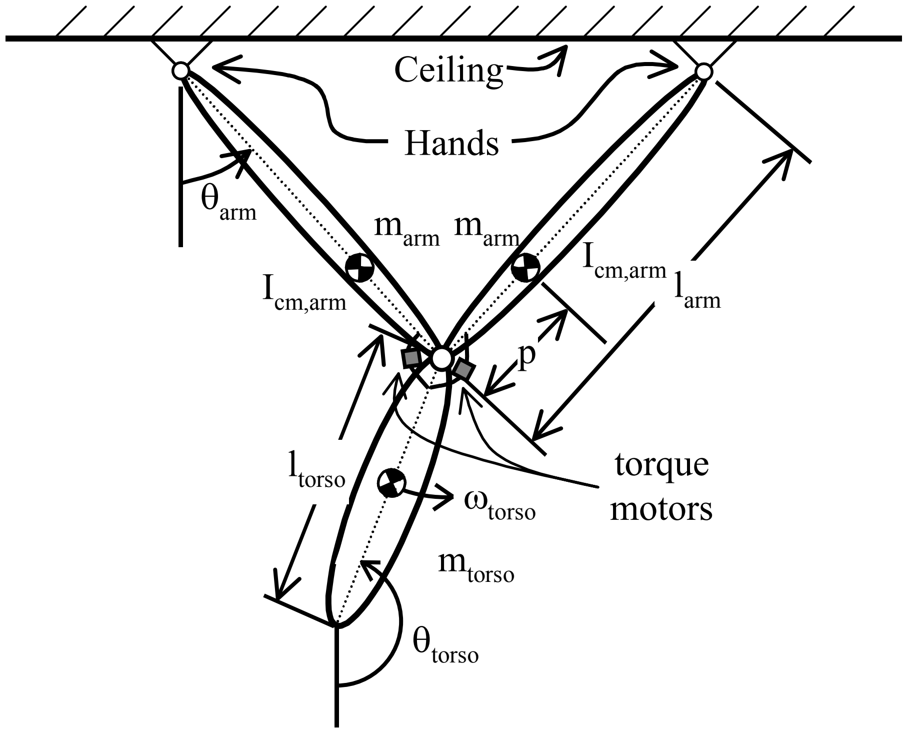

Fig. 1. The three rigid bodies that make up the brachiators consist of two arms and a trunk, which all connect at a common shoulder. Torque is created between the arms and the body by torque motors, which are controlled by the torque function stored in the genome. Note that the centers of mass for the two arms do not lie in the centers of the arms. Also, the ceiling contains an infinite number of handholds, not just the pin joints shown.

When both arms are attached to the ceiling, there are only 3 variables that are needed to describe the system: the angle of the body, the angular velocity of the body, and the angle of one of the arms.

Friction was not intended to be a part of the system. However, due to the nature of the simulation, small computation errors arose that slowly took energy from the system, performing a similar function as friction. This did not largely affect the system, but it would have prevented any type of purely passive brachiator from being designed.

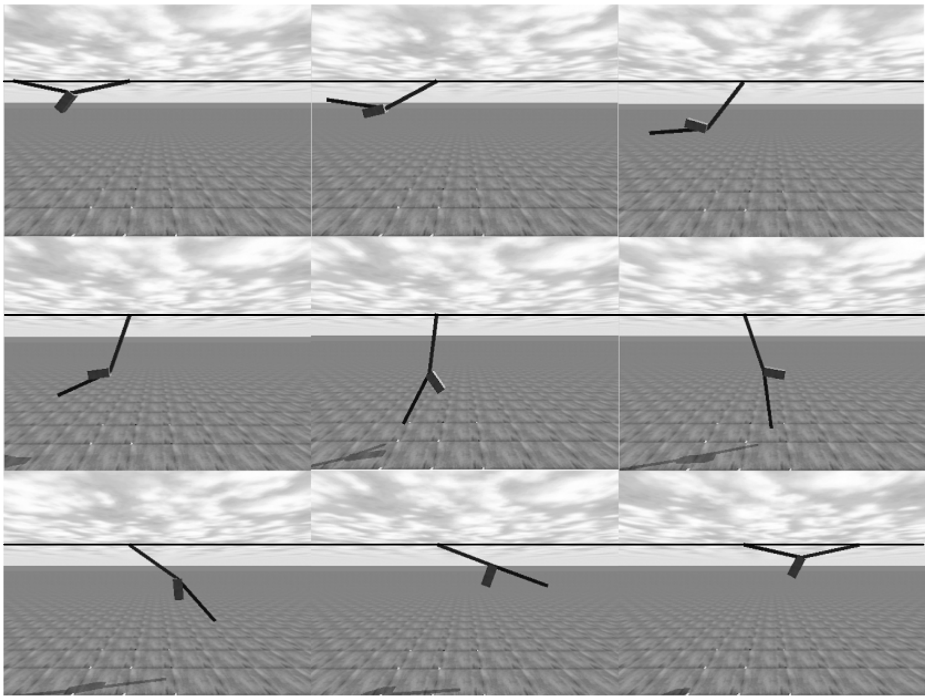

Fig. 2. This is a series of screenshots from the Open Dynamics Engine™ simulation. The steps are evenly spaced starting at t = 0 and ending at t = 1.335. This particular brachiator can travel 167 meters over the course of 60 swings, with an efficiency of 0.26 meters/joule.

2.1 Mass and Geometry Parameters

Mass and geometry parameters were taken from physical data on adult gibbons compiled by Gomes [1]. However, gibbons with these parameters did not perform very well in terms of efficiency or brachiation distance. The arm value was raised in length from 0.92 m to 1.37 m, and a significant boost in performance was observed. While this departure from such desirable numbers was distasteful, it was necessary to achieve any sort of result.

Table 1. Brachiator body parameters. The parameters for both arms are the same. The moment of inertia is measured around the axis going into the page.

Length	l_{arm}	0.92 m
	l_{torso}	0.50 m
Mass	m_{arm}	0.8 kg
	m_{torso}	6.0 kg
Center of mass (cm) location	p/L	0.125
Moment of inertia, arm	$I_{cm,arm}$	0.055 kg m^2

2.2 Torque motors

Two torque motors were used to control brachiation. The functions that control these torque motors were derived from the genome of the brachiator and were purely functions of time. The motors applied torques between the arms and body that were equal and opposite. As soon as the free arm grabbed the ceiling, the torque motors switched between arms, and the swing time was set to zero. This was done to minimize the size of the genome. Note that a periodic torque function does not necessarily imply periodic brachiator dynamics. Indeed, brachiator motion in initial generations was not periodic.

2.3 Energy, Distance, and Efficiency Calculations

The simulation progresses in time by finite steps. Over one of these time steps, the torque motors apply constant torques to the various bodies. The energy expended between one of the arms and the body over a time step is calculated using the following equation:

$$E = \left| T(t-\Delta t)((\theta(t)_{body} - \theta(t)_{arm}) - (\theta(t-\Delta t)_{body} - \theta(t-\Delta t)_{arm})) \right| . \quad \textbf{(1)}$$

E is energy in joules (always positive), t is the current time, Δt is the time step, T is the torque exerted between the body and arm, θ_{body} is the angle of the body, and θ_{arm} is the angle of the arm. The total energy used over the course of the brachiation is simply the above equation summed over time for both arms.

Distance is calculated whenever the free-swinging arm grabs onto the ceiling. This is the same as the distance between the current handhold and the first handhold.

Efficiency is calculated on a length-per-unit-energy basis. When the brachiator grabs the next handhold, the new efficiency is calculated by dividing the new distance by the total energy expended.

2.4 Quantification of Periodicity

The simplest and most logical method of quantifying periodicity is by comparing the positions and velocities of the brachiator at successive ceiling-grabbing events. This provides a natural time of comparison, as there are only 3 angles (two for position, one for velocity) that describe the system at that particular moment. Periodicity is found by first calculating the distance in Euclidian space between the vectors that describe the start and finish of a swing. A brachiator that has very periodic motion will have a very low distance between these vectors. By dividing the number of swings by the sum of the distance vectors over many swings, a total measure of periodicity can be found. When this number is high, the average periodicity over the swings will also be high.

3 Evolutionary Algorithm

The simulation of brachiators was performed in two dimensions using rigid body dynamics [1]. The population consisted of 100 brachiators. Brachiation of each individual ceased upon fulfillment of one of several stop conditions, whereupon the performance characteristics of the brachiator were calculated, and the next individual was loaded into the simulation. When the entire population had brachiated to completion, a new population was created from the individuals selected by a Pareto curve where the two axes of the Pareto chart were the total distance traveled and energy-efficiency of motion.

3.1 Fitness parameters

Two parameters were measures of fitness: the total distance traveled, and the energy-efficiency of motion. The total distance traveled was simply the position difference between the initial point of contact ("handhold") and the last handhold before the brachiation was stopped. The energy-efficiency of motion was defined as the total distance traveled divided by the total energy used to brachiate.

3.2 Selection

Individual brachiators were selected for reproduction if they lay on the first or second Pareto-optimum curve comparing distance traveled and efficiency. 98 offspring were created by combining the Pareto winners via crossover; the other 2 were the brachiators that had the highest distance and highest efficiency. However, when this was used by itself, it led almost invariably to a population that had only one long-distance brachiator, with the rest being "efficiency experts." This was due to the fact that it is much harder to achieve long-distance brachiation than high-efficiency brachiation (the efficiency can be infinite if the torque function and energy are zero, which is not hard to accomplish). Also, super-efficient brachiators generally have poor performance in the realm of distance. Long-distance brachiation is much more sensitive to small changes in the genome than is efficient brachiation. To combat this effect, individuals were also put in the breeding pool if they demonstrated stable brachiation (greater than 60 swings) and also had a higher efficiency that the longest-distance brachiator. This had the effect of adding an additional selective pressure that favored long-range brachiators, which was crucial when using a population that began from a random set. The origins of the 60-swing number are discussed in section 3.2.

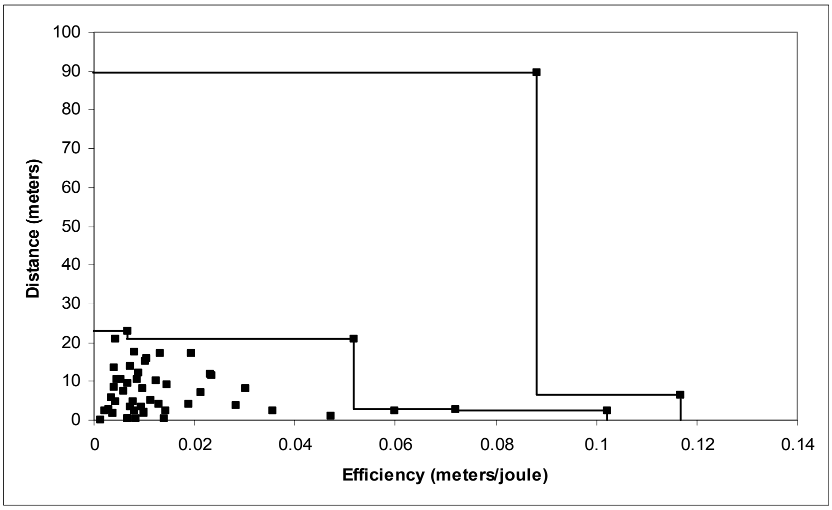

Fig. 3. The brachiators selected for reproduction lay on the first and second Pareto optimization curves. Two curves were used as to not so severely limit the gene pool. This particular data is from the first generation of randomly generated brachiators. There are roughly 50 brachiators represented here – the rest failed to even swing once for a positive distance.

Distance is more constrained than efficiency in terms of the potential upper limit because the combination of the brachiator geometry and the potential number of swings set an upper limit for it.

3.3 Genome Components

The genome contained the two inputs for the simulation: the initial state of the system and the control functions. Every brachiator had the same physical shape and mass parameters. The only differences between them at the beginning of each brachiation were the angles at which the body parts started. The genome contained the initial 2 angles and 1 angular velocity that were required to set up the system. During the course of the brachiation, the torque motors were controlled by the torque control function, which was also encoded in the genome. The genome values were simply the values of the torque function at particular times spaced at a regular interval. Intermediate values of the torque function were evaluated by linearly interpolating between points. There were two torque functions, one for each arm, and they both contained 11 values spaced at 0.15 seconds. This provided torque control for both arms for 1.5 seconds. This time was found to be sufficient in duration to control the brachiators.

3.4 Brachiation Stops

There were 4 potential events that forced the brachiation of an individual to stop: the time of the swing grew larger than 2 seconds, the swing resulted in backward motion, the total number of swings grew larger than 60, or the torso inverted itself during brachiation. Upon cessation of brachiation, the next individual was loaded into the simulation. These stops were created to halt brachiation that no longer progressed toward a positive result and would have otherwise wasted processor time.

When the time of a swing grew too large, brachiation became too slow, and it was unlikely that brachiation is occurring efficiently. That is because efficient brachiation depends largely on passive-dynamical motions that require little or no energy to perform. These motions have set periods. By approximating the 3 bodies as a single-bodied pendulum and calculating the half-period thereof, a very rough approximation for the time of a swing was found. Such a pendulum would have a length that is approximately equal to the length of an arm plus half the length of the body. The half-period of a pendulum is:

$$P = \pi \sqrt{L/g}\ . \tag{2}$$

For the brachiators used in this simulation, this was 1.3 seconds. When the time of any swing grew larger than 2 seconds the simulation was stopped, as ample time for the brachiator to complete its swing had already passed.

When a swing resulted in backward motion, brachiation was not progressive because the brachiator had ceased to move forward. Therefore, brachiation was stopped when the next handhold was closer to the starting point than the current handhold.

When the number of swings grew larger than 60, brachiation was stopped. This number was found through experiment to be important. Once brachiators were able to reach a certain number of swings, it became very likely that they could keep brachiating forever. The effect this had on the simulation is that it halted progress of the algorithm, because neither of the first two stop cases could have been met and no new individual could be simulated. 60 was found to be the number of swings where the transients had mostly died out and endless brachiation began.

The last event that stopped brachiation occurred when the torso inverted itself. Such motion is not life-like. Before this was implemented, brachiators would exploit this loophole and swing madly, causing the torso to loop again and again. Though not energy-efficient, this behavior sometimes enabled the brachiator to travel long distances, which allowed these particular brachiators to remain in the gene pool.

3.5 Population Generation

The initial populations were generated to maximize the spread of torque functions between brachiators but also keep them within reasonable bounds. At the same time, a series of random numbers did not seem like it would result in good brachiation, because the torque control function would be wildly changing from value to value. For these reasons, an algorithm was developed that provided a wide range in values yet maintained torque function smoothness. This was done by assigning a random value to the spot in the genome that represented time 0, then creating a random slope, and applying the slope to calculate successive genome spots. During the course of this, the slope was changed by small increments (accelerated), which changed the concavity of the torque function. This can be compared to a thrown ball that is being subjected to turbulent winds – it mainly stays the same course but experiences some alterations during flight.

4 Efficiency-Periodicity and Distance-Periodicity Correlations

Periodicity in brachiation emerges naturally when distance and efficiency are optimized. Figs. 6 – 8 below support this conclusion.

4.1 Periodicity vs. Distance

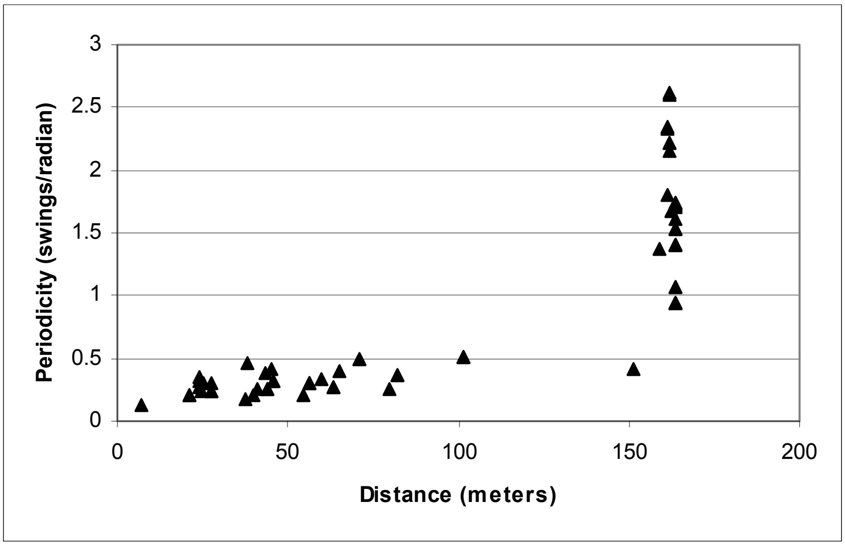

Fig. 4. A scatter plot showing periodicity vs. distance brachiated for a population of 100 brachiators after 53 generations. While not all of the long-distance brachiators exhibit high levels of periodicity, they are they only group that does.

Long-range brachiation must behave in a stable manner, and it is clear from Fig. 6 that the long-range brachiation exhibits more periodicity (stability) than short-range brachiators. Instabilities would otherwise trigger one of the stop mechanisms, which include backward brachiation, swing period lasting too long, etc.

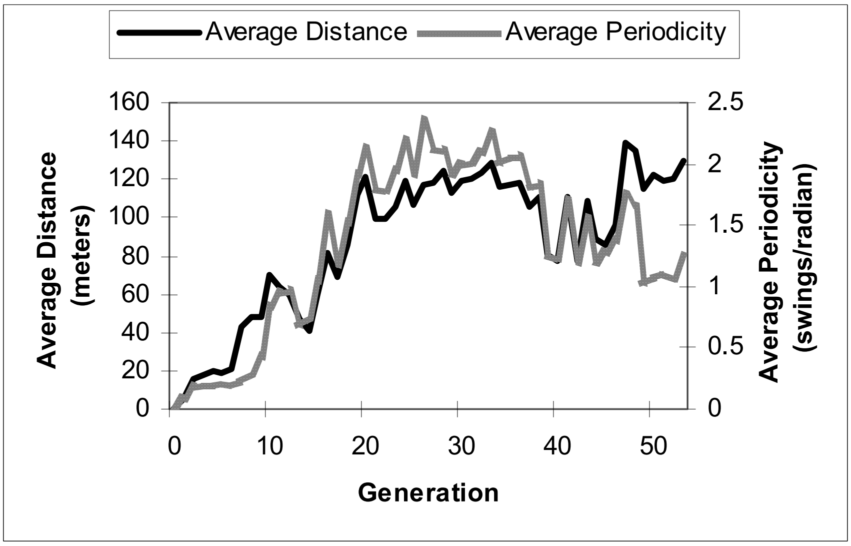

Fig. 5. There is a strong correlation between the average periodicity and the average traveling distance of the population. This data reflects that correlation over 53 generations.

4.2 Periodicity vs. Efficiency

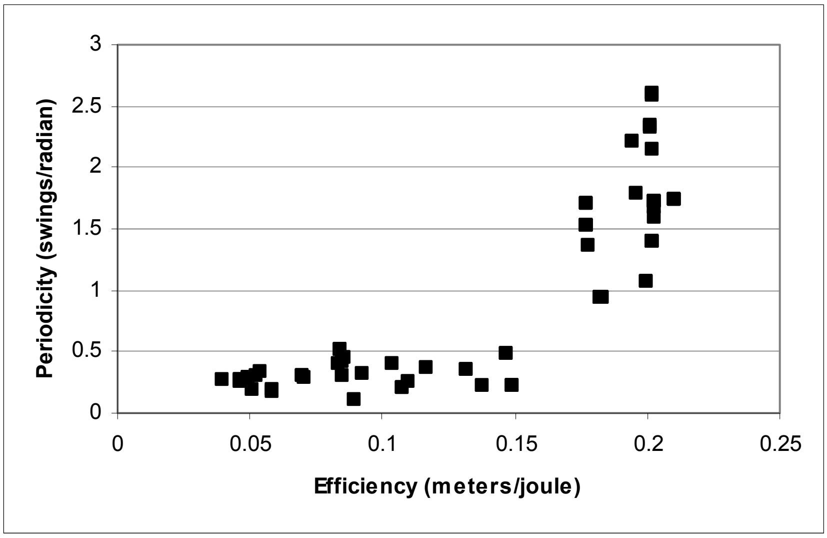

Fig. 6. There is also a strong correlation between efficiency of motion and periodicity.

The figure above suggests that periodic motion has indeed arisen from efficient motion. All the best energy-efficient and long-range brachiators are also the most periodic.

This would also be the case for a more simple system consisting of a single brachiation pendulum. Such a brachiating machine would be capable of no energy losses if friction were not present. It could do this by attaching itself to the next handhold without colliding with it (velocity equal to zero just as it reaches it). This type of system would be perfectly efficient and perfectly periodic. It would appear that a more complex system such as the one detailed in this paper might have the potential of similar behavior.

Acknowledgments

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