Using evolutionary robotics to estimate maximum running speeds under non-Earth gravitational conditions

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1 Introduction

Gravity is a major determinant of the performance of the locomotor system and the forces required to accelerate against a gravitational field cause significant loading on skeletal elements. Measurements on the surface of the Earth report at least a 0.7% variation between 9.76 and 9.83 ms^{-2} [1], although commonly in biomechanics this local variation is ignored and a conventional value of 9.81 ms^{-2} chosen [2]. Different values of gravity can be simulated by accelerating the local frame of reference using centrifuges [3] or aircraft following a variety of flight paths [4]. The effects of gravity (and specifically micro-gravity) on the musculoskeletal system have been the subject of considerable study since the early days of space flight with the conclusion that gravity has profound effects on many aspects of the biology of organisms underpinning the later planning of space missions and astronaut wellbeing [5].

Such experimental approaches are very expensive and difficult to perform and the evolutionary robotic paradigm is a useful alternative especially if we want to extend our species coverage to include extinct animals [6]. In this approach a robot is created that is anatomically and physiologically matched to the target species and evolutionary algorithms are used to generate the muscle activation patterns that optimise some global metric such as velocity or cost of transport. Such robots can be physical [7] or created as multibody dynamic simulations which allows much higher biofidelity than can be achieved with current manufacturing processes and also allows high performance computing to be used to speed up the optimisation process [8]. Using a digital twin can also allow multiphysics simulations where, for example, skeletal strain can be used as an optimisation constraint and this can improve the accuracy of the gait reconstructions, particularly in fossil animals where experimental validation is not an option [9].

There is considerable interest in simulating locomotion under the different gravity conditions that are found on the Moon and the various potential habitable planets whether to understand the underlying biomechanics [10], or to improve the design of living spaces [11], or for generating animated sequences that can be used in games and movies [12]. None of these approaches so far consider the impact of gravity on skeletal loading and our previous work suggests that this is a major limiting factor, especially for animals with high body masses [9]. The aim of this study is therefore to re-evaluate two of our previously published forward dynamic simulations to explore the effects of different gravity conditions when limits are placed on maximum bone loading.

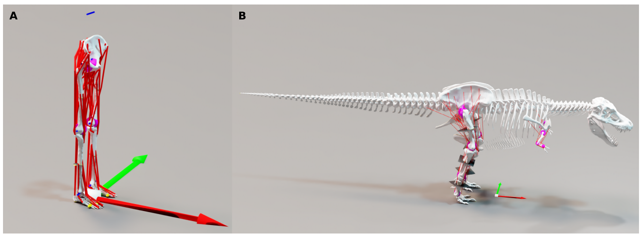

Figure 1: The 3D models (rendered using NVIDIA Omniverse). A: *Tyrannosaurus*, B: Human.

2 Methodology

Two previously published bipedal simulations of animals with very different body masses were used in this study: human (70.8 kg) [13] and *Tyrannosaurus rex* (7206.5 kg) [9]. These simulations are based on best estimate anatomical and physiological reconstructions with the muscle activation pattern for each gait cycle being chosen using a distributed genetic algorithm (GA) machine learning system. The underlying rigid body simulation is performed using the GaitSym2017 simulator[1] which implements wrappable Hill-style muscles with serial and parallel elasticity, and the bone bending strain is calculated using standard beam mechanics equations at the midshaft of the major leg bones. The anatomical details of the models are illustrated in Figure 1 and the full specification is available online[2]. The GA is set to maximise the forward distance travelled in a fixed amount of time and thus estimates the maximum speed achievable given the environmental conditions. The simulations are repeated under different values for the acceleration due to gravity and for different permissible peak bone stress. The gravity values chosen were for the Earth 9.81 ms^{-2}, Mars 3.71 ms^{-2}, the Earth's moon 1.62 ms^{-2}, and the exo-planet Kepler-452b ˜16 ms^{-2} [14]. The peak stress values were set at 50, 100, 200, and 400 MPs, and additionaly 800 MPa for *T. rex*. 100 MPa corresponds to the predicted maximum bone stress for terrestrial vertebrates allowing a safety factor of 2 [15].

[1]https://github.com/wol101/GaitSym_2017
[2]https://github.com/wol101/Model-Zoo

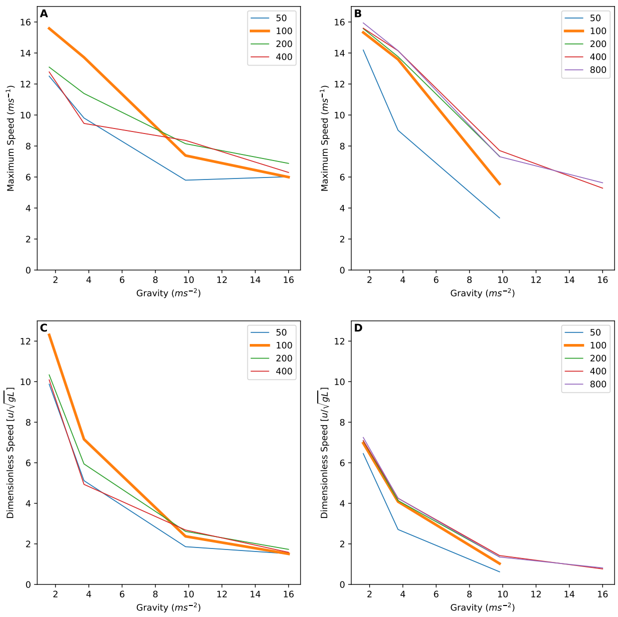

Figure 2: Maximum forward velocities for different maximum stress limits [MPa]. AC: Human; BD: *Tyrannosaurus*.

3 Results

The GA machine leaning system was able to find muscle activation patterns that would allow stable locomotion in almost all cases except for the 50, 100, 200 MPa stress limits under Kepler-452b gravity. The maximum speeds achievable under all conditions are illustrated in Figure 2 (both absolute forward velocities and also converted to Froude Numbers [dimensionless speed] using the standing hip height as the characteristic length) and movie files showing these maximum speed examples are also available online[2].

4 Discussion

The results show that bone loading has a major effect on the ability to run under different gravitational conditions, and this effect is greater for *T. rex* than the human. The *T. rex* simulation is not even able to sustain low speed locomotion without putting undue strains on its skeleton under gravitational conditions that are higher than Earth, whereas the human can at least walk in all the cases. Dynamic similarity predicts that walking speeds should increase as gravity increases [10]. This has been verified experimentally for walking [4] but would be expected to apply to any gravity dominated locomotor mode. However the results from this simulation study do now show such dynamic similarity for maximum running speed and this is in line with experimental results on running in simulated reduced gravity [16]. Increased gravity leads to reduced peak running speeds even in situations where bone loading is in not a factor (the 400 and 800 MPa limit cases) which would suggest that higher power outputs required to generate a significant aerial phase at higher gravity may be the main issue. However the *T. rex* model was unable to produce any stable gaits at physiologically believable safety factors under high gravity conditions illustrating once again that bone loading is the main limiting factor for very large bodied animals.

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