Effects of exoplanetary gravity on human colonization and the evolution of native lifeforms

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ODYSSEUS

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Project background

Our goals were to determine the range of gravity suitable for human settlement and predicting the course of evolution in altered gravity.

We studied the limit at which our bones and muscles fail, as well as the gravitational effect on locomotion. We discussed the role of gravity in organism size and build.

Finally, we applied our conclusions to a list of discovered exoplanets.

1.

COLONIZING EXOPLANETS

Let’s start with the human body

Do we have what it takes?

Static compressive stress
The first obstacle to colonizing a high-gravity planet is the question of whether or not our skeleton can support us while standing upright.

Muscular endurance
With an increase in gravity, menial tasks such as standing oneself up from the ground become difficult, if not impossible.

Energy for locomotion
Being able to walk is the most crucial aspect of everyday human life, assuming we wouldn’t be willing to accept permanent vehicle-assisted transportation.

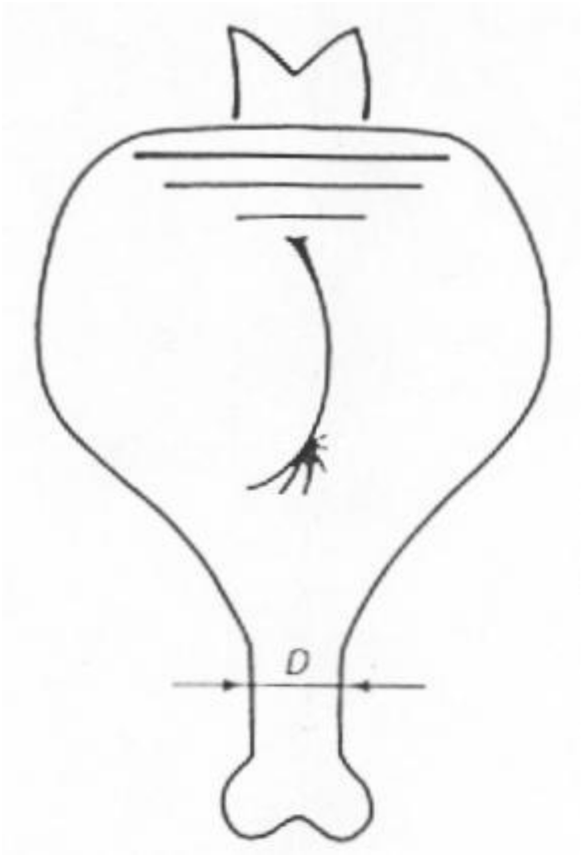
Standing → Rising → Walking

Bone failure
The simplest model of an animal constitutes of a single bone supporting the center of mass. [Hokkanen, 1985]

Taking the average cross-section of a tibia, and the compressive strength of bone (170MPa), we obtain:

$$g_{max} \approx 918\, m/s^2$$

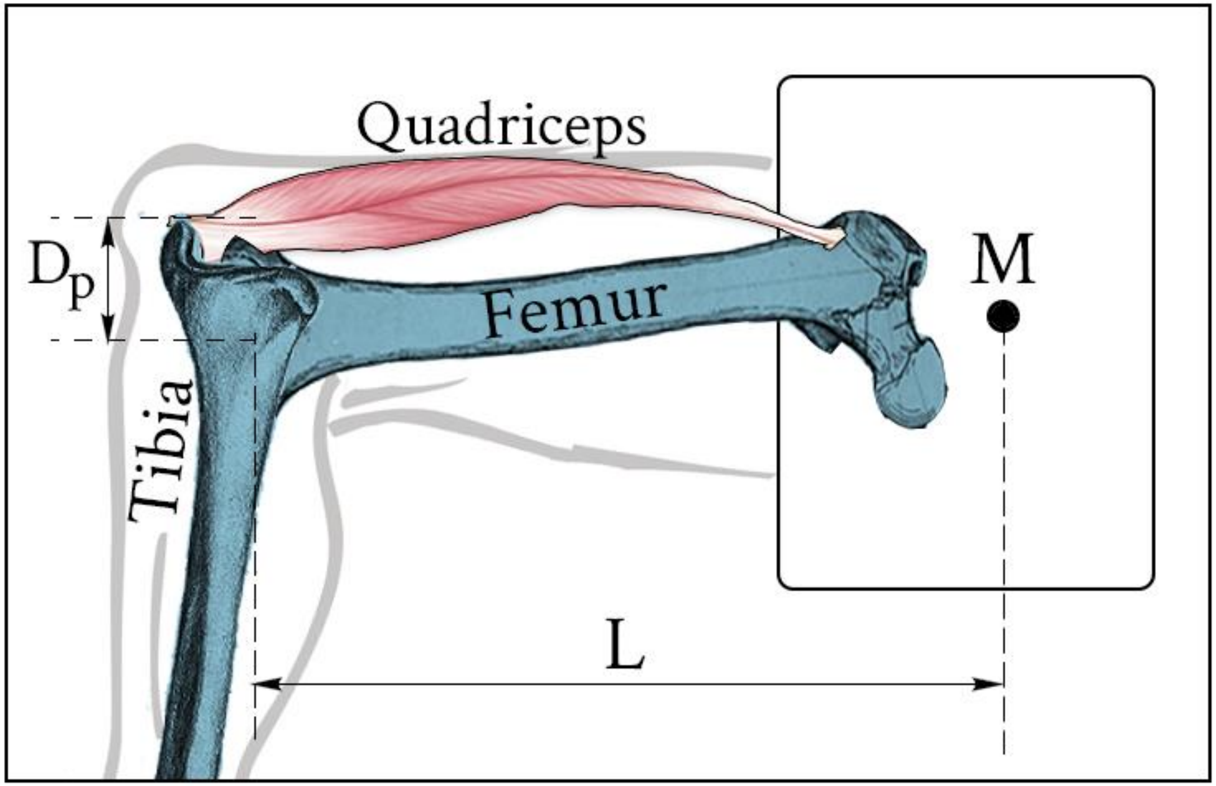
... or, factoring in dynamic stress, 10 times Earth gravity g_E.



Physicist's rendering of animal, pen on paper, 1985

Standing → **Rising** → Walking

- in case of a fall, the ability to stand oneself up from the ground is crucial, and presents a good criterion to test the limits of our muscular system
- quadriceps must balance the gravitational torque on mass M



Standing → **Rising** → Walking

- the maximum force a quad can produce is documented in medical literature via isometric stress, which yields:

$$g_{max} \approx 10.7\ m/s^2$$

Amazingly, our muscular system
is very well-adapted to Earth!

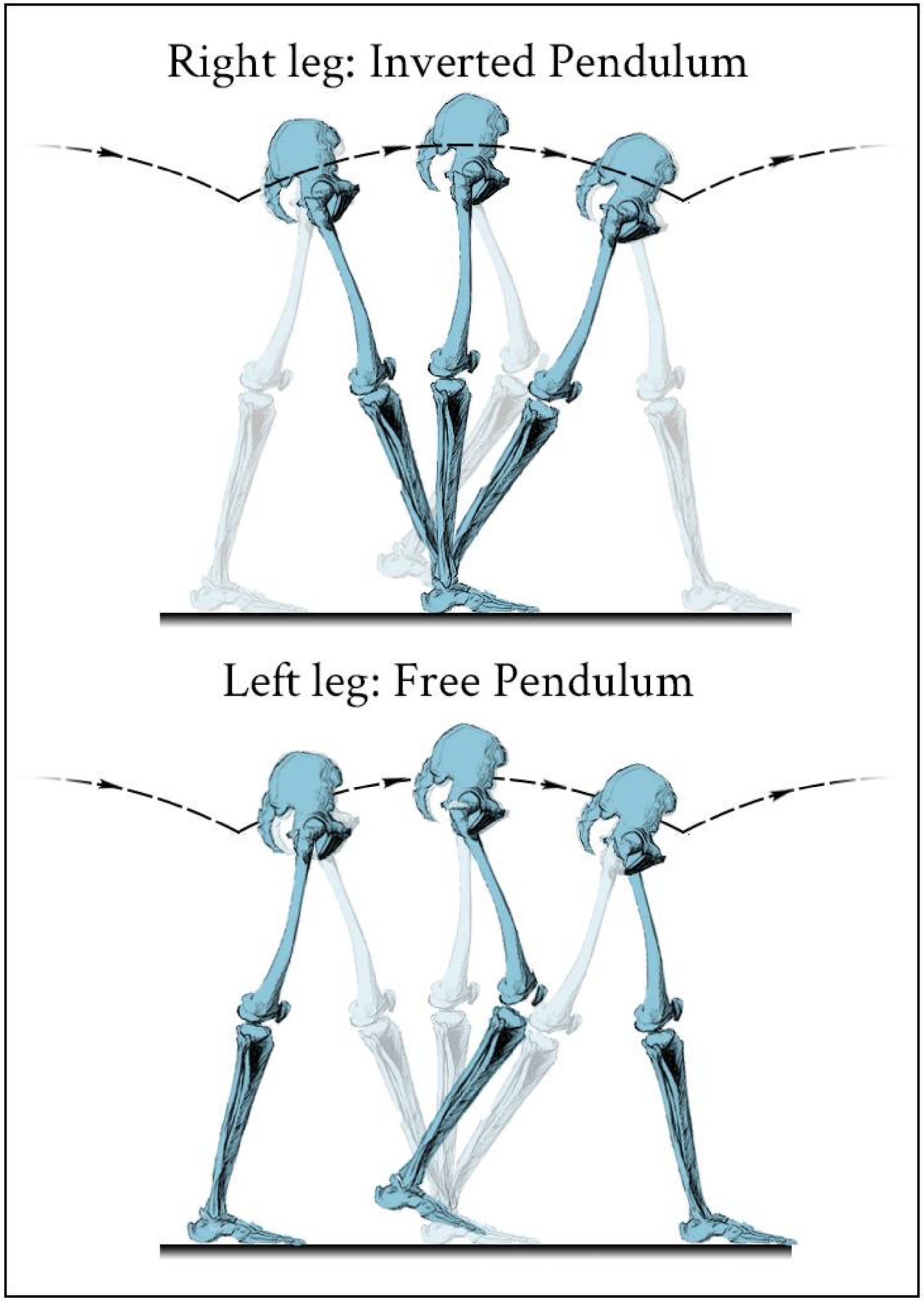
- however, squat standards show an elite athlete can lift 4x more than the average person, and if we add 20% as assistance from other muscles whilst standing up:

$$g_{max} \approx 5g_E$$

The inverted pendulum gait

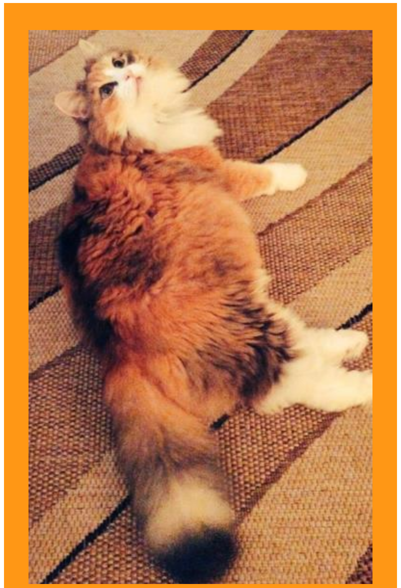
In order to proceed with our analysis of locomotion, first we must introduce the concept of the *inverted pendulum gait*.

This is the most energy-efficient means of limb-assisted locomotion. In an ideal world, an organism would not require any energy to maintain this type of gait.



Where do we find the inverted pendulum gait?

Two-legged organisms



Four-legged organisms

Many-legged organisms

Everywhere, regardless of limb number, species, environment, and possibly even planet. Nature is remarkably energy-efficient.

One more thing: The Froude number

For walking to be possible on the surface of a planet, centrifugal force at the top of the movement arch must be weaker than the gravitational pull.

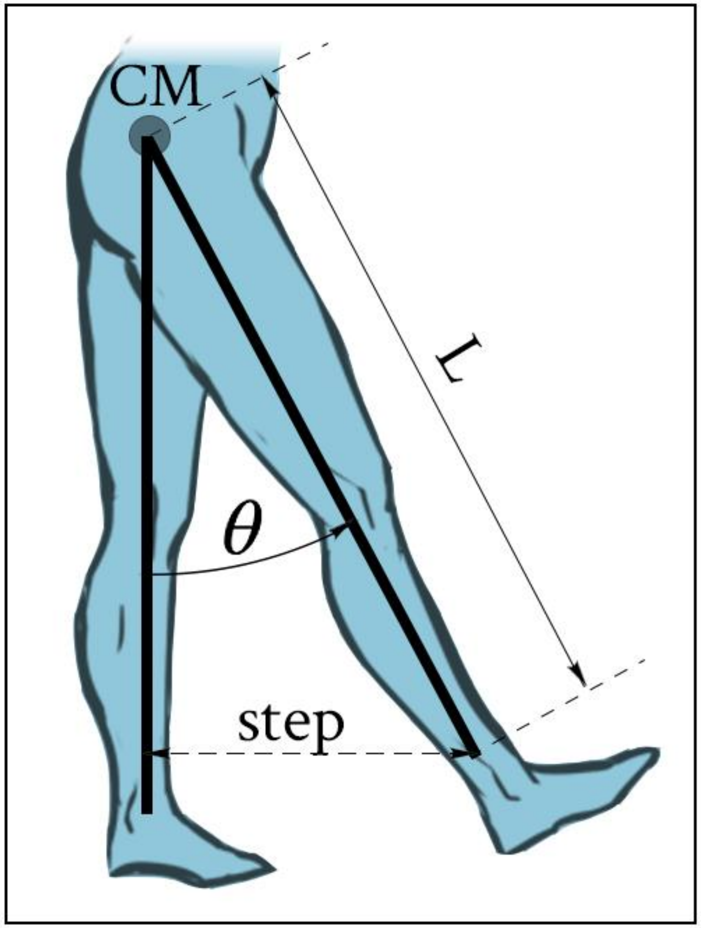
$$\frac{mv^2}{L} < mg, \quad \text{or} \quad F = \frac{v^2}{gL} < 1$$

Froude number

(universal characteristic of gait)

All animals transition to a run, trot or bounding gait already at $F \approx 0.5$, regardless of gravity! This sets the limits for our model.

(You felt it! Walking under water is difficult because F is large.)



The energetic expenditure of walking
We are finally ready to make our analysis of the work required to take one step forward.

$$W_s = mgL(1 - \cos\theta)$$

$$\sin\theta = \frac{vt_s}{L}$$

Natural period of human leg: $4t_s = 2\pi\sqrt{2L/3g}$

$$W_s = mgL\left(1 - \sqrt{1 - \frac{\pi^2}{6}F}\right)$$

But what is the greatest energy the human body can put into walking?

Meet our benchmark.

Hafþór Björnsson

Standing → Rising → **Walking**

Strongman Hafþór Björnsson walked 5 steps with a 649 kg log on his back, breaking a 1000 year old Viking record.

We'll use this result to find the gravity at which Hafþór's free walking requires the same energy as walking with the log here on Earth.

$$W_s = mgL\left(1 - \sqrt{1 - \frac{\pi^2}{6}F}\right) \xrightarrow[\text{Taylor}]{\text{small } v} g_{max} \approx 4.6 g_E$$

~10 g_E

Gravity our skeleton can withstand

~5 g_E

Gravity at which we can stand up from the ground

~4.6 g_E

Limit after which walking becomes impossible

2.

GRAVITY AND EVOLUTION

How does gravity shape life?

How would long-term settlement of an exoplanet reshape humanity?

Low-*g* humans

- lower blood pressure
- low-placed heart
- muscle atrophy
- shriveled limbs
- leaping gait

High-*g* humans

- higher blood pressure
- high-placed heart
- increased muscle mass
- thicker limbs
- slow pace

How does gravity shape exoplanetary lifeforms?

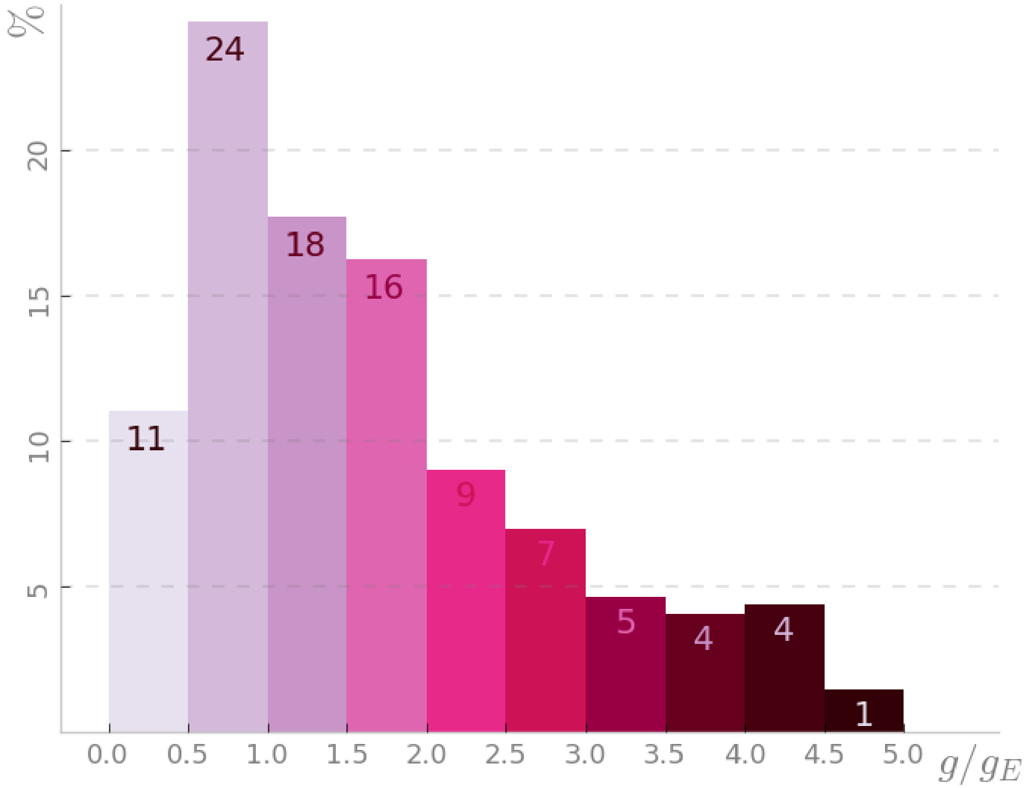
Gravisensing
Cellular colonies can communicate changes in gravity via electrical signals. Studies have found that cellular radius $\sim g^{-1/4}$.

Skeletal Young modulus
For bones of given Young modulus, limb thickness would have to grow proportionally with gravity to prevent breaking.

Circulatory system
Even sedentary lifeforms, like trees, need to circulate fluids. To increase the maximum allowed height, one must decrease density of fluid.

Swimming and flying
Creatures which aren’t confined to land can circumvent these limitations. Their mobility depends on atmospheric density.

Where do we stand, relative to exoplanetary lifeforms?



Out of 1932 confirmed exoplanets, 344 fit our sub-$5g_E$ category.

Others go as far as $50g_E$ or even $200g_E$. Most lifeforms we encounter are expected to be polar bear sized.

However, majority of known sub-$5g_E$ planets show promise for colonization.

Conclusions

Humans are well-adapted to Earth gravity. Even with intense training, we could not colonize planets with $g > 5g_E$.

High/low gravity would force humans to evolve differently. Gravity severely limits native organism size.

The span of exoplanets habitable for humans is relatively small.

Thanks!

Any questions?

You can read my paper at:
app.box.com/v/Exoplanetary-Gravity

Credits:

Image resources:

Slide 1 & 2: ESA/Hubble
Slide 6: Hokkanen, 1985
Slide 8: Kyoko Hamada
Slide 10: Oleg Nikishin
Slide 11: AFP/Boris Horvat
Slide 13: Guinness World Records
Slide 14: Ilkka Kinnunen

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