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OBRAZLOŽENJE MENTORA

Poštovani,

Studenti četvrte godine istraživačkog studija fizike **Dora Klindžić** i **Mateo Kruljac** prošle su me godine kontaktirali u želji da se uključe u izradu rada za natjecanje Odysseus (https://www.odysseus-contest.eu). Odysseus je vodeće svjetsko natjecanje vezano uz svemirsku znanost za mlade. Na natjecanju postoje 3 grupe ? "Skywalkers", "Pioneers" i "Explorers". U sve tri kategorije u prosjeku se prijavi preko 100 radova. Posljednja kategorija je za studente 17-22 godine i traži od studenata da postave znanstvenu tezu, istraže ju, naprave znanstveni rad te ga prezentiraju. Natjecanje se organizira na razini države, regionalnoj razini i svjetskoj razini. Dora i Mateo prošle su godine na razini države osvojili prvu nagradu, a na regionalnoj razini nagradu za najinovativniju ideju. Valja spomeuti da su sudionici na natjecanju studenti su iz cijelog svijeta (npr. Indija i Kamerun 2016.), no broj im nije točno poznat jer se objavljuju samo radovi koji se plasiraju na regionalno natjecanje.

Dora i Mateo prihvatili su temu koju sam im ponudio te samostalno krenuli u istraživanje, teorijsku razradu i pisanje teme. Specifično, u ovom slučaju tema je bila "Effects of exoplanetary gravity on human colonization and the evolution of native life forms", u prijevodu "Efekti egzoplanetarne gravitacije na kolonizaciju čovječanstva i evoluciju živih bića". Kao što se vidi iz naslova teme, radi se o sinergiji fizike, svemirskog istraživanja i biologije. Temu su studenti podrobno istražili u literaturi te razvili svoje modele koji su unaprijedili znanje u području egzobiologije.

Rad je prihvaćen od strane hrvatskog povjerenstva za Odysseus natjecanje te je osvajanjem prvog mjesta u državi plasiran na regionalno natjecanje. Natjecanje se održalo u Gnasu/Grazu, Austrija, 2.-4.5.2016. Studenti su na natjecanju morali samostalno prezentirati rad kao na konferenciji te napisati znanstveni članak. Obje su radnje obavili izuzetno uspješno, i iako se nisu plasirali na svjetsko finale, osvojili su nagradu za najinovativniju znanstvenu ideju.

Uz dodatnu činjenicu da se radi o inače izvrsnim studentima, vidljivo je da je obavljen izvrstan znanstveni posao, te su uz istraživanje studenti svoj rad i napravili u formi znanstvenog članka, prezentirali na natjecanju i osvojili nagradu. Iz tih ih razloga toplo preporučam za dodjelu Rektorove nagrade.

Srdačno,

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Effects of exoplanetary gravity on human colonization and the evolution of native life forms

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ABSTRACT At some point in the future, if mankind hopes to settle planets outside the Solar System, it will be crucial to determine the range of planetary conditions under which human beings could survive and function. Additionally, we should be able to anticipate the traits of any lifeforms we could possibly encounter. For this purpose, in the first part of our paper, we observe the limitations which gravity imposes on the human body, and in the second part, the influence of gravity on the course of evolution.
Initially, we examine the ultimate limits at which the human skeleton breaks and muscles become unable to lift the body from the ground. We also produce a new model for the energetic expenditure of walking, by modelling the leg as an inverted pendulum. Both approaches conclude that, with rigorous training, humans could perform normal locomotion at gravity no higher than 5 g_{Earth}. Bearing this limit in mind, we consider the long-term effects on humans inhabiting planets with weaker or stronger gravity.
In the section on exoplanetary life, we recount how gravity dictates the scaling of size from the cellular to the macroscopic level. We use this information to speculate on the form and internal build of lifeforms that evolved in alternate gravity, ultimately applying our findings to examples of known exoplanets.

KEYWORDS
Gravity
Evolution
Exoplanets
Astrobiology

1. COLONIZING EXOPLANETS

With the discovery of many new potentially habitable exoplanets, one needs to consider which ranges of planets' physical parameters are suitable for immediate human settlement. Aside from the average temperature, insolation, pressure, atmospheric composition, etc., all of which can be solved with spacesuits, the basic parameter of a planet is its **surface constant of gravity**, which will determine if a person can stand upright and move reasonably fast from one place to another.

Studies of animal sizes [1] have already determined many physical limits the animals can reach in conditions existing on Earth. In this text, we aim to take another approach, fixing the size of the animal, in this case a human, and determining the range of gravitational accelerations g in which it can stand and move. To do so, we will look at the largest g in which our skeleton still won't fail and in which our muscles can still perform the basic movements of standing up and walking.

A. Bone failure

Let us, for the sake of simplicity, imagine the whole human weight being supported by a single upright bone, in this case representing the entire skeleton. The weight Mg of the entire human mass acts on the bone with a diameter D and a cross section A and produces an axial compression equal to:

$$\sigma = \frac{Mg}{A} \propto \frac{Mg}{D^2} \propto gD\,, \tag{1}$$

where we used the fact that the cross section of the bone is proportional to the square of its dimension and the mass of the human to its cube. Since we want to obtain a numerical result, it is not enough to deal with proportionalities. Measurement data [2][3] shows that for an average 50 kg mammal, which we can take as a first approximation of a human, the cross sectional area A of a tibia equals $2.7 \cdot 10^{-4}\mathrm{m}^2$ and the compressive strength σ of the bone is about 170MPa, giving the maximum gravity the human can support as:

$$g_{\max} = \frac{\sigma A}{m} = 918\,\mathrm{m/s^2}\,. \tag{2}$$

This is indeed a large number, corresponding to more than 90 times the Earth gravity! However, this maximum value needs to be reduced since it considers only static compressive stress on the bone. Once we start moving, the dynamic stress takes over due to bending of the bones subject to gravitational torques. It has been shown experimentally [2][4] that the total stress increases approximately by a factor of 10 during normal running, thus reducing the maximum gravity to $\approx$ 10 times the Earth gravity. The same studies suggest that a factor of 10 might be too large, however, as these were conducted on larger animals (such as cows) they can not be reliably extrapolated to human sized mammals.

B. Muscle strength

A criterion for muscle strength will be the ability of the human to get up while seated or lying down. A visual representation of the problem is given in Fig 1.

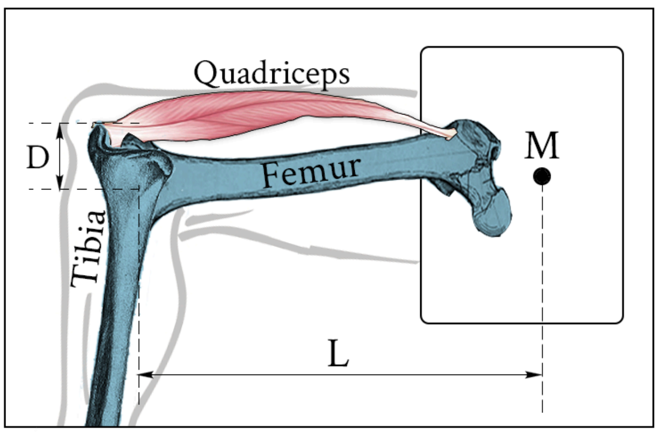

Figure 1 A representation of the human leg. The human has a mass M. The distances denoted in the image are discussed in the text.

We consider the entire mass M of the human to be located in its center of gravity. The quadriceps connects the massless femur and tibia and is responsible for getting up. In order to do so, the force with which the quadriceps must pull has to be at least:

$$F \geq \frac{MgL}{2D}\,, \tag{3}$$

in order to at least balance the gravitational torque on mass M. In this expression, D is the torque arm of the muscle force and L is the torque arm of the gravitational force. The factor 2 arises since humans have 2 legs and each needs to lift only half of the total mass. Another way to express the maximum force the quadriceps produces is with the help of the maximum isometric stress σ_m muscles can produce:

$$F = \sigma_m A_m = \sigma_m \frac{M_m}{\rho_m L_m}\,, \tag{4}$$

where the indices m denote the muscle and A is the muscle cross section, expressed in the second equation with the help of muscle mass M, its density ρ and and its length L. Once again, the values for these parameters are known for a mammal of 50 kg [2][5]. Finally, the torque arm L is longer than the muscle length and approximated by $L = 1.5L_f$, where L_f is the femur length. Plugging in all the numerical values, we obtain the limiting value of g:

$$g_{\max} = \frac{2\sigma_m M_m D}{\frac{3}{2} M \rho_m L_m L_f} = 10.7\mathrm{m/s^2}\,. \tag{5}$$

This is an extraordinary result, showing how well our muscle system is adapted to life on Earth! It would appear that living on planets with increased gravity would be very difficult due to our relatively weak muscles. However, we could either try to increase our muscle strength or move around with the help of technology. Evidence from Earth suggests that increase in muscle strength is possible within some limits. Looking at isometric squat standards for 50 kg men [6], one can see that an average person can lift about 36 kg, while an elite athlete can lift 145 kg, which is an increase by a factor of $\approx$4. Of course, we also use our arms and other muscles when getting up, so we'll include that help as, say, an extra 20%. Thus, one could safely assume that with rigorous training, we could get up at gravity values of $\approx 10.7 \cdot 4 \cdot 1.2\,\mathrm{m/s^2} \approx 5g_{\mathrm{Earth}}$.

One could argue that we could have used the world squat record for a 50 kg man, but that's a result only one person can achieve, while there are quite a few elite athletes. The latter is far more useful information if we wish to colonize a planet. Since the quoted strength increase factor of $\approx$4 is the same for all weight classes [6], $5\,g_{Earth}$ should be the maximum gravity for them as well.

We can see that increased gravity induces stress on the muscular system much more so than on the skeletal system. This was to be expected, since we all know it is relatively easier to get strong than to break a bone. The limit on the surface gravitational constant therefore arises mostly from the ability to get up from the floor using your muscles. However, assuming that vehicle-assisted transportation is unacceptable for long-term settlement on planets, we must also examine the energetic expenditure of walking.

C. Locomotion

Walking can be accurately represented by the '**inverted pendulum gait**', as in figure 2. The leg that supports the weight is stiff and behaves like an inverted pendulum, with the body's center of mass on top. The free leg swings forward as a free pendulum, although in reality, it's not a completely conservative system - we know we have to use energy to swing it. In an ideal scenario, though, once an organism started walking in such a stance, it would not require any energy to maintain the walk. Therefore, walking in the inverted pendulum gait is the most energy-efficient means of limb-assisted locomotion, and since it appears in every land animal on Earth, we can assume that it will be present in extraterrestrial life, too.

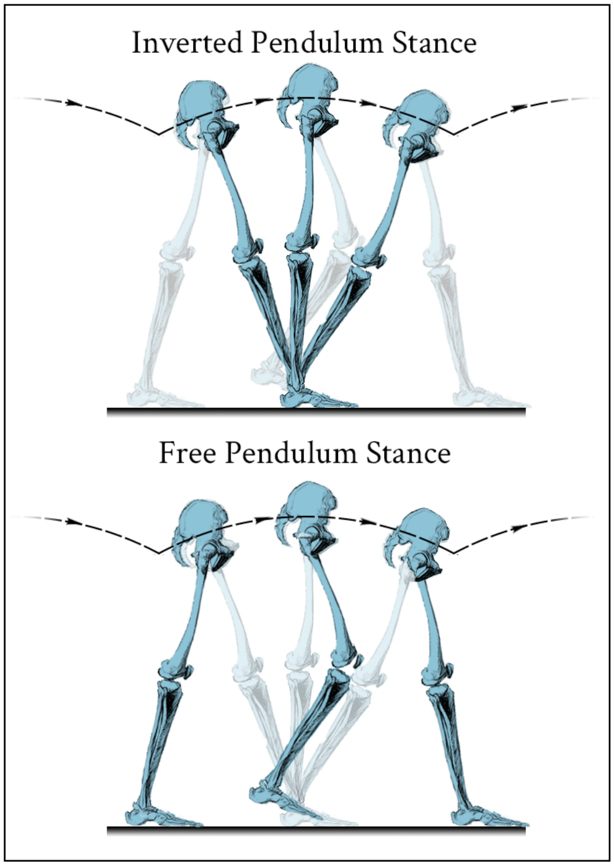

Figure 2 Whilst walking, one leg behaves as an inverted pendulum, and the other as a swinging pendulum.

Now, we may consider that most of the work is spent on making the center of mass (CM) 'bob' up and down [7]. In that case, the CM repeatedly oscillates between maximum kinetic energy, at the bottom of the movement arch, and maximum gravitational potential energy at the top. The ratio of those two energies is proportional to

$$F = \frac{v^2}{gL}, \tag{6}$$

where v is the traveling speed, g is the surface gravitational constant and L is the limb length. The number F is called the **Froude number**, and studies have conclusively found that animals with nearly the same F exhibit the same gait [8] [9]. That is, the ratio of kinetic and potential energy of the CM determines if an animal will walk, run, trot or gallop at a certain speed, regardless of species.

How does this apply to the walk of bipedals, quadrupedals, or other creatures with an even number of legs? At the high point of the CM 'bobbing' at each pair of legs, there is a centrifugal force lifting it upwards, and at the same time, a gravitational force downwards. If the centrifugal force exceeds it, it will become impossible to keep the foot on the ground. (Think about the Moon - the astronauts could not walk at usual Earth walking speeds because every step sent them flying and they had to adopt a leaping gait.) The condition for this is:

$$\frac{mv^2}{L} < mg, \quad \text{or} \quad F < 1. \tag{7}$$

When the Froude number exceeds 1, walking becomes impossible. In reality, nature never pushes physics to the limits, so humans and animals consistently adopt a trot or run at around F = 0.5. A study [10] has shown that the transition from walking to running occurs at F≈0.5 regardless of gravity, by simulating a low-g environment and measuring the speed at which the transition occurs. This should work for every surface and every planet.

Now that we have the link between movement speed and limb length, let's see what we can say about the energetics of walking. The work required to 'bob' the CM upwards for a step that has the legs separated by an angle θ (figure 3) is equal to the difference of gravitational potential energies of the feet,

$$W_s = mgL\,(1 - \cos\theta). \tag{8}$$

We will use the step length s as a parameter, so we identify $\sin\theta = s/L$, and $s = v\,t_s$, where t_s is the time required for one step. Since the most energy-efficient way for the swinging leg to move is like a stiff pendulum, we can take the step time to be one quarter of the period of such a pendulum.

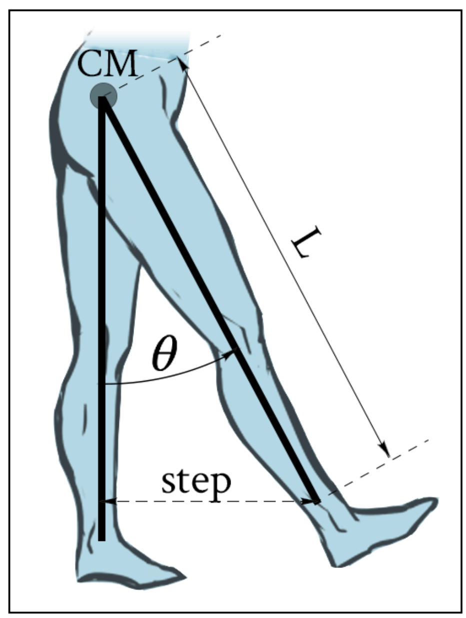

Figure 3 A sketch of our pendulum model. The legs have length L and are separated by an angle θ before each step.

Using equation (6) and the natural period of the human leg, $4t_s = T = 2\pi\sqrt{2L/3g}$ [11], we get:

$$W_s = mgL\left(1 - \sqrt{1 - \frac{\pi^2}{6}F}\right). \tag{9}$$

Let's put this to the test. According to medical information [12] used by the Wolfram Alpha computational engine, a woman of 65 kilograms and 20 years of age, briskly walking at 1.4 m/s, makes 100 steps per minute and spends 15 kJ of energy. That is roughly 150 Joules per step. Her Froude number should be around 0.3. By plugging all this into equation (9), we can estimate her leg size as 0.8 meters. This turns out to agree with the average leg length for the female population of this age [13], as well as the popular '45% of total height' estimate.

Notice that for equation (9) to hold, the expression under the square root has to be positive, i.e. $F \leq 0.6$. As mentioned before, it's been shown that the transition from walking to running occurs at $F \approx 0.5$ and the pendulum model does not apply for larger values of F anyway. Thus, we can assume our model is accurate within the order of magnitude for all creatures with the inverted pendulum gait. The energetic contribution of the swinging leg to energy expenditure is a few Joules at best, due to the leg's small mass.

Let's try to find the maximum gravity at which we could make a step. For that purpose, we'll look at the record set by a strongman (and Game of Thrones star) Hafþór Björnsson, who walked 5 steps with a 649 kg log on his back [14]. We used the world record because there are no official elite athlete results for log carrying, as we've found for squatting. Regardless, it is reasonable to assume Hafþór is close enough to an elite athlete that any error in setting him as our benchmark is probably negligible. We'll use equation (9) to find the gravity at which Hafþór's "free" walking is the same as walking with that log here on Earth. Now, he was walking very slowly, meaning $v^2 \ll 1$, i.e. $F \ll 1$. We will assume that Froude numbers on both planets are small and equal and use the Taylor expansion $\sqrt{1-x} \approx 1 - \frac{1}{2}x$ in equation (9), which then reduces to:

$$(M_{man} + M_{log})g_{Earth} = M_{man}g_{max} \tag{10}$$

which, for Hafþór's mass of 179 kg, gives $g_{max} \approx 4.6\, g_{Earth}$.

Comparing this result to the former result in subsection B, we find the models give a very similar result for the maximum bearable gravity.

2. THE REDIRECTION OF HUMAN EVOLUTION

In the last section we have analysed only the problem of transportation, discarding other changes that could influence our lives. That might be enough if we didn't plan on staying on the planet for too long, but if we were to permanently settle on a planet with different gravity, our bodies would undergo some important changes. While changes due to low gravity are known from space flights and adaptations that astronauts go through, as well as experiments on life development in space [15], not much is known about adapting to high gravity. It is logical to expect that if changes due to low gravity go "one way", then high gravity should drive them "the other way".

A. Cardiovascular system

Since gravity is pulling our blood down to our legs, the heart has to work to pump it up into the brain. Once we're subject to low gravity, blood rushes from our legs into the face. To adapt, the heart needs to work differently and change the blood pressure. To keep blood thin, new blood cells are destroyed and blood pressure lowers. Upon returning to Earth, astronauts have trouble standing because of blood rushing into their legs, sometimes causing fainting.

Following these results, we can conclude that subject to high gravity, blood goes from the chest region into the legs, resulting in larger blood volume and higher blood pressure. Because blood cells are more easily destroyed than created, the body's cardiovascular system should adapt sooner to low than to high gravity. Until enough blood cells are created, we could feel weak, like after donating blood, in addition to having trouble standing and walking.

We also know there are health risks due to low [16] and high [17] blood pressure, meaning high-g planets could cause damage to the heart, arteries, kidneys and the brain as well as leave us with dizziness, nausea and fatigue. Studies have shown that the average human body could not withstand gravity greater than $5\, g_E$ without passing out [18], because the heart couldn't pump enough blood into the head, so we'll assume that $4\, g_E$ is the maximum gravity the human body can withstand in the long run.

One can wonder if heart placement within the body could aid in adapting to different g-conditions. It has been shown [19] that tree snakes, climbing up and down trees, fighting gravity, have their hearts placed closer to their head than those crawling horizontally on the ground. We can conclude that organisms living on high-gravity planets would need to have their hearts close to their brains to function normally. Thus, "high-g humans" could have their hearts somewhere in their necks, or might not even have necks. "Low-g humans" would have their hearts placed somewhere in the middle of the body, in the stomach perhaps, so that it can pump blood equally to all parts of the body. It is logical to expect that the heart will be protected by chest bones, so "low-g humans" might have a skeletal stomach or a long rib cage. A high-g human might have a thicker neck, bigger shoulders and collar bones, protecting his heart. Additionally, our organs would also have to be stronger to prevent ripping and internal bleeding under a strong gravitational pull.

B. Bones and muscles

We know that working a muscle makes it grow and if it's unused, it shrinks. On space flights, astronauts suffer muscle atrophy, despite all the physical training they do. Muscle loss occurs mostly in the neck, back and leg muscles, which are our body's supporting group. With no gravity, no effort is needed to support the weight of the body or to keep our spine straight. Because of that, posture also changes.

Experiments with life development in space [15] produced newborn rats with shriveled limbs. It seems the rat's body "decided" not to develop its legs without the stimulus of gravity saying they're necessary. When the rats were brought back to Earth, their limbs never grew back to their usual size. So if we were to stay on a low-g planet, the next generation might already look differently as a result of low gravity during embryonic development. Although losing muscle happens quicker than building it, we can expect the same response on high-g planets. Our support muscles would have to grow bigger for us to be stronger.

3. EVOLUTION OF EXOPLANETARY LIFEFORMS

As we've demonstrated in the former sections, the human body is perfectly evolved for Earth gravity. Colonizing new worlds would not only be challenging in terms of physical adaptation to changed gravity, but also in terms of encountering the planet's native lifeforms, which are far better adapted to their environments than us. Therefore, we shift our focus to predicting how exoplanetary gravity would shape alien lifeforms, from the microscopic to the macroscopic level.

A. Single cells

When investigating the direction of evolution for complex organic life, it's natural to begin one's analysis with the building blocks: isolated cells. If we expect macroscopic organisms to evolve differently with varying gravity, then there surely must exist an underlying cellular sensitivity to gravitational forces. The principle by which cells detect the amplitude of gravity is dubbed '**gravisensing**' [20], a process which involves detection of all forces from which a cell must filter out and isolate the weak signal of gravity.

Obviously, such a process is highly energy-consuming, especially in the realm of cells, where forces of electricity vastly dominate over gravity and Brownian motion takes place. For this reason, gravity has long been neglected by science as a factor in determining cellular structure. However, some new explanations have proved gravisensing to be possible. For example, Albrecht-Buehler [20] demonstrates that colonies of cells have unique ways of communicating gravitational changes. By a simple calculation he shows that, due to viscous flow, a group of cells 'senses' the change of gravity. The electrical potential on cell membranes is so large that gravitational perturbations are easily amplified and filtered out by colonies of cells, causing them to alter their membrane structure, followed by a complete internal restructuring. This change of shape, in turn, reinforces the choice of a new shape, causing a feedback loop for further adaptation.

The arguments presented are reinforced by a study [21] which discovered the purpose of **F-actin**, a protein found in high concentration within the nuclei of very large cells. F-actin acts as an internal scaffold for mechanical stabilization of the cytoskeleton against gravity. In other words, the reason uncharacteristically large cells, like oocytes in mammals, can exist without collapsing in on themselves, is the additional internal support of a three-dimensional network of actin. This was a groundbreaking discovery, because it showed gravity to be a determining factor even at the cellular level.

Now, what does 'uncharacteristically large' mean? On Earth, a typical eukaryotic cell is of the order of $\sim 10\mu m$, whereas oocytes in the extreme can reach up to 1mm in size. The Princeton study [21] developed a model to help explain how gravity determines typical cell size. They define the *sedimentation length* L_{sed} as a length scale at which thermal energy is comparable to gravitational energy. For cells larger than L_{sed}, gravity will dominate. If we model the cell as a sphere of radius R and a difference in density $\Delta\rho$ with respect to the surrounding fluid, equating thermal and gravitational energies gives

$$L_{sed} = \frac{k_B T}{\frac{4}{3} R^3 \pi \Delta\rho g}. \quad (11)$$

The critical cell size radius R_{crit} will be equal to L_{sed}. It follows that

$$R_{crit} = \left(\frac{3 k_B T}{4\pi\Delta\rho g}\right)^{\frac{1}{4}}. \quad (12)$$

By plugging in the data [21] for eukaryotic cells on Earth, we obtain the result that gravity indeed dominates for cells larger than 10μm. But this equation also provides us with the means to predict the average dimensions of cells on planets with a different gravitational constant, because $R_{crit} \sim g^{-1/4}$. We may also consider surface temperatures on these planets, and find the ratio of average cell size on an exoplanet and on Earth:

$$\frac{R_{crit}}{R_E} = \left(\frac{T}{T_E}\frac{g_E}{g}\right)^{1/4}, \quad (13)$$

where the subscript E defines values on Earth (290 K for temperature and $9.81 m/s^2$ for the gravitational constant).

Apparently, living beings on high-g planets would comprise of rather small cells. For instance, on 2g, the typical cell would be 15% smaller than on Earth. On warmer planets, cells could grow to be larger, but there's also a limit to this as most proteins coagulate (get destroyed) at high temperatures. On the other hand, low-g organisms could support very large cells, most likely visible by the naked eye.

B. Size

We can predict the average size of an exoplanetary population by looking at its energy expenditure. A way of estimating the energy available to an individual organism is modeled after Simpson [22]; where we take the mean population size N, available surface A, total incident energy per unit surface E_s (insolation flux), the organism's efficiency η and express the energy demands of an individual as

$$E_i = \frac{\eta\, A\, E_s}{N}. \quad (14)$$

We'll assume our organism to be completely efficient ($\eta = 1$). This formula makes sense to us intuitively from observing our animal kingdom - animals with very large population sizes (ants, insects) have very small masses and volumes, whereas animals which live in smaller numbers (elephants) grow to be very large. Therefore, the size of lifeforms can vary within a certain range, due to energy availability, but the maximum is set by gravity. Let's reinforce this argument by looking at another physical parameter such as bone strength.

Objects of same mass will weigh differently on other planets. Size has its limitations because bones need to support that weight. The force on the bone of length L and cross section A pressed by a weight mg is

$$\frac{mg}{A} = Y\frac{\Delta L}{L}, \tag{15}$$

where Y is Young's modulus of elasticity. Imagine scaling an animal [23]. Since $m = \rho V$, where ρ is body density, and V its volume, mass depends as $m \sim L^3$. Area changes as L^2, so just enlarging the animal with its shape staying the same means its bones would eventually break, at constant Y. We insert these dependences into (15) to get:

$$\rho g L \propto Y\frac{\Delta L}{L}. \tag{16}$$

If we now compare the sizes of similar organisms on different planets, forming a ratio by using (16), assuming ρ and Y the same on different planets, we have

$$\frac{g_1 L_1}{g_2 L_2} = \frac{\Delta L_1 / L_1}{\Delta L_2 / L_2}. \tag{17}$$

$\Delta L/L$, the deflection of the bone, takes on a fixed value before it breaks under stress. So setting the right side of eqn. (17) to 1, we're actually observing the upper limits of organism size, and we have

$$\frac{L_1}{L_2} = \frac{g_2}{g_1}, \tag{18}$$

so high-g planets can only produce small organisms, while low-g planets can produce large organisms. Since objects on high-g planets are heavier the life on it needs to be bigger and stronger to move them around. Eqn. (18) says we'd have to be smaller, but we also know we'd need more muscle to be strong. To solve this issue, what we need is more mass in less volume, i.e. larger density. Let us form the ratio with (16) again, but now allowing ρ to change:

$$\rho_1 g_1 L_1 = \rho_2 g_2 L_2 \tag{19}$$

We define $\eta = g_2/g_1$, L_2 as L and ρ_2 as ρ so:

$$L(\eta;\rho) = L_1 \frac{\rho_1}{\rho}\frac{1}{\eta}. \tag{20}$$

Since $m_{muscle} \propto \rho V$, with eqn. (20) we have:

$$m \propto \rho A L \propto \frac{\rho_1 L_1}{\eta} A \implies A \propto \eta m. \tag{21}$$

In conclusion, to have bigger mass and more muscles, we'd have to be wider, thicker and shorter. Following that logic, low-g planets would allow tall, slim creatures, because they wouldn't have trouble moving in low gravity. A good example can be found in The Lord of the Rings. Dwarves, strong, thick and short, living close to the ground, would be dominant humanoid creatures on high gravity planets, while agile, elegant elves could dominate low-gravity ones.

It is not difficult to imagine the extreme - at the highest gravity, life would most likely be confined to the surface, like two-dimensional colonies of moss and bacteria and rarely grow into the third dimension. If it did, its support system would suffer great axial compression due to the creature's weight, and would ultimately break. Or otherwise, if the cross-section of this organism's support keeps increasing, not only will motion be impossible, but the energy demands will be huge. Still, let's assume that our organism has adapted perfectly to the problem of weight support in its respective gravity, as nature tends to do. Also, let's assume that it has made terms with **sedentary life**. Many organisms may not be willing to pay the energetic cost of transportation. What other limitations might be in play?

In this thought experiment, we look to trees. They are a fine example of sedentary life which grows to enormous heights. It turns out that the maximum tree height is determined by gravity not due to the tree's weight, but due to the limitations of its capillatory system [24]. Trees stop growing when the pressure delivering nutrients to the topmost branches becomes weak. The Cohesion-Tension theory [25] predicts pressure drops Δp in every xylem (transport tissue) which raises water to a height Δh to be equal to

$$-\Delta p = LAE/K_h + \rho g \Delta h, \tag{22}$$

where A is the leaf area, L is the xylem length, E is the evaporative flux and K_h is the hydraulic conductivity.

It can be seen that the pressure of water available to the plant decreases linearly with height. Extrapolated data for Earth suggests maximum tree height to be 122-130 meters, in agreement with historical data.

Since any kind of organic extraterrestrial being would require a circulatory system, and passive systems (such as the cohesion-tension in trees) are clearly limited by gravity, higher-g inhabitants would have to develop active circulatory systems with pumping mechanisms, like our cardiovascular system, to reach greater heights. Alternatively, they could evolve to circulate fluids of very small density, perhaps even gaseous instead of liquid.

All in all, low-gravity creatures may seem to have drawn the better end of the bargain, with greater mobility for less energy and no need for robust skeletal structure and complex circulatory systems. However, all these factors would also make planetary colonization extremely difficult - a low-g organism would almost certainly die when landing on a higher-g planet, whereas the opposite would not be true for the high-g organism, as we know from our Moon landing experience.

At the end of the discussion, let's point out that we've addressed the problem of living on solid ground and within a low density atmosphere. Flying and swimming organisms would also be affected by changes in gravity, but not nearly as much as land creatures. Because of buoyancy, a sea creature's size and movement would not be drastically affected by gravity, but most of the food would sink deeper, putting bottom-dwellers in a better position. Similarly, the biggest problem for flying creatures wouldn't be gravity, but atmospheric density.

4. EXAMPLES OF EXOPLANETS

Now that we have found $5\,g_E$ as the upper limit of the surface gravitational constant on acceptable planets, we can look at real data [27] and find out how many exoplanets satisfy our condition.

Out of 1932 confirmed exoplanets (as of January 2016), 462 have known radii and masses, which are needed to determine g. A short calculation shows that 344 of these fit our criterion. A chart of the distribution of g is given on figure 4. We can easily notice the peak in the percentage of planets in the gravitational range from $0.5\,g_E$ to $1.5\,g_E$, which represent the planets we could relatively easily adjust to.

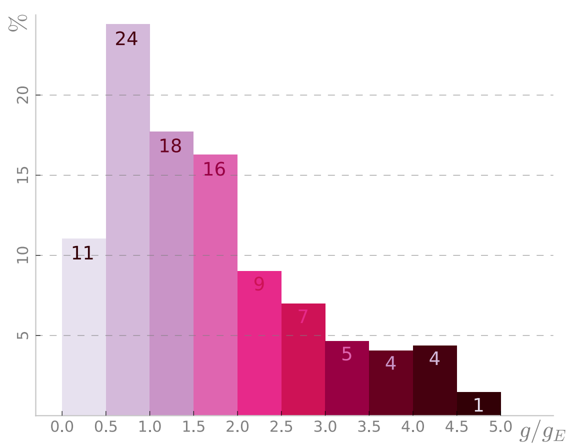

Figure 4 Distribution of the gravitational constant g among confirmed exoplanets [27]. The values displayed are rounded-off percentages of the total number of sub-$5\,g_E$ exoplanets made up by exoplanets in a given range of surface gravity.

It should be noted that planets with gravity less than $5\,g_E$ are in fact very low-g planets when compared to 35 planets discovered with gravity stronger than $50\,g_E$ (12 of them even go as high as $200\,g_E$). This reinforces previous mentioned studies which classify humans as low-g organisms on the galactic scale and predict most exoplanetary life we may encounter to far outweigh and outgrow us [22]. Fortunately, the majority of discovered exoplanets fit in the low sub-5 g_E group, which means a greater chance of colonisation and, perhaps, meeting alien life forms which are in some ways similar to us.

5. CONCLUSION

In the first section, we concluded that the human musculoskeletal system is well-suited to Earth gravity, and would consequently have difficulty functioning under increased gravitational force. However, physical training effectively quadruples our available strength and enables us to raise the limit up to 4-5 g_{Earth}. Our model of walking confirms this limit, with a strongman as our extreme example.

Studying the adaptation of astronauts' bodies to prolonged exposure to low gravity, we were able to make a prediction about the redirection of human evolution caused by permanent settlement of different exoplanets. High gravity would yield shorter, stockier humans, whereas low gravity would see weaker humans with shriveled limbs.

Higher gravity seems to severely limit organism size: from cellular radius, inversely proportional to g^4, to the dimensions of an organism's skeleton, $L \sim g^{-1}$. To overcome these obstacles, lifeforms would have to develop new and interesting supportive and circulatory systems. Without a doubt, nature would adapt even in the most extreme conditions.

Our research has led us to conclude that, from the human perspective, the range of habitable planets is much narrower than the range of potentially life-supporting planets in the universe. This restriction arises primarily from gravity, as the only environmental factor which we cannot manipulate. Being aware of this enables us to make our search for potential future exoplanetary colonies more precise.

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Dora Klindžić, Mateo Kruljac

Efekti egzoplanetarne gravitacije na kolonizaciju čovječanstva i evoluciju života

U ovom radu, koji je sudjelovao na natjecanju Odysseus 2016., razmatramo kako egzoplanetarna gravitacija utječe na čovjekovu sposobnost gibanja i predviđamo kako izgledaju životni oblici na drugim planetima te kako će se razvijati, ukoliko postoje. Odysseus je vodeće natjecanje vezano uz svemirsku znanost za mlade. Na natjecanju postoje 3 grupe – «Skywalkers», «Pioneers» i «Explorers». U sve tri kategorije u prosjeku se prijavi preko 100 radova. Posljednja kategorija je za studente 17-22 godine i traži od studenata da postave znanstvenu tezu, istraže ju, naprave znanstveni rad te ga prezentiraju. Natjecanje se organizira na razini države, regionalnoj razini i svjetskoj razini. Prošle godine smo na razini države osvojili prvu nagradu, a na regionalnoj razini nagradu za najinovativniju ideju. Sudionici na natjecanju studenti su iz cijelog svijeta (npr. Indija i Kamerun 2016.).

U nekom trenu u budućnosti, ako čovječanstvo želi naseliti planete van Sunčeva sustava, bit će potrebno odrediti raspon planetarnih uvjeta u kojima bi ljudi mogli preživjeti i funkcionirati. Uz to, trebali bismo moći predvidjeti svojstva mogućeg života koji bi se mogao susresti, ako postoji. Iz tog razloga u prvom dijelu rada razmatramo koja ograničenja gravitacija postavlja na ljudsko tijelo, a u drugom utjecaj gravitacije na evoluciju.

U početku, razmotramo u kojim granicama se ljudski skelet lomi i mišići više ne mogu dići tijelo s poda. Uz to, razvili smo novi model koji razmatra energetsku potrošnju hodanja tako da se noga modelira kao obrnuto njihalo. Oba pristupa potvrđuju da bi se uz rigorozni trening moglo ostvariti hodanje na planetima koji imaju gravitaciju do $5g_{Zemlja}$. Uzimajući u obzir dobiveno ograničenje, razmatramo dugotrajne učinke na ljude koji bi živjeli na planetima s gravitacijom manjom ili većom od one na Zemlji.

U dijelu rada o egzoplanetarnom životu, razmatramo kako lokalna gravitacija utječe na veličinu gradbenih elemenata života. Iz dobivene informacije pokušavamo zaključiti kako će izgledati unutarnja građa i geometrijski oblik mogućih oblika života koji su se razvili uz drugačiju gravitaciju. Na kraju rada svoje zaključke prenosimo na dosad otkrivene egzoplanete.

Studente se predlaže za Rektorovu nagradu na temelju osmišljanja nove znanstvene ideje, istraživanja i pisanja znanstvenog rada čija je vrijednost prepoznata na međunarodnom natjecanju, kao i prezentacije tog rada na skupu pred stručnom komisijom. Vrijednost rada potvrđuje činjenica da je na državnoj razini osvojio prvu nagradu, a na međunarodnoj razini osvojio je nagradu za najinovativniju ideju.

Dora Klindžić, Mateo Kruljac

Effects of exoplanetary gravity on human colonization and the evolution of native life forms

In this work, which took part on the Odysseus 2016. competiton, we consider how exoplanetary gravity influeneces the ability of a person to perform locomotion and we anticipate the evolution of possible lifeforms on other planets. Odyssues is the leading world competition for young scientists. There are 3 competition groups – «Skywalkers», «Pioneers» and «Explorers». Every year, there are more than 100 submitted projects. The last group is for students of 17-22 years of age and requires the students to form a scientific hypothesis, perform a research, write a paper and present it. The competition consists of 3 stages – country, regional and world. Last year we won the national competition and won the prize for the most innovative idea on the regional competition. Students from all around the world take part in the competition (i.e. India and Cameroon in 2016).

At some point in the future, if mankind hopes to settle planets outside the Solar System, it will be crucial to determine the range of planetary conditions under which human beings could survive and function. Additionally, we should be able to anticipate the traits of any lifeforms we could possibly encounter. For this purpose, in the first part of our paper, we observe the limitations which gravity imposes on the human body, and in the second part, the influence of gravity on the course of evolution.
Initially, we examine the ultimate limits at which the human skeleton breaks and muscles become unable to lift the body from the ground. We also produce a new model for the energetic expenditure of walking, by modelling the leg as an inverted pendulum. Both approaches conclude that, with rigorous training,

humans could perform normal locomotion at gravity no higher than 5 g_{Earth}. Bearing this limit in mind, we consider the long-term effects on humans inhabiting planets with weaker or stronger gravity.
In the section on exoplanetary life, we recount how gravity dictates the scaling of size from the cellular to the macroscopic level. We use this information to speculate on the form and internal build of lifeforms that evolved in alternate gravity, ultimately applying our findings to examples of known exoplanets.

The students are recommended for the Rector's award based on coming up with a new scientific idea, performing a scientific research and writing a paper the value of which was recognized by an international committee in a prestigious competition. An added plus is that the students successfully presented the work in a conference-like setting. The value of this work is further confirmed by the fact that it won the national competition and was awarded a prize for the most innovative idea on the international competition.