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Small creatures can lift more than their own bodyweight and a human cannot-an explanation through structural mechanics

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Abstract. Living beings are formed of advanced biological and mechanical systems which exist for millions of years. It is known that various animals and insects right from small ants to huge whales have different weight carrying capacities, which is generally expressed as a ratio of their own bodyweights i.e., Strength to Bodyweight Ratio (SBR). The puzzle is that when a rhinoceros beetle (scientific name: Dynastinae) can carry 850 times its own bodyweight, why a man cannot accomplish the same feat. There are intrinsic biological and mechanical reasons related to their capacities, as per biomechanics. Yet, there are underlining principles of engineering and structural mechanics which tend to solve this puzzle. The paper attempts to give a plausible answer for this puzzle through structural mechanics and experimental modeling techniques. It is based on the fact that smaller an animal or creature, it has larger value of weight lifting by self-weight ratio. The simple example of steel prism model discussed in this paper, show that smaller the physical model size, larger is its SBR value. To normalize this, the basic length of the model need to be considered and when multiplied with SBR, a constant is arrived. Hence, the aim of the research presented is to derive this constant on a pan-living being spectrum through size/scaling effect.

Keywords: animal behavior; strength to bodyweight ratio; load carrying capacity; biomechanics; structural mechanics; size/scaling effect

1. Introduction

Nature is a treasure-house of puzzles which has paved the way for development of science and technology. Humankind has been working on understanding the various phenomenon of nature that has ended up in the evolution of new laws and theories. Yet many amazing questions are to be answered. The metabolic energy consumed by a walking or running animal is related to the magnitude and rate of isometric force development as well as the mechanical work performed by muscles, but it is not yet clear what portion of the energy should be attributed to each of these factors (Kram and Taylor 1990, Alexander 1991). Every human and animal body is a complex structural system, exhibiting a highly coordinated and actively controlled structural form (Balcombe 2009, Broom 2010). The structure of a human body passively standing on two legs is

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inherently an unstable system. This means that without the action of active controls like electrical impulses sent by the central nervous system which involve inherent tightening or loosening of muscles, a man may trip and fall.

The control is coordinated by feed-back signals sent all the time by in-built sensors like eyes, ears and skins and received by the brain, which tries to send back electrical impulses to muscles. This happens so in-voluntarily, that at cognizance level of consciousness, one hardly recognizes the complexity of such actions. The human body can be claimed to be a reverse of structural reinforced concrete, a material used in modern civil infrastructures like bridges and buildings. Hence, the human structure made of muscles, under the action of electrical impulses have good tensile strength, which are reinforced by a compressively strong material (bone). As discussed by Selker and Carte (1989), most long bone fractures are the result of bending and/or torsional loading. It therefore appears that, in spite of differences in scaling of length and external diameter, the bending and torsional strengths scale similarly across a broad range of animals. For example, a more upright limb posture reduces the moment about the joints produced by the ground reaction force. A smaller joint moment requires a smaller muscle force (Biewener 1989). Strength of a person or animal species is generally judged by the development in the strength of bones and muscles at critical body parts (Ahlborn 2006). The higher bone mass ratio and relatively higher muscle fiber density give rise to better strength and stamina. Suppose, the weight carried by an animal species is written as a ratio of its own bodyweight, generally the species and animals of smaller size carry higher proportion of weight as a fraction (or a multiple) of their own bodyweight. Mathematically, the Strength-Bodyweight Ratio (SBR) is defined as,

$$SBR = \frac{maximum\ weight\ carried\ (strength)}{self\ weight} \tag{1}$$

This is analogous to a concept called as Demand Capacity Ratio (DCR) in structural mechanics and earthquake engineering (Harris and Sabnis 1999) where, it is defined as,

$$DCR = \frac{demand\ from\ environmental\ force}{lateral\ capacity\ of\ structure} \tag{2}$$

For a passive structure to be safe under the action of any external loads, DCR should be less than 1.0 (Saravanan *et al.* 2017). The body structure exhibits another adaptable attribute, that if DCR of a body structure tends towards unity for prolonged duration (under food, fight or flight conditions), the muscle fiber density and bone mass increases such that the factor SBR actually increases in an adaptable fashion over a period of time. This explains the fact that continuous weight-trainers have a high value of SBR.

1.1 Puzzle to be solved

It is a known fact that species of smaller sizes show larger values of this factor SBR and the common notion is that smaller species are generally stronger. The other papers in this field are described subsequently and by no-means the list is exhaustive (Noyes and Grood 1976, Alexander 1985, Bartholomew *et al.* 1988, Thompson *et al.* 1995, Kram 1996, Christman and Leone 2007, Nguyen *et al.* 2014, O'Neill *et al.* 2017). Tiny leaf-cutter ants, which weigh around 500 mg can lift and carry something like 50 times their own body weight by clutching these weights through their jaws. This is stating that a human should lift and carry 3.5 tons of a small truck weight through his teeth. A species called as rhinoceros beetles falling under the subfamily of the scarab beetle

Table 1 Load carrying capacities of typical animals/species

Animals	*SBR* value	Characteristic Length (l) (cm)	$C = SBR*l$	Normalized Length
Rhinoceros beetle	850	0.6	510	0.009
Leafcutter ant	50	1.8	90	0.008
Eagle	4	84	336	1.292
Human	0.7	65	45.5	1.000
Gorilla	10	75	750	1.154
Grizzly bear	0.8	198	158.4	3.046
Ox	1.5	200	300	3.077
Tiger	2	250	500	3.846
Elephant	1.4	350	490	5.385

(*Scarabaeidae*) can lift about 850 times their own weight. If a human being has the same strength as that of a rhinoceros beetle, he will be able to carry 65 tons of weight very easily on his shoulders. If the mighty elephant had equal strength to the rhinoceros beetle it would be able to carry 850 elephants on its back. When a tiny leafcutter ant can lift more than 5000 times why mighty animals cannot lift even their own weights? In spite of the change in the materials the various animals are composed of, the effect of geometry could be a possible reason why the smaller animals are able to carry larger loads (Carpinteri and Pugno 2005). The present paper attempts to discuss how the variation of geometry of the animals affects the load carrying capacity of the animals.

Table 1 shows the load carrying capacity of animal/species along with their characteristic length, which is defined as their typical trunk length added with head length. The respective load carrying capacity of species are obtained from the past literature (Nguyen *et al.* 2014, Alexander 1985, Kram 1996, Noyes and Grood 1976, Thompson *et al*. 1995, Christman and Leone 2007, O'Neill *et al.* 2017). It is more important that a mathematical relationship between their characteristic length (l) and their SBR need to be established. Also, it illustrates the normalized length after normalizing their characteristic length with the corresponding human length. A rough glance shows that factor SBR is inversely proportional to characteristic length and given as,

$$SBR \propto \frac{1}{l} \tag{3}$$

Or, it can also be expressed as,

$$SBR * l = constant\ (C) \tag{4}$$

The strength of animals/species can be classified based on the factor, C. An animal of factor, C=300 to 500, is of good strength (normal). More than 500 is super strength and less than 300 is weak. It looks like in the evolution cycle the immediate predecessor for the human being is of super-high strength and where as a human being is of weak category. Somewhere down the ages, there is a tremendous priority shift from brawn to brain and physical strength has seemingly lost out in the race of evolution. Thus, it is seen that the developed mathematical relationship is seemingly empirical and it need to be validated. It is better to examine the statistics for humans, which is low with C=45.5. However, the value of SBR is 0.7, which itself is high and a figure of

SBR = 0.3 may be appropriate (Maloiy *et al.* 1986). Hence the factor further falls to C=19.5. Correspondingly, where human weightlifters record breakers fare (Garhammer 1991). The SBR value for men's category range from 2 (snatch) to 3 (clean and jerk) under 56 kg of body weight. For men of higher weight (105 kg), these values are from 2 (snatch) to 2.5 (clean and jerk). Similarly, for women's category range from 1.9 (snatch) to 2.3 (clean and jerk) under 48 kg of body weight. For women of higher weight (75 kg), these values are from 1.9 (snatch) to 2.5 (clean and jerk). Even a maximum SBR value of 2.5 for exceptional categories amongst human, will yield only a value, C=162.5.

2. Structural mechanics based explanation

2.1 What is a model and a prototype-a simple example?

A model is a replica of the larger prototype (Harris and Sabnis 1999). In many of the structural testing applications smaller models are tested under reduced loads with smaller dimensions and the results are suitably extrapolated to the original prototype structure (Saravanan *et al.* 2017). For example, while testing the super-sonic performance of a Sukhoi fighter (a Russian aircraft manufacturer) under turbulent conditions in a simulated air-flow field of a wind-tunnel, a reduced size replica of the original Sukhoi is made, tested and the results are extrapolated for the actual prototype fighter aircraft (Rochmat *et al.* 2018). Correspondingly, for a mammal, it is assumed that the offspring is a reduced length model of his/her parent (McMahon 1975, Schmidt-Nielsen 1984). Any physical, chemical or biological system can be defined by a number of parameters, namely, input parameters (or design parameters) and output parameters. This is similar to a mathematical problem of dependent and independent variables (Bažant 2005). There may be 'N_1' variables as input parameter and 'N_2' variables as output parameters. Nondimensionalization of N_1 input parameters can be performed by utilizing basic dimensions (like length, Young's modulus of the material and other properties). Thus, the number of input parameters may reduce to (N_1-3) for a dynamic problem and (N_1-2) for a static problem. Nondimensionalization of N_2 output parameters can also be performed using those two or three input basic parameters. [Not as (N_2-2) or (N_2-3) as in the case of input parameters].

Consider a simplest problem in structural mechanics (Harris and Sabnis 1999), a simply supported beam representing a bridge and made of a prismatic rectangular section of dimensions, depth 'd', width 'b' and length between the spans 'l' (Fig. 1). Let us assume the material is linear, elastic and homogeneous and has a constant Young's modulus of 'E'. Let this bridge be loaded with a concentrated, knife-edge load of 'P' at a distance of 'a' from the left support (the distance from the right support is (l-a). The output parameters (independent variables can be, the maximum stress developed at a critical location, 'σ', maximum bending moment at a critical location 'M' and the maximum deflection of the structure 'δ'. The input and output parameters can be expressed as, $\{d, b, l, E, P, a\}$ and $\{\sigma, M, \delta\}$ respectively. As this is a time-invariant problem, it is possible to select two basic parameters as, $\{l, E\}$. Length (or span of the bridge) 'l' and Young's modulus 'E' have dimensions of meters (m) and N/m^2 and are essentially linearly independent and are admissible parameters. Using these two parameters and well-known Buckingham's π theorem (Sabnis and Mirza 1979, Sabnis 1980), the various non-dimensional parameters can be written as π_1, π_2, π_3 and so on. Each of these π parameters can be listed for input parameter as, $\pi_1, \pi_2, \pi_3, \pi_4$: $\left\{\frac{d}{l}, \frac{b}{l}, \frac{a}{l}, \frac{P}{El^2}\right\}$. The number of π parameters are reduced to (N_1-2) as it is static problem and

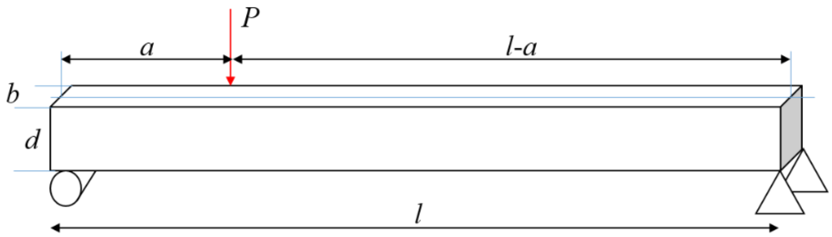

Fig. 1 Simply support beam structure with point load

similarly, output parameter as, π_5, π_6, π_7: $\left\{\frac{\sigma}{E}, \frac{M}{El^3}, \frac{\delta}{l}\right\}$.

Mathematically one can write the output π parameters as function of input π parameters in the following manner

$$\pi_5, \pi_6, \pi_7 = f\,(\pi_1, \pi_2, \pi_3, \pi_4) \tag{5}$$

In structural mechanics' problem, so long as the input parameters are same in the model and prototype, output parameters will not be changed. This is exactly the trick played in experimental mechanics to tame and get the behavior of an otherwise un-controllable wild prototype. Suppose, it is required to observe the stresses developed, deflections and moments of a simply supported bridge, which is made of a prismatic rectangular section (this is little trivial example as many of the normal bridges, though of simply supported boundary conditions are of non-rectangular sections). It is necessary to construct a one-tenth model of the bridge in the laboratory, with a material different or same. If the model material is same as that of the original prototype material, such that Young's modulus 'E' is constant for both, the loading that needs to be applied on the model is 1/100 of the original structure. Depth, width and position of loading are one-tenth of the prototype. Hence a true model is constructed in the laboratory and after application of the load, the stresses developed, deflection and the bending moment of the models are measured. From the output π parameters, it can be concluded that whatever is the stress measured for the model will be the same as will be developed in the prototype. The bending moment in the prototype will be 1000 times as that in the model and the deflection of the prototype shall be 10 times as that of the model.

2.2 Are there differences between linear and non-linear problems for applicability of Buckingham's π theorem?

The answer is an emphatic no and it is heartening. Henceforward, this theorem is equally applicable for linear as well as non-linear mechanics problem. Non-linear mechanics scaled down experiments with non-linearity stemming out of geometric or material constituent relationship also can be experimentally extrapolated, provided that the scaling is proper. To further understand the meaning of non-linearity in physical sciences, certain terminology needs to be understood:

(a) Un-conservative system: It is the one whose potential energy is not preserved during the process of loading. It may start with one energy datum and end up with another energy datum with energy leaking out to a thermodynamically infinite sink. A damped dynamic system, which is otherwise linear and elastic is an example of an un-conservative system.

(b) Non-holonomic system: It is a path dependent system and loading and un-loading is path

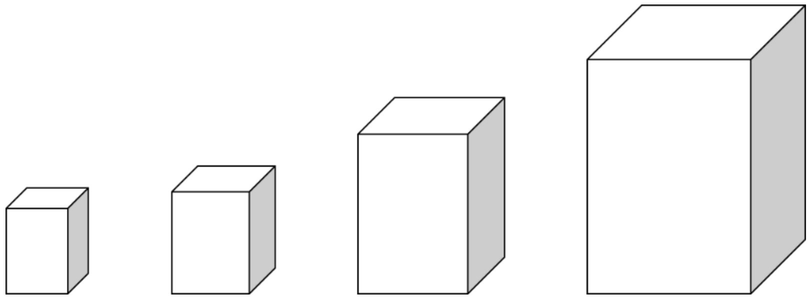

Fig. 2 Scaled models of a simple mild steel blocks

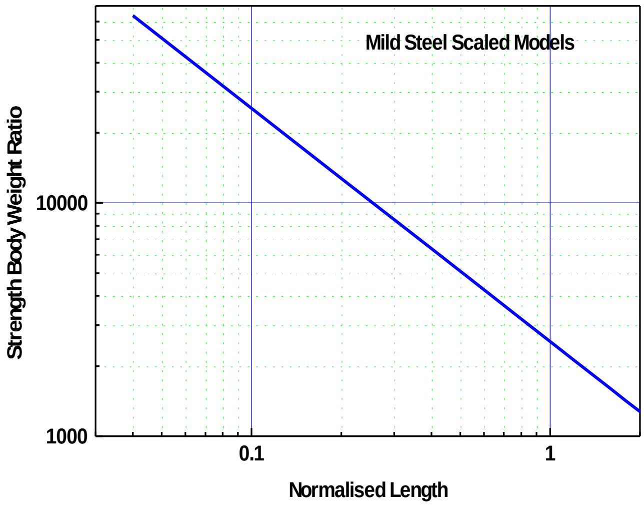

Fig. 3 Variation of SBR vs. Normalised Length of the steel block models

dependent. Depending on the path a system takes, it may end up in a different final position as compared to its starting initial position.

(c) System which do not obey linear superposition during the sequence of loading and un-loading. (this is analogous to a non-holonomic system).

3. Illustration through a set of simple mild steel scaled models

Let us assume scaled models of various sizes of steel specimen as shown in Fig. 2. The yield strength of the material is assumed to be 250 MPa. Based on the mass density (7.85 grams/cm^3) and yield strength of steel, ratio of ultimate load carrying capacity to weight of the specimens are calculated. If a 25 cm×25 cm×125 cm steel block is assumed as prototype (datum) then 1 cm×1 cm×5 cm block is the 1:25 scaled model of the datum block. Let us make a comparison between the weight of each block compared to the prototype block and it can be clearly seen that the weight drops proportional to the cubic power of the length scale. This means that the weight of 1:25 scale model is 25^3 (15625) times smaller than the datum block. Since both prototype and models are of the same material (scale factor for stress will be unity), load capacity calculated in

Table 2 SBR value of simple physical models (steel blocks)

Cross Section (cm × cm)	Length (l) (cm)	Self-weight (kg)	Load capacity (kg)	SBR value	Normalized ratio	Normalized length
1×1	5	0.03925	2500	63694.27	25	0.04
5×5	25	4.90625	62500	12738.85	5.0	0.2
10×10	50	39.25	250000	6369.43	2.5	0.4
15×15	75	132.4688	562500	4246.28	1.667	0.6
20×20	100	314	1000000	3184.71	1.25	0.8
25×25	125	613.2813	1562500	2547.77	1	1
30×30	150	1059.75	2250000	2123.14	0.833	1.2
35×35	175	1682.844	3062500	1819.84	0.714	1.4
40×40	200	2512	4000000	1592.36	0.625	1.6
45×45	225	3576.656	5062500	1415.43	0.556	1.8
50×50	250	4906.25	6250000	1273.89	0.5	2

the axial direction is only a function of the cross sectional area of the model. This implies that the load capacity of 1:25 scale model is 25^2 (625) times smaller than the datum block. In the smaller scales, load capacity reduces proportional to $\boldsymbol{l}^2$ whereas weight diminishes faster proportional to $\boldsymbol{l}^3$. Hence the SBR increases as it approaches smaller and smaller scales proportional to $\boldsymbol{l}$. A plot has been shown in Fig. 3, between normalized length with respect to 25 cm×25 cm×125 cm steel block and the SBR value of various scaled model specimens as illustrated in Table 2.

The linear nature of the log-log plot with a negative slope shows that the relationship is, $SBR * l = constant = C,$ as it is derived in Eq. (4). Here also, the basic Buckingham's π parameters are, $\{l. E\}$. Hence, if the same material is used for the model and prototype, the stresses developed in both should be same. Since the dead load stresses are different in each of the cases, there is a distortion. For non-holonomic systems, where linear super-position is invalid, the final destination stresses will be different and this plays a significant role in the post elastic performance of a structure. The mathematical deductions made for different biological species seemingly work same here, as it is discussed in Eq. (3). It may be very clear at this stage that the above logic can be extended to a bio-structural system as well. Let the above discussed analogy be extended to the biological problem, that the SBR value of smaller species are considerably more.

The two assumptions, which are probably sweeping:

(1) Nature creates animals/species as scaled model of each other. This actually means that if a characteristic length of an animal is 'n' times as that of another animal, then all its body parts and other details are also correspondingly factored by 'n' times.

(2) The material by which each of the species made, is essentially the same.

Neither of these two assumptions is strictly valid and biological researchers may point to the gross violations in these assumptions. Nevertheless, the elegance with which the biological puzzle can be solved using these assumptions make it worthwhile to carry on with these assumptions. Hence the bio structures can be made analogous to a physical structure and similar to physical structure, as scale diminishes, bio structures also carry more weight as a factor of their body weight. In simple terms, the reasoning can be summarized as follows: A smaller species has reduced stresses due to the action of its own self weight and hence has more reserve strength available to carry external loads. This explains that smaller species can carry more weight as

Fig. 4 Shake table testing of a steel building-Case study

compared to their own body weight.

3.1 Are there evidence of size effects in biological structures?

Size effect is the increased strength observed in physical systems, when their size progressively reduces. Evidence of size effects in structural materials like concrete have been reported by varies researchers (Bažant and Cao 1987, Bažant and Kazemi 1991). Size effects is important while extrapolating the results of a model experimentation to prototype scales. Experimental physical models tested till ultimate loads would give non conservative estimation of the load-carrying capacities of the prototype due to size effects. Hence, in this case of bio-structures, a plot can be essentially made between C and l, instead of between SBR and l and look for size effects. If size effects are actually present, then C should have been an increasing function with reference to reducing values of l. From Table 1, it is seen that this is not actually happening. It can be inferred that, up to the scales observed in this paper, bio-structures have not exhibited great size effects (Alexander 1985).

4. Experimental investigation on seismic testing of a steel model frame

In the foregoing section, it is seen that a normal scaling down process actually under-estimates the stresses developed under dead load conditions and this is to be corrected. A case study of an experiment conducted using the shake table at the Advanced Seismic Testing and Research Laboratory, CSIR-Structural Engineering Research Centre, India is described in this section. The size of the shake table is 4×4 m, and its payload capacity is 30 t. The photographic view of the one-fifth scaled model of a steel building frame is fixed on the shake table as shown in Fig. 4.

The actual building is of G+7 stories. If the building satisfactorily performs under seismic motions corresponding to laboratory conditions, it shall be deemed to have performed equally well under actual design earthquake. Structural scaled down models in experimental dynamics and earthquake engineering have to follow Buckingham's- π- theorem and certain non-dimensional parameters (π parameters) have to be evaluated for the structure such that these parameters are kept constant for both the model and prototype (Saravanan *et al.* 2017). For non-linear in-elastic models and where the structure is un-conservative (in terms of energy) and non-holonomic, linear superposition of stress resultants and displacements are not valid, distortion of dead load stresses is not permissible. Generally, length 'l', Young's modulus 'E' and mass density 'ρ' are the basic parameters for a linear elastic structure tested for seismic loads. For non-linear in-elastic and un-conservative structures (where superposition structural actions are not exactly valid), where dead load stresses and effects have to be exactly scaled down, the basic parameters are length, 'l', acceleration due to gravity 'g' and Young's modulus, 'E'. In the case of this experimental structure, where the material for the prototype and model are same, length scaling is the only possibility and this is fixed as 1:5 (one-fifth scaled down model). Distortion in the form of reduced dead-load stresses have to be compensated through addition of suitable artificial weights and masses which have to be rigidly attached to the structure. For example, a mass or weight which is scaled down proportional to the third power of the length ratio will not produce the required dead load induced stresses in columns and other critical members. The simulation of dead load stresses shall result in weight scaling proportional to only the quadratic power of length (and not the cubic power of length). Hence additional weights are added at each floor. The additional weights that have to be added are calculated as,

$$W_{additional} = \left({W_P}/{S_l^2} \right) - \left({W_P}/{S_l^3} \right) \tag{6}$$

where, $W_{additional}$, is the additional weight/mass, which has been rigidly fixed to the one-fifth scaled model at each floor; W_P is the design dead load and live load (with associated mass) acting on the prototype structure; S_l is the scale ratio for length and in the case of this experimental structure, this is 5.0. It may be pointed out that absence of the negative term in the Eq. (6) for distorted scaled models as that of biological structures gives additional leverage for smaller species to carry extra weights.

5. Discussion

The strength of a living being depends more on the arrangement of the skeletal "machinery" than the cellular makeup of the muscles (Ahlborn 2006). The strength of an animal depends more on their nature of physical activities. Beetles seems to have increased strength for burrowing wood, whereas human have developed more strength for walking, running etc. Apart from the change in strength due to the nature of work, the physical aging process seems to cause a reduction in the general performance of an animal (Schmidt-Nielsen 1984, Alexander 1985). It is important to understand that the mass varies proportional to the volume and the strength varied proportional to the surface area. Hence, in general mechanics as per scaling law, a smaller object requires more load than required by a bigger object to create a same stress state in the materials. In other words, as one gets smaller in size, the stronger one gets relative to their body weight. This is the concept which describes why an ant can survive when flicked away while humans cannot. The relative strength of an animal increases with the decrease in the size of the animal. For the same stress level to be developed in the muscles of an ant, the load required proportional to the weight of the body is much higher than that of the humans. If humans are as small as ant, then they could also do the same (Federle *et al.* 2000, Nguyen *et al.* 2014). Similar conclusions have been arrived by researchers who have tried to relate the fatigue strength of various vertebrates (Taylor 2000). The stress in the bones of various vertebrates were studied and it was seen that the smaller vertebrates tends to carry more stress than the larger ones. But when the size effects were taken into account by normalising the fatigue strength of various species with the stressed volume, it was clearly evident that the smaller vertebrates seem to have lower fatigue strength. It is the volume indeed the size which plays a role. Same way more than the muscles of the ant, the ant being smaller in size make it to carry greater loads than humans. Ants can lift so much because of the ratio between their body size and body mass; their small size means they do not have a large body mass and the proportion of their mass that is muscle is very high (Stepanov 1995). As a result, they can lift weights that are many times larger than their own body weight. In comparison elephants have massive size and the proportion of their mass that is muscle is quite low; although they can lift incredible weights they are unable to lift or carry their own body weight. The load carrying capacity can depend on the metabolic rates of the animal. Few species like rhinoceros beetle showed great economy while carrying loads (Kram 1996). They were able to carry ten times their load with only two times increase in the metabolic rate. Whereas such an economy is not possible in humans because of the way the muscles are tied up with the bones or in other words the anatomy. *Archegozetes longisetosus* (tropical moss mite) can hold a force up to 1180 times its weight and pull a force of 530 times its weight (Heethoff and Koerner 2007). The force carried as a ratio of the weight of the body can be attributed to be proportional to the body mass rather than the volume because of the errors occurring by linear scaling of length, that are not linearly proportional. However, the animals of same mass may exert different force because of the variation in the properties of the muscles they are composed of.

6. Conclusions

The paper attempts to give a structural mechanics based reasoning for the biological fact that smaller a biological species, more is its ‘Strength-Bodyweight ratio (SBR)’. Within the limits of sizes referred in this paper, size effects are apparently absent for bio-structural-systems. However, this point requires further reflection and research. Only assumption is that each animal in an animal kingdom is simply a scaled model of each other. Even though the considered hypothesis is less evident, considering the entire domain with both vertebrates, in-vertebrates, mammalian and reptiles, the derived constant is a bounded value. Hence, the better way to represent the real strength of a species is to plot the product of, $SBR.l = C$ and not just SBR alone. Though arbitrary, it can be claimed that biological species seem to have a mean C factor of around 500. *Homo sapiens* (human beings) grossly under-perform and our immediate predecessor in the evolution cycle (Gorilla) actually tops the scales. Changes and small perturbations are only brought about by evolutionary process from brawn to brain.

References

Ahlborn, B.K. (2006), *Zoological Physics: Quantitative Models of Body Design, Actions, and Physical Limitations of Animals*, Springer Science & Business Media.

Alexander, R.M. (1985), “The maximum forces exerted by animals”, *J. Exper. Biol.*, **115**(1), 231-238.

Alexander, R.M. (1991), “Energy-saving mechanisms in walking and running”, *J. Exper. Biol.*, **160**(1), 55-69.

Balcombe, J. (2009), “Animal pleasure and its moral significance”, *Appl. Anim. Behav. Sci.*, **118**(3-4), 208-216.

Bartholomew, G.A., Lighton, J.R. and Feener Jr, D.H. (1988), “Energetics of trail running, load carriage, and emigration in the column-raiding army ant eciton hamatum”, *Physiol. Zool.*, **61**(1), 57-68.

Bažant, Z.P. (2005), *Scaling of Structural Strength*, Butterworth-Heinemann.

Bažant, Z.P. and Cao, Z. (1987), “Size effect in punching shear failure of slabs”, *ACI Struct. J.*, **84**(1), 44-53.

Bažant, Z.P. and Kazemi, M.T. (1991), “Size dependence of concrete fracture energy determined by RILEM work-of-fracture method”, *Int. J. Fract.*, **51**(2), 121-138.

Biewener, A.A. (1989). “Scaling body support in mammals: Limb posture and muscle mechanics”, *Sci.*, **245**(4913), 45-48.

Broom, D.M. (2010), “Cognitive ability and awareness in domestic animals and decisions about obligations to animals”, *Appl. Anim. Behav. Sci.*, **126**(1-2), 1-11.

Carpinteri, A. and Pugno, N. (2005), “Are scaling laws on strength of solids related to mechanics or to geometry?”, *Nat. Mater.*, **4**(6), 421.

Christman, M.C. and Leone, E.H. (2007), “Statistical aspects of the analysis of group size effects in confined animals”, *Appl. Anim. Behav. Sci.*, **103**(3-4), 265-283.

Federle, W., Rohrseitz, K. and Holldobler, B. (2000), “Attachment forces of ants measured with a centrifuge: Better ‘wax-runners’ have a poorer attachment to a smooth surface”, *J. Exper. Biol.*, **203**(3), 505-512.

Garhammer, J. (1991), “A comparison of maximal power outputs between elite male and female weightlifters in competition”, *Int. J. Sport Biomech.*, **7**(1), 3-11.

Harris, H.G. and Sabnis, G.M. (1999), *Structural Modeling and Experimental Techniques*, CRC Press.

Heethoff, M. and Koerner, L. (2007), “Small but powerful: Theoribatid mite archegozetes longisetosus Aoki (Acari, Oribatida) produces disproportionately high forces”, *J. Exper. Biol.*, **210**(17), 3036-3042.

Kram, R. (1996), “Inexpensive load carrying by rhinoceros beetles”, *J. Exper. Biol.*, **199**(3), 609-612.

Kram, R. and Taylor, C.R. (1990), “Energetics of running: A new perspective”, *Nat.*, **346**(6281), 265.

Maloiy, G.M.O., Heglund, N.C., Prager, L.M., Cavagna, G.A. and Taylor, C.R. (1986), “Energetic cost of carrying loads: Have African women discovered an economic way?”, *Nat.*, **319**(6055), 668.

McMahon, T.A. (1975), “Using body size to understand the structural design of animals: Quadrupedal locomotion”, *J. Appl. Physiol.*, **39**(4), 619-627.

Nguyen, V., Lilly, B. and Castro, C. (2014), “The exoskeletal structure and tensile loading behavior of an ant neck joint”, *J. Biomech.*, **47**(2), 497-504.

Noyes, F.R. and Grood, E.S. (1976), “The strength of the anterior cruciate ligament in humans and rhesus monkeys”, *J. Bone Joint Surg.*, **58**(8), 1074-1082.

O’Neill, M.C., Umberger, B.R., Holowka, N.B., Larson, S.G. and Reiser, P.J. (2017), “Chimpanzee super strength and human skeletal muscle evolution”, *Proceedings of the National Academy of Sciences*, **114**(28), 7343-7348.

Rochmat, T.A., Wibowo, S.B., Iswahyudi, S., Wiratama, C. and Kartika, W. (2018), “The flow visualization CFD studies of the fuselage and rolled-up vortex effects of the chengdu J-10-like fighter canard”, *Mod. Appl. Sci.*, **12**(2), 148.

Sabnis, G.M. (1980), “Size effects in material systems and their impact on model studies: A theoretical approach”, *Proceedings of the SECTAM X Conference*, Knoxville, Tennessee, U.S.A.

Sabnis, G.M. and Mirza, S.M. (1979), "Size effect in model concretes", *J. Struct. Div.*, **105**(6), 1007-1020.
Saravanan, T.J., Rao, G.V.R., Prakashvel, J., Gopalakrishnan, N., Lakshmanan, N. and Murty, C.V.R. (2017), "Dynamic testing of open ground story structure and in situ evaluation of displacement demand magnifier", *J. Perform. Constr. Facilit.*, **31**(5), 04017055.
Schmidt-Nielsen, K. (1984), *Scaling: Why is Animal Size So Important*?, Cambridge University Press.
Selker, F. and Carter, D.R. (1989), "Scaling of long bone fracture strength with animal mass", *J. Biomech.*, **22**(11-12), 1175-1183.
Stepanov, I.A. (1995), "The scale effect is a consequence of the cellular structure of solid bodies: Thermo fluctuation nature of spread in the values of strength", *Mater. Sci.*, **31**(4), 441-447.
Taylor, D. (2000), "Scaling effects in the fatigue strength of bones from different animals", *J. Theoret. Biol.*, **206**(2), 299-306.
Thompson, D.D., Simmons, H.A., Pirie, C.M. and Ke, H.Z. (1995), "FDA guidelines and animal models for osteoporosis", *Bone*, **17**(4), 125-133.

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