Abstract

Scaling laws are pervasive in biological systems, found in a large number of life processes, and across 27 orders of magnitude. Recent findings show both biological and engineered motors adhering to two fundamental regimes for the mass scaling of maximum force output. This scaling law is of particular interest for the robotics field as it can affect the design stage of a robot. In this study we present data of motors commonly used in robotic applications and find an adherence to a similar power law of mass scaling of maximum torque output in two groups, group \( a \) (\( G_a \propto m^{1.00} \)) and group \( b \) (\( G_b \propto m^{1.27} \)). Findings imply that there could exist an upper motor limit of maximum specific torque/force that should be taken under consideration in robot design. Additionally, we show how a robot’s minimum mass can be calculated with motor mass being the only necessary parameter.

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1. Introduction

A major part of the design process of a robotic system requires identifying a number of relevant parameters, such as (1) energy consumption, (2) weight, (3) material selection, (4) actuator torque, (5) dexterity and defining them for a robot performing a specific task. In a number of cases, some of these requirements are completely disregarded as not relevant to the robot or task at hand. For example, the material used to design robotic hand manipulators is mostly metal, chosen for its high structural strength. However, this choice of material affects all other parameters of the design, e.g. weight and actuator torque required. It also, in turn, severely limits the task space of the robot itself. In the above example, such a robotic hand would probably not be acceptable for use in prosthetic research with human subjects, due to its increased weight and limited power autonomy. We speculate that the inter-relation of the above parameters can be optimized by identifying potential scaling laws that are present.

Life processes cover more than 27 orders of magnitude in mass scale, from molecules to whales. Despite the large degree of complexity, observations indicate that the coarse-grained behaviour of such processes is dictated by universal, quantifiable laws that capture essential features of these systems [1], [2]. Scaling laws identified are relating mass to a diverse number of processes, from a species lifespan, growth rate, heart rate, DNA nucleotide substitution rate, genome and aorta length [2], to metabolic rate [3], tree respiratory metabolism [4] and bone length [5], [6]. Recent findings outline a scaling law of the maximum specific force of both biological and engineered actuators [7], [8] whereby motor force either scales allometrically with the cross section of the motor (\( G_1 \propto m^{0.667} \)), including winches and linear actuators, or isometrically (\( G_2 \propto m^{1.00} \)), including piston engines, electric motors and jets) with motor mass. This law

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is of particular interest for the robotics research field, as it can affect the design phase of robots. In this study, we aim to identify whether the maximum specific force scaling law mentioned above holds for motors that are pervasively used in robotics, and if so, how it can influence the design process of robotic systems.

2. Actuators in Robotics

The main criteria that define motor selection in robotic design are (1) the type of motor, (e.g. electric, pneumatic or hydraulic), (2) the $F_{\text{max}}$ required as calculated by the maximum load of the robot for its given task and (3) motor pricing. In what is established as synthetic methodology [9], where design of robots is driven by on-line optimizations during robot construction, motors of choice are usually on the lower end of the price scale. In contrast, with classical robot design, high-end motors in terms of performance are used, also reflected by their pricing. In this study we focus on rotary electric motors, consisting of (1) popular hobby servo motors (RC servos) and (2) a high-end motor manufacturer, Maxon motor. The former are on the lower price range, light, popularly used in hobby modeling but also in robotics, while the latter are higher in price, heavy-duty and mostly used in robotics and automation.

Data included in this study consists of 497 motors from six companies (Futaba, Hitec, GWS, JR, Robotis, Maxon), with 322 RC servos and 175 motors spanning 12 power scales (from 0.3 W to 250 W). Values were taken from specifications given from the respective companies.

The relation of motor maximum torque ($T_{\text{max}}$) to motor mass is shown in Fig. 1. Two distinct regimes of maximum torque scaling with mass are apparent. Group $a$ motors (RC servos) have maximum torque outputs that scale isometrically with motor mass ($Ga \propto m^{1.00}, R^2 = 0.74$). Motors in this group include a rotary electric motor plus a gearbox. Group $b$ motors (Maxon) have maximum torque outputs that scale allometrically to motor mass ($Gb \propto m^{1.27}, R^2 = 0.96$). Motors in this group consist of only rotary electric motors, without a gearbox.

3. Discussion

The two regimes regarding motor maximum torque comes in accordance to previous findings [7], [8] regarding motor maximum specific force. For RC servo motors, it is difficult to calculate an objective maximum specific force due to the fact that the output shafts of the motors do not scale with motor mass, they rather come in three to four
standard scales, for manufacturing purposes. One potential solution would be to use the provided levers (servo horns), that vary for each motor, to calculate the respective maximum specific force.

The large dispersion of Ga motors that is apparent around $10^{-1}$ Kg is surprising. We hypothesize that it can be explained by fatigue studies that would indicate whether motors with higher specific maximum torque will fail faster than their lower maximum torque counterparts in this scale. If this hypothesis is true, it would mean that motors that have an increase of maximum specific torque exchange it for a reduced number of load-life. Of note here is that for each power scale of Gb, there are motors with identical mass that deliver different torques. From the specifications acquired it is apparent that mass does not change as much as other parameters that show a significant change (resistance, inductance, speed constant). This potentially explains the dispersion observed on maximum torque for Gb.

The above results can be used to describe the minimum required mass of a robot, which can be almost fully defined by the maximum torque required for actuating it and performing its corresponding task. If $m_{rob}$ is the mass of the robot then $m_{rob} = m_{mot} + m_{str} + m_{el} + m_{bat}$, where $m_{str}$ is the mass of the mechanical structure, $m_{el}$ the mass of electronics including sensors and $m_{bat}$ the mass of the battery (for an autonomous robot). For a fixed runtime, $m_{bat}$ depends on $m_{mot}$. If we assume the mechanical structure excludes the gearbox or any actuation related mechanism (we assume that Ga motors are used), then the mechanical structure is also dependent on $m_{mot}$, $m_{str} = bm_{mot}$. For macroscopic scale robots, the weight of the electronics is usually negligible, so can be replaced by a constant $c$. Finally, we have that $m_{rob} = (a + b + 1)m_{mot} + c$. Even though a large number of assumptions must hold for the above, it is a reasonable rough approximation in terms of calculating the mass of a robot during the design phase.

4. Conclusions

In this study we show there exists a scaling law describing the maximum specific torque of engineered actuators that are pervasively used in robotics. Further studies will aim to explain the reason behind the two different groups of motors apparent. If it is indeed the case, as speculated by Marden et al. [7], that the two groups are related to fatigue and load-life of these motors, it would imply an upper limit of maximum specific torque for any given scale, that should be taken into consideration in robotic design. In addition, further research should focus on whether other such scaling laws exist in robotics (for instance limb length), and whether they are linked to the above law.

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