Peer Review File

Manuscript Title: Engineered jumpers overcome biological limits via work multiplication

Reviewer Comments & Author Rebuttals

Reviewer Reports on the Initial Version:

Referees' comments:

Referee #1 (Remarks to the Author):

Summary of key results:
The authors present a model for jumping systems (defined as systems that can jump repeatably by applying forces to the ground, powered by an onboard energy supply). This model focuses on losses due to the ratio of actuator to system mass, energy loss before the jumper leaves the ground, losses due to any motion outside of the relevant 1-DOF, air drag, and energy transfer between components and the authors claim that this model can be used to explain how jump height varies across all scales for both biological and engineered systems. The authors also identify work amplification for the actuator as a key component to improve energy density in jumping robots and use this idea in a jumping robot that can jump an incredible 26 m.

Originality and significance:
The jumping robot is amazing. The jump height result (unclear that there is more than one result though) from the robot itself is clearly significant. It was wonderful to see all of the pieces put together for the first time.

I am less convinced by the significance of the "unifying" modeling approach. As is made abundantly clear by Extended Data Fig. 1, the model does not predict takeoff velocities (and corresponding jump heights in Fig 1c/d) of jumpers that use latched energy storage, of which there are many and the authors' robot also uses. It is telling that data points like the froghopper and locust were not included in Fig. 1. Line 105 indicates that you're only considering energy reductions for non-latched energy storage jumpers. Therefore, it is unclear that it explains how jump height varies across all scales and types of jumpers, as the authors claim. If the model is not describing how these jumpers jump, what can I learn from this model that is not covered in work like Sutton et. al. (ICB, 2019)?

In fact, defining a velocity limited regime is exactly what Ilton et. al. (Science 2018) did. It seems that the contribution of this work is also defining a work-limited regime? Another interesting point included in this manuscript is the importance of work amplification from the actuator. It should be noted that there have been several publications from the Pister group at UC Berkeley that utilize a clutch-based design for jumping "robots" (robots in quotes because they are tiny and not fully contained as the example here), e.g.
* Bergbreiter and Pister, ICRA 2007
* Greenspun and Pister, Hilton Head 2018
There have also been previous winch-based robots that provide work amplification similar to that demonstrated by the authors, e.g.

* Stoeter and Papanikolopoulos, IEEE T-Ro 2006
Another key point to amplify the significance of this — are there any examples of biological systems that take advantage of work amplification?

Data and methodology:
For methods section, just stick with using the term specific energy when talking about J/kg and energy when talking about J. Otherwise, it gets confusing.

What is considered to be the actuator in spring driven systems? Is it the motor + spring? Spring only? Motor + spring + latch? This is a key point. I think Ilton et al, Longo et al (JEB 2019) would define the spring as the actuator which removes the velocity limitation in this work and model. It is unclear that this work is considering the same.

For non-vertical motions, would help to define coordinate systems — looks like you are using some kind of spherical coordinates, but Euclidean terms. Otherwise, unclear why I should only be concerned about motion in x vs x and y (assuming z is vertical).

For energy transfer, unclear how spring is counted since some of the spring is moving and some isn't? This was addressed to some degree in Ilton et al (Science 2018).

For scaling, I have several concerns for a more general scaling argument. While muscle force does indeed scale as L^2, that is not necessarily true for engineered actuators. There are several papers on this (Wautelet 2001, Fearing 1998, etc). It was also unclear what authors took as their starting point for scaling arguments. Lines 122-123 for example, it was unclear where 80%, 35% etc #s come from.

Line 483: Ilton et al does illustrate that jump height decreases at small scales for spring-powered jumpers. It is unclear if the authors are disputing the data presented in this paper or saying that the theoretical limit does not actually change? Ilton et al suggests that the limit is due to material properties of the spring and therefore, that the work density does in fact drop off for these systems (at least for biological materials). I don't believe it has anything to do with the fact the spring may be attached or not attached to the projectile. In biological jumpers for which data is presented, clearly the spring is attached.

Very unclear how m_body and m_foot are actually defined? Where does the spring connecting the body to the foot fall in this division? Might help to include a table with relevant masses and numbers for your robot.

The idea that I should add weight to my system to increase jump height (as discussed in section starting at line 635) is still completely unintuitive. Can you actually demonstrate this?

The robot design looks very much like the Jollbot (Armour et al, Bio-Bio 2007) and Kovac et al (Autonomous Robots 2010) — should probably be cited when discussing design, especially self-righting mechanism.

Drag coefficient is dimensionless and A has units of m^2, so all C_d*A quantities should have units. This shows up in section starting at 768.

Appropriate use of statistics and treatment of uncertainties:
As far as I can tell, N = 1 for the jumper. Number of jumps are not provided, nor are any statistics on jump height. This would be super helpful to have considering that the authors define jumping only as a repeatable task (and it clearly does jump multiple times as evidenced in videos).

Conclusions:

Overall, this is a fantastic engineering design of a jumping robot. Super cool and I can’t emphasize that enough. I also appreciate the identification of work amplification as a mechanism that engineering can use to outperform biology (although it is important to recognize that other systems have used this in the past). However, the modeling approach provided is not nearly as general as claimed, leaving out a large group of jumping insects and robots (including the authors’ robot design) and the lessons learned form this model are unclear.

Suggested improvements:

Many of my suggestions for improvement show up above from methodology section and significance / contributions. But some other thoughts are included below.

Line 28-29: It’s pretty clear that not all jumpers have the objective to maximize height or distance. Many jumpers target and control their jumps and do not maximize. I do not maximize my jump height or distance every time that I jump and I doubt other systems do either.

Would be helpful to clarify contributions beyond modeling in Longo et. al. (JEB 2019) and Ilton et. al. (Science 2018) that focused on spring actuation only and Sutton et. al. (ICB, 2019) that looked at both muscle and spring actuation in jumpers early in the introduction.

While it is true that jumping systems will be defined based on their inherent energy density and losses as illustrated by the developed model, the lessons learned from this are somewhat scattershot throughout the paper. What are the larger lessons learned (if any) other than maximize energy density and minimize losses? Can I learn anything about the choices that biology is making based on this? Or is it only really a design guideline for jumping robots? For the length scale indicated, what does the point between velocity limited and work limited mean? Is a squirrel jumping significantly different from a deer jumping?

Energy loss due to drag and non-vertical motions are pretty straightforward to understand (at least if the only goal is jumping straight up -- and unclear that any bio system is doing this or that any engineered system should). “Energy to stand” seems too simple if trying to create a very general model. This depends heavily on implementation. For the Sand Flea robot or another thrust driven robot that can jump multiple times, this will be 0 and won’t scale with length. You’re really trying to quantify energy losses while the foot is still on the ground here. Similarly, energy transfer between components is also quite simple and doesn’t encompass energy loss due to viscoelastic effects, friction, etc. The spring is often moving on one end and not moving on the other end — how does that get counted here? Many jumping robots and occasional insects slip against the ground. Where does this energy loss come into this framework? Is the ground a sub-component?

Should be clear that the design of the spring alone is not what provides a high specific energy. A chunk of material in tension would have higher specific energy due to constant strain throughout the material. The key point is that you are matching the spring to the actuator. This point is also discussed in Sutton ICB 2019 and other papers by Azizi's group. I do like the inclusion of a constant force spring here though.

Payload and reset time come out of the blue to some degree on line 208 and in Fig. 3. Is this completely separate from the modeling from earlier? How does it matter?

For work amplification, unclear why you care about anything other than torque if your only goal is to jump as high as possible. Why should I care about and report motor power other than time to store energy and jump? And why do I care about this? Parts of Fig 3 seemed very much an afterthought as a result. Similarly, if thinking about tradeoffs, how do you consider the battery given that repeatability is part of jumping definition here? Do you optimize size of battery too to get multiple jumps and maximum total height traveled?

How do you take into account losses due to spring still moving around after full extension? Would that be in your transfer bucket?

The videos are fun. Cleary this thing did jump more than once so some stats on the jump height would be great.

Would also be interested in finding out if there were any challenges with mechanical robustness. Did parts break when it landed? Did you have to do much glue reinforcement? This information would be valuable in supplemental material at minimum.

Figures:
Fig 1a — not sure what collision is supposed to indicate. How is height really defined? In this figure it looks like from the ground surface to the bottom of the foot? In general, I think most previous work tracks the delta between the COM.
Fig 4c — unclear what data point references refer to.

References:
Several additional citations that are relevant are presented in comments above.

Clarity and context:
Overall, the paper was written well.

81-87: "; this leaves the total kinetic energy…" 'leaves' is an ambiguous word choice here. It could mean that something is subtracted from or something remains and those mean totally different things here.

145: drain -> dissipate. Air resistance is not really ‘draining’ energy.

The switching between biological, engineering and general jumping systems can get confusing sometimes. For example, line 153, “Because the energy stored in the spring cannot exceed the work the muscle can do in a stroke, the specific jump energy remains capped…” — true for biological systems (only as far as I’m aware — I haven’t done much research on this and not sure if any bio systems use a clutch, but they do use gears as evidenced by Sutton). As you demonstrate, engineering systems can surpass this. Other than ‘muscle’ vs actuator, it is unclear that this sentence is only referring to bio systems. This is just one example. There are many throughout the text.

Be careful about using the same variable to mean multiple things. Beta is used at multiple points — I assume just to indicate a percentage, but it gets a bit confusing regardless.

Referee #2 (Remarks to the Author):

The presence of a unified model for jumping is a very interesting part of this paper; but I see the connection between the robot and the biological data as a little bit of a stretch that requires, at least, more explanation.

There is also citation of papers in the literature, but re-apportion of some of the key results of these papers in the main manuscript without attribution to the relevant papers. For instance, reference 9 is specifically about how leg length of a jumper restricts jump height, an analysis which seems identical to this manuscripts discussion of 'energy to stand' and its restriction of jump height; and yet the manuscript does not mention this connection in the manuscript when 'energy to stand' is discussed. The discussion of an velocity related zone and an energy limited zone is the point of reference 6 (in general) and reference 33 (in specific), but while the papers are mentioned, the connection between this manuscript's conclusions and these papers is also not discussed. Equation 1 could be greatly accentuated if the individual terms of this equation were also cited with the papers that discuss the individual terms (for example reference 9 discusses 'energy to stand' while reference 10 and 11 discusses drag).

Figure 1 also does not include insect data, for reasons that are clear in the supplemental material, but not discussed in the main text (there are, btw, non-latched jumping insects that could be included on this plot that, I think, would fill the data between salticid and frog quite nicely....)

Overall, I approve of the wholistic model of jumping, but am concerned about how the relevant papers are engaged... I'm willing to be convinced otherwise, but I'd like to see the authors justify these decisions.

The robot, however, does not connect to this data as well as the authors suggest. Yes, the robot jumps spectacularly high, but a ratcheting latch mediated jumping system could, in theory, jump almost arbitrarily high, could it not; with the limits only being the mass of the motor/spring system relative to the amount of stored spring energy? It is a spectacular video, no doubt, but its connection to the biological data - particularly since the biological data shows a limit on jump height of about 1 m...connecting this to the 26m jumping robot seems a major stretch. I do have a 2 specific questions - 1 was the spring stiffness optimized to the motor properties to maximize energy storage? and 2) why does reset time affect jump height? Shouldn't the spring energy stay 'stored' during arbitrarily long resets?

So, overall, I'm happy with the analysis, but would like the authors to address why the literature was engaged the way it was - there may be spectacularly good reasons for this that I may not recognize.

As for the robot, I don't see how these analyses affect the robots jump height - is the robot at a 'maximum' for its size? The movie is stunning, but the authors need to justify the applicability of the robot a bit more...

I'm somewhat discomforted, specifically by the use of the word 'supernatural' in the manuscript - this is not a precise word and can cause difficulties if used in a scientific manuscript.

Referee #3 (Remarks to the Author):

This paper introduces a model that attempts to capture many of the important effects that determine jump height in animals and mechanical systems. These include the relative mass of the foot and body, actuator speed, work output per actuation cycle, air drag, and the potential energy that is absorbed in the course of elevating while the foot is still in contact with the ground, which is larger for a longer stroke length. The authors give evidence of the validity of their model by plotting its prediction of jump hight versus measured jump heights of animals of various size scales ranging from spiders to elephants. The approximations and physics-based modeling effort (described in detail in the SI) is well-founded and I do not have any concerns with it. The authors then consider the design of an engineered jumper that is not subject to the constraint largely present in nature that a latch-clutch (ratchet?) mechanism is impossible. Building on this relatively un-surprising innovation (a few previous examples of spring-loading jumpers in the literature are given below), the authors nevertheless introduce a robot that achieves a substantial jump height of 26 m by optimizing a number of factors in their jump height model. The robot also has the desirable property that its design includes the ability to self-right during the process of resetting the spring loading, as well as low frontal area for low air drag in flight. I have no reason to doubt the strength of their optimization approach given the convincing robot demonstration.

The paper has merit and should be published somewhere, but has three main issues:

First, it suffers substantially from the need to condense its material into the nature format. For example, fig. 1a and b are so dense as to be nearly unintelligible. A bit more tutorial would help here. After the fourth or fifth reading I think I can make sense of it, but I had to figure out that “specific energy” refers to kinetic + potential - stored potential (per unit mass). The same holds to a lesser degree for Fig. 3.

Second, it it is not stated how the assumptions were made to create fig. 1c in the main text (“shown here with values relevant to biological jumps”), e.g. what quantities were used or, in many cases, how they were estimated, anywhere I could find. Some detail for numbers here and why and how they were chosen for animals is needed here; as it is I am not convinced that numbers in the model werent just chosen to fit the data set of jump heights that are available.

Third, the jumper design is innovative, but it is not surprising that a high jump is possible using an engineering design effort that is focused on maximizing this metric and the use of a geared motor to slowly load the elastic mechanism.

The combination of a weak biological claim, too much detail needed for the proposed paper length, and an un-surprising engineering do not meet Nature's criterion of being “of extreme importance.” I suggest that a better venue might be a publication available with longer format and robotics emphasis. Examples might be Nature Communicaitons , Science Robotics, or Royal Society Interface.

References:

Burdick, Joel, and Paolo Fiorini. "Minimalist jumping robots for celestial exploration." The International Journal of Robotics Research 22.7-8 (2003): 653-674.

Bhushan, Palak, and Claire Tomlin. "An Insect-scale Untethered Laser-powered Jumping Microrobot." arXiv preprint arXiv:1908.03282 (2019).

Author Rebuttals to Initial Comments:

We sincerely thank all referees for their time and most thorough and insightful comments. After much thought, we concluded that simple editing would not sufficiently address the concerns and elevate the previous manuscript. Instead, we decided to write a new paper based around the suggestions. Thus, we present not an edited version, but a rather a new manuscript driven and shaped by the reviewer comments.

Because it is pertinent to all reviewers, we briefly describe the major improvements in the new manuscript.

Refocused model

The original model focused on a series of energetic losses during a jump, assuming an input energy. We have since come to appreciate the importance of how this input energy is produced. In particular, we find that key differences in biological versus engineered jumpers arise in the energy production. Thus, we now focus on the input or "energy production" model and have moved the original loss model to the Methods, terming it "energy utilization" model.

Insights from model

From the energy production model, we find two key insights about the differences between biological versus engineered jumper energetics:

1) The upper limit of jump energy for biological jumpers is set by motor specific work, whereas for engineered jumpers it is set by spring specific energy.
    -We find this is because engineered motors can do "work multiplication," in which the motor (whether ratcheted linear or rotary) can do multiple strokes to "multiply" the work put into the jump; biological motors are limited to the work of a single stroke.
2) Consequently, to maximize jump energy, engineered jumpers should have a spring mass to motor mass ratio at least a hundred-fold larger than that of biological jumpers.

New robot spring and mechanism design

The insights from the model add to the general understanding of jumping in biological versus engineered jumpers, and also offer design guidance for the presented jumper. Such starkly different spring-motor mass ratios imply engineered jumping mechanisms should potentially not look like biological mechanisms. Indeed, we designed a new mechanism that does not have the traditional bio-inspired "leg-like" linkage design, pushing the limit of spring specific energy. We also pushed the spring-motor mass ratio to almost 3, compared to approximately 0.03 in biology. The new mechanism shows a 25% increase in specific energy over our original design, leading to a 32 m jump.

We note that the new jumper represents an order of magnitude improvement in jump height over previous motor-driven jumpers, many of which sought to maximize jump height. While the field has shown incremental improvements, slowly increasing to ~3.5 m over decades, our work represents a step change, significantly altering what should be expected of engineered jumpers.

Finally, we mention that we added two new co-authors to the project, one an expert in theory to drive the new modeling work, and one an expert in robot design, to lead efforts on the new jumper mechanism.

Responses to referees' comments:

Referee #1:

R1.1 Summary of key results:
The authors present a model for jumping systems (defined as systems that can jump repeatably by applying forces to the ground, powered by an onboard energy supply). This model focuses on losses due to the ratio of actuator to system mass, energy loss before the jumper leaves the ground, losses due to any motion outside of the relevant 1-DOF, air drag, and energy transfer between components and the authors claim that this model can be used to explain how jump height varies across all scales for both biological and engineered systems. The authors also identify work amplification for the actuator as a key component to improve energy density in jumping robots and use this idea in a jumping robot that can jump an incredible 26 m.
Thank you for this nice summary.

R1.2 Originality and significance:
The jumping robot is amazing. The jump height result (unclear that there is more than one result though) from the robot itself is clearly significant. It was wonderful to see all of the pieces put together for the first time.
Thank you for your comment on the robot. We hope the new paper conveys more than this singular result!

R1.3 I am less convinced by the significance of the "unifying" modeling approach. As is made abundantly clear by Extended Data Fig. 1, the model does not predict takeoff velocities (and corresponding jump heights in Fig 1c/d) of jumpers that use latched energy storage, of which there are many and the authors' robot also uses. It is telling that data points like the froghopper and locust were not included in Fig. 1. Line 105 indicates that you're only considering energy reductions for non-latched energy storage jumpers. Therefore, it is unclear that it explains how jump height varies across all scales and types of jumpers, as the authors claim. If the model is not describing how these jumpers jump, what can I learn from this model that is not covered in work like Sutton et. al. (ICB, 2019)?
This is one of the comments that led us to our new focus, as it made us realize the importance of energy production, how it differs for latched versus unlatched, and how it differs for biological versus engineered.
Before we describe the changes we made, we do want to clarify that the original energy utilization model was general enough to describe latched and unlatched (i.e., power amplified and direct drive) systems. However, we did a very poor job of communicating this. We wrote in the original line 105:
"Next, we consider how the five reductions scale, and illustrate with values relevant for biological jumpers without latched energy storage (Fig. 1c)."
We were trying to indicate that this was an illustration of the model for the case of unlatched jumpers. Not only was this written unclearly, but Extended Data Fig. 1 was even less clear. We plotted the latched data on the plot with only the unlatched model; this was a huge oversight on our part, and we should have also plotted the model for the latched case.

However, we have refocused our model, now considering both the “energy production” and the “energy utilization,” whereas the original model focused on energy utilization only.

> *Ln 47-49: Energetically, we examine a jump in two steps: energy production limits (the maximal energy the jumper could create for a single jump) and energy utilisation (the efficiency of converting this energy into jump height)*

The model now explains the difference in energy production for biological and engineered jumpers across scale, both with and without power amplification. We believe in doing so, we offer a contribution not found in previous work like Sutton et al.

R1.4 In fact, defining a velocity limited regime is exactly what Ilton et. al. (Science 2018) did. It seems that the contribution of this work is also defining a work-limited regime? Another interesting point included in this manuscript is the importance of work amplification from the actuator. It should be noted that there have been several publications from the Pister group at UC Berkeley that utilize a clutch-based design for jumping “robots” (robots in quotes because they are tiny and not fully contained as the example here), e.g.
* Bergbreiter and Pister, ICRA 2007
* Greenspun and Pister, Hilton Head 2018

There have also been previous winch-based robots that provide work amplification similar to that demonstrated by the authors, e.g.
* Stoeter and Papanikolopoulos, IEEE T-Ro 2006

Another key point to amplify the significance of this — are there any examples of biological systems that take advantage of work amplification?
Again, this comment helped us refocus. “Work multiplication” (we renamed it to better represent its behavior in multiplying the work done in a single stroke) is a key difference between biological and engineered jumpers, as demonstrated nicely by these examples. All have been added to the manuscript.

R1.5 Data and methodology:
For methods section, just stick with using the term specific energy when talking about J/kg and energy when talking about J. Otherwise, it gets confusing.
This helps clarify the paper. We have followed this suggestion and use the term “specific” when we refer to J/kg or W/kg.

R1.6 What is considered to be the actuator in spring driven systems? Is it the motor + spring? Spring only? Motor + spring + latch? This is a key point. I think Ilton et al, Longo et al (JEB 2019) would define the spring as the actuator which removes the velocity limitation in this work and model. It is unclear that this work is considering the same.
We have clarified our terminology and now also show it visually in Fig. 1. We now examine the “jumping mechanism,” which we define as the motor, spring, and any required linkage.

> *Ln 55-56: In the model, we consider the jumper to comprise a payload and a jumping mechanism, which in turn comprises a motor, a linkage, and an optional latched spring*

(Fig. 1b).

R1.7 For non-vertical motions, would help to define coordinate systems — looks like you are using some kind of spherical coordinates, but Euclidean terms. Otherwise, unclear why I should only be concerned about motion in x vs x and y (assuming z is vertical).

This has been corrected to clarify that we are using Euclidean coordinates: translational velocities v_x, v_y, v_z about the x,y,z axes, as well as rotational velocity ω about the instantaneous axis of rotation.

> *Methods Ln. 497-498: This deducts the fraction of the kinetic energy due to movements in any horizontal direction (β_{xy}) and due to rotations (β_θ).*
> *Details of the derivation and definitions of v_x, v_y, v_z are defined in the Supplementary Information.*

R1.8 For energy transfer, unclear how spring is counted since some of the spring is moving and some isn't? This was addressed to some degree in Ilton et al (Science 2018).

We agree that spring mass is important, and that there is a gradient of velocity along the spring during a jump. Our model accounts for this using two lumped masses (m_{body} and m_{foot}) which include and match the spring's mass and momentum. We note this in the model and provide greater detail in the Supplementary Information.

> *Methods Ln. 501-503: It effectively removes energy of internal relative motions, accelerating the foot and the portion of the spring that was stationary prior to launch.*
> *Definitions and formulas for m_{body} and m_{foot} are provided in the Supplementary Information.*

R1.9 For scaling, I have several concerns for a more general scaling argument. While muscle force does indeed scale as L^2, that is not necessarily true for engineered actuators. There are several papers on this (Wautelet 2001, Fearing 1998, etc). It was also unclear what authors took as their starting point for scaling arguments. Lines 122-123 for example, it was unclear where 80%, 35% etc #s come from.

This was an important comment that aided in our refocusing. To make the model able to capture the behaviors of engineered jumpers, it is key that it accounts for differences in motor scaling between biological and engineered motors. Indeed, muscle force scales as L^2, muscle velocity as L, and thus muscle specific power as L^0. Electromagnetic motors, in contrast, have torque that scales as L^4, and angular velocity that scales as L^{-1} (with the consideration of an isometrically scaled moment arm on the rotary motor, force scales as L^3 and velocity scales as L^0). Interestingly, and most importantly, specific power thus scales as L^0, just as in the case of the biological muscle. We incorporate these scaling laws into our new model.

> *Methods Ln. 439-444: In biology[48,49], muscle forces scale with area, $F_{max} \propto L^2$, while distance (stroke) and velocity scale with length, $d \propto L$, $v_{max} \propto L$, and mass scales with volume, $m \propto L^3$. In engineering, with rotary motors, the torque scales with the 4th power of length, $\tau \propto L^4$, while angular speed scales inverse linearly, $\omega \propto L^{-1}$, so again the power remains scale invariant[48,50,51]. Similar to biological muscle, all spring forces scale with area, $F_{max} \propto L^2$, while distances (stroke) scale with length, $d \propto L$, such that spring specific energies are scale independent.*

R1.10 Line 483: Ilton et al does illustrate that jump height decreases at small scales for spring-powered jumpers. It is unclear if the authors are disputing the data presented in this paper or saying that the theoretical limit does not actually change? Ilton et al suggests that the limit is due to material properties of the spring and therefore, that the work density does in fact drop off for these systems (at least for biological materials). I don't believe it has anything to do with the fact the spring may be attached or not attached to the projectile. In biological jumpers for which data is presented, clearly the spring is attached.

Thank you for raising this concern, as upon re-reading it was not clear that we were indeed noting a difference in the conclusion of our work with that of Ilton et al. We first note that the authors of this paper published more recent work (Sutton ICB 2019) in which they conclude that takeoff velocity (and work density) should be scale-independent for these small biological jumpers, and present new data that backs up this conclusion.

We believe that the theoretical conclusion from Ilton et al. was a result of a catapult-based model and how it predicts that material limits would decrease performance for a constant-size catapult launching smaller and smaller projectiles. If one scales down the size of the projectile (but keeps the scale of the catapult constant), eventually the spring performance decreases or gets too stiff and fractures. This model, however, does not capture the case where the scale of the spring changes with the scale of the projectile, as is generally the case in jumpers. If one works through the scaling in the case of jumpers, the spring can produce the same specific energy regardless of scale, assuming a constant modulus. We have added text hopefully clarifying this point.

> *Methods Ln. 455-463: We finally note that our model showing that spring-powered jumpers are scale-invariant in specific energy production contrasts with the conclusions of previous work[34], which stated that specific energy production decreases at small scales for spring-powered jumpers. The discrepancy arises from differing model assumptions: the previous work considered a catapult launching a projectile, where only the projectile, but not the catapult, changed size during scaling. This led to the conclusion that the catapult's spring would meet material limits; however, during scaling of a jumper, spring and all, this effect is not present, and spring-powered biological jumpers should be scale-invariant, as shown in more recent work[27].*

R1.11 Very unclear how m_body and m_foot are actually defined? Where does the spring connecting the body to the foot fall in this division? Might help to include a table with relevant masses and numbers for your robot.

Although this is much less a focus of the paper (the model is now focused on energy production, and the original model of energy utilization is now in the Methods), we still tried to clarify. The m_foot and m_body are lumped mass parameters that match the momentum and mass of the distributed masses with distributed velocity of any jumper. We have added clarifications to the Methods and precise definitions and formulas for $\mathrm{m}_{\mathrm{body}}$ and $\mathrm{m}_{\mathrm{foot}}$ are provided in the Supplementary Information.

> *Methods Ln. 501-503: It effectively removes energy of internal relative motions, accelerating the foot and the portion of the spring that was stationary prior to launch.*
> *Definitions and formulas for m_{body} and m_{foot} are provided in the Supplementary Information.*

R1.12 The idea that I should add weight to my system to increase jump height (as discussed in section starting at line 635) is still completely unintuitive. Can you actually demonstrate this?
We agree that it is very surprising! We have added a thought experiment to the section to help explain how this could be possible. As this is no longer related to our central focus, this discussion was moved into the Supplementary Information.

> *Supplementary Information Ln. 957-959: Should the body mass fall below the foot mass, it is beneficial to add a payload to the system body. (Imagine a heavy foot and massless body; only by adding mass to the body would this system jump.)*

R1.13 The robot design looks very much like the Jollbot (Armour et al, Bio-Bio 2007) and Kovac et al (Autonomous Robots 2010) — should probably be cited when discussing design, especially self-righting mechanism.
This is an excellent observation and we have cited both of these robots now when we show self-righting.

R1.14 Drag coefficient is dimensionless and A has units of m^2, so all C_d*A quantities should have units. This shows up in section starting at 768.
Thank you, this is corrected.

R1.15 Appropriate use of statistics and treatment of uncertainties:
As far as I can tell, N = 1 for the jumper. Number of jumps are not provided, nor are any statistics on jump height. This would be super helpful to have considering that the authors define jumping only as a repeatable task (and it clearly does jump multiple times as evidenced in videos).
We now include three jumps and include the average and standard deviation of the jumps.

Conclusions:

R1.16 Overall, this is a fantastic engineering design of a jumping robot. Super cool and I can't emphasize that enough. I also appreciate the identification of work amplification as a mechanism that engineering can use to outperform biology (although it is important to recognize that other systems have used this in the past). However, the modeling approach provided is not nearly as general as claimed, leaving out a large group of jumping insects and robots (including the authors' robot design) and the lessons learned form this model are unclear.
We really appreciate the excitement for the jumper! And the comment that work amplification (now work multiplication) is important led us to bring it more to the fore (while making clear that this is a mechanism that many engineered jumpers use). We hope the new focus of the model makes clear that it applies to both latched and unlatched jumpers. Finally, we believe the new model offers some interesting lessons (biology is limited by motor specific work, whereas engineering is limited by spring specific energy; engineering should have a spring-motor mass ratio ~100x larger than biology).

Suggested improvements:

Many of my suggestions for improvement show up above from methodology section and significance / contributions. But some other thoughts are included below.

R1.17 Line 28-29: It's pretty clear that not all jumpers have the objective to maximize height or distance. Many jumpers target and control their jumps and do not maximize. I do not maximize my jump height or distance every time that I jump and I doubt other systems do either.
This is a good point, and we have rephrased this.

> *Ln. 23-24: It is found across diverse species and size scales, yet is performed in strikingly similar manners and has a clear, quantifiable metric: jump height or distance.*

R1.18 Would be helpful to clarify contributions beyond modeling in Longo et. al. (JEB 2019) and Ilton et. al. (Science 2018) that focused on spring actuation only and Sutton et. al. (ICB, 2019) that looked at both muscle and spring actuation in jumpers early in the introduction.
Another comment that helped us refocus on what our modeling contributions are. We believe we now offer a clear contribution to the literature in the form of a comparison between the energetics of biological versus engineered jumping.

> *Ln. 31-42: …The performance limits of jumping across scale are thus well-studied, within the domain of biology.*
>
> *These studies have informed the design of many bio-inspired engineered jumpers, dating back to at least 1967[3]. However, a general modelling framework to capture and quantify inherent differences in biological and engineered jumpers across scale is missing from the literature. Most engineering works focus on specific designs[3–18,31]**,** draw conclusions based on previous biological models[10], or present models of motors that only describe single-stroke motors as found in biology[14,32].*
>
> *Here we present an energy-based model of jumping able to compare the underlying phenomena of both biological and engineered jumpers…*

R1.19 While it is true that jumping systems will be defined based on their inherent energy density and losses as illustrated by the developed model, the lessons learned from this are somewhat scattershot throughout the paper. What are the larger lessons learned (if any) other than maximize energy density and minimize losses? Can I learn anything about the choices that biology is making based on this? Or is it only really a design guideline for jumping robots? For the length scale indicated, what does the point between velocity limited and work limited mean? Is a squirrel jumping significantly different from a deer jumping?
These comments about clear lessons really drove our thinking in developing our new paper. We hope now that the lessons are clear: biology is limited by motor specific work, whereas engineering is limited by spring specific energy; engineering should have a spring-motor mass ratio ~100x larger than biology. Further, these lessons directly guide our robot design. We focus now on spring design to push the limits of the spring specific energy limit (resulting in a new design of a hybrid compression-tension spring with ~25% higher specific energy than our previous design). We also focus on creating a high spring-motor mass ratio. With these two

efforts, we increased the jump height by ~20% to over 32 m.

R1.20 Energy loss due to drag and non-vertical motions are pretty straightforward to understand (at least if the only goal is jumping straight up -- and unclear that any bio system is doing this or that any engineered system should). “Energy to stand” seems too simple if trying to create a very general model. This depends heavily on implementation. For the Sand Flea robot or another thrust driven robot that can jump multiple times, this will be 0 and won’t scale with length. You’re really trying to quantify energy losses while the foot is still on the ground here. Similarly, energy transfer between components is also quite simple and doesn’t encompass energy loss due to viscoelastic effects, friction, etc. The spring is often moving on one end and not moving on the other end — how does that get counted here? Many jumping robots and occasional insects slip against the ground. Where does this energy loss come into this framework? Is the ground a sub-component?
These are all helpful questions. Although the original energy utilization model is now a minor part of the paper (moved to Methods and SI), we have still tried to clarify these concerns. In particular, the “energy to stand” reduction or aspect of the utilization model is not attempting to capture all losses during the contact time-period, but only to describe the potential energy difference between stand and crouch positions. As such, it is our understanding that even a robot like the Sand Flea pushes the ground to accelerate its body upward, even if only momentarily; here too, we would see a difference in the body’s potential energy between the instant when the foot first touches the ground and when the foot leaves the ground. We now better clarify other losses due to viscoelastic effects, friction, etc. in stage 1, losses due to ground slippage in stage 4, and losses due to distributed spring mass and velocity in stage 5.

> *Methods Ln. 486-487 = Stage 1: Any impedance mismatches between components or viscous losses will reduce the available energy.*
> *Methods Ln. 498-499 = Stage 4: This also includes potential losses due to sliding on the ground surface or frictional losses in joints.*
> *Methods Ln. 501-503 = Stage 5: It effectively removes energy of internal relative motions, accelerating the foot and the portion of the spring that was stationary prior to launch.*

R1.21 Should be clear that the design of the spring alone is not what provides a high specific energy. A chunk of material in tension would have higher specific energy due to constant strain throughout the material. The key point is that you are matching the spring to the actuator. This point is also discussed in Sutton ICB 2019 and other papers by Azizi’s group. I do like the inclusion of a constant force spring here though.
This is an interesting point that led us to delve much deeper into spring and mechanism design. It is entirely true that the highest specific energy spring is a tension spring. However, such a spring cannot by itself drive a jump, and instead requires a passive linkage. Thus, we consider compression springs as well as tension springs plus linkages during our design process. And yes, the constant-force spring (much more so in the current design than before) is important, allowing us to match the spring to the gearmotor to store more energy than a non-constant force spring.

Ln 140-146: We evaluate three distinct spring designs, comparing the overall specific energy, as the integral of specific output force over compression (Fig 4a). A tension spring offers the highest spring specific energy (7,000 J/kg as shown Fig. 2,3) but requires an additional passive linkage to push the jumper upward (resulting in an overall 1,894 J/kg). A compression bow-spring can avoid much of the linkage mass, but has a lower inherent spring specific energy (2,037 J/kg). A hybrid spring, supporting the high-specific-energy tension spring with the compression bow-spring rather than a passive linkage, integrates both benefits (2,555 J/kg). Further, this spring has a nearly constant force-displacement curve, which provides the best overall energy for a given force level, for example governed by a given gearmotor (spring-motor mismatch in biology leads to lower stored energy).

We further elaborated on the point of matching the spring to actuator and cite Sutton ICB 2019.

Ln 521-523: Practically, the force-displacement profiles of biological muscle and tendons limits jumpers to obtain 30-50% of the potential muscle energy[26,27]. In contrast, our constant force matches the nearly constant force output of our motor, mitigating this loss.

R1.21 Payload and reset time come out of the blue to some degree on line 208 and in Fig. 3. Is this completely separate from the modeling from earlier? How does it matter?

This is a good point. The new modeling removes this discussion. We instead frame the model in terms of the ratio of spring mass to motor mass. An engineered jumper will maximize jump energy by maximizing this ratio, with the tradeoff that it will take a long time to preload the spring.

Methods Ln. 618-620: Given the small size of the motor, reset time is roughly 2 minutes. This could be decreased by increasing the motor size (e.g., doubling the motor mass (and power) would approximately halve reset time).

R1.22 For work amplification, unclear why you care about anything other than torque if your only goal is to jump as high as possible. Why should I care about and report motor power other than time to store energy and jump? And why do I care about this? Parts of Fig 3 seemed very much an afterthought as a result. Similarly, if thinking about tradeoffs, how do you consider the battery given that repeatability is part of jumping definition here? Do you optimize size of battery too to get multiple jumps and maximum total height traveled?

Upon reflection, we agree with your assessment. We have, as mention in the previous point, removed the examination of reset time as a tradeoff, and instead look at spring-motor mass ratio, which is a key parameter in jumper design. Motor power now only shows up as limiting energy production for direct-drive systems (and not for power-amplified systems). As for battery sizing, we consider the battery part of the payload, and thus is covered in the energy utilization model. Because a battery has a much higher specific energy than any other component of the device, adding more battery within practical constraints allows more total height/distance to be covered, at the expense of smaller individual jumps.

R1.23 How do you take into account losses due to spring still moving around after full extension? Would that be in your transfer bucket?

Exactly, yes this is in the energy transfer loss. During the transfer, momentum is conserved, but energy is not, and some of the lost energy goes to heat, some to sound, some to other things, and some to internal movements, like the motion of the spring.

> *Methods Ln. 501-503 = Stage 5: It effectively removes energy of internal relative motions, accelerating the foot and the portion of the spring that was stationary prior to launch.*

R1.24 The videos are fun. Cleary this thing did jump more than once so some stats on the jump height would be great.

We appreciate this suggestion and have done three jumps and report an average and standard deviation.

> *Methods Ln. 602: We find the jump heights to be 32.2, 32.8, and 33.6 m for the three jumps (32.9±0.7 m).*

R1.25 Would also be interested in finding out if there were any challenges with mechanical robustness. Did parts break when it landed? Did you have to do much glue reinforcement? This information would be valuable in supplemental material at minimum.

Great suggestion. We have added more text in the Methods describing is robustness (surprisingly, it can handle landing even on concrete) and reinforcement.

> *Methods Ln. 595-597: Cyanoacrylate adhesive is used throughout for bonding. The combination of a lightweight construction and high-strength materials means the jumper can survive landing on even concrete surfaces from its apex height of 32 m.*

Figures:

R1.26 Fig 1a — not sure what collision is supposed to indicate. How is height really defined? In this figure it looks like from the ground surface to the bottom of the foot? In general, I think most previous work tracks the delta between the COM.

We have redrawn Fig. 1a based on your comments, and hopefully it is more clear. We have added text in the Methods and Supplementary Information to clearly define jump height.

> *Methods Ln. 493-495: This delivers the jump height as the change in height of the centre of mass above its position when the jumper is fully standing.*
> *Supplementary Information Ln. 814-815: It is important to note that jump height is defined as the change in height of the centre of mass above its position when the jumper is fully standing[21,22].*

R1.27 Fig 4c — unclear what data point references refer to.

We have added references onto the plot to clarify. Thank you for the suggestion.

References:

R1.28 Several additional citations that are relevant are presented in comments above.

All references added above have now been included.

Clarity and context:
R1.29 Overall, the paper was written well.
Thank you. We hope the new paper is equally, if not more, so.

R1.30 81-87: "; this leaves the total kinetic energy…" 'leaves' is an ambiguous word choice here. It could mean that something is subtracted from or something remains and those mean totally different things here.
This is a good point. The text has been completely rewritten, and this has been removed.

R1.31 145: drain -> dissipate. Air resistance is not really 'draining' energy.
Another good point, and also removed during re-writing.

R1.32 The switching between biological, engineering and general jumping systems can get confusing sometimes. For example, line 153, "Because the energy stored in the spring cannot exceed the work the muscle can do in a stroke, the specific jump energy remains capped…" — true for biological systems (only as far as I'm aware — I haven't done much research on this and not sure if any bio systems use a clutch, but they do use gears as evidenced by Sutton). As you demonstrate, engineering systems can surpass this. Other than 'muscle' vs actuator, it is unclear that this sentence is only referring to bio systems. This is just one example. There are many throughout the text.
This is a good point, and we have worked to address this in our new text. We have tried to be very clear by stating explicitly every time we refer to either biological or engineered jumpers.

R1.33 Be careful about using the same variable to mean multiple things. Beta is used at multiple points — I assume just to indicate a percentage, but it gets a bit confusing regardless.
Thank you, this has been corrected.

Referee #2 (Remarks to the Author):

R2.1 The presence of a unified model for jumping is a very interesting part of this paper; but I see the connection between the robot and the biological data as a little bit of a stretch that requires, at least, more explanation.

We hope that in re-writing our paper, we have addressed this primary concern. We hope that the new model now elucidates differences in the energetics of biological versus engineered jumping, and offers insights into differences in how biological and engineered jumping mechanism should be designed to maximize jump height or distance. Please see R2.5 below for further details.

R2.2 There is also citation of papers in the literature, but re-apportion of some of the key results of these papers in the main manuscript without attribution to the relevant papers. For instance, reference 9 is specifically about how leg length of a jumper restricts jump height, an analysis which seems identical to this manuscripts discussion of 'energy to stand' and its restriction of jump height; and yet the manuscript does not mention this connection in the manuscript when 'energy to stand' is discussed. The discussion of an velocity related zone and an energy limited zone is the point of reference 6 (in general) and reference 33 (in specific), but while the papers are mentioned, the connection between this manuscript's conclusions and these papers is also not discussed. Equation 1 could be greatly accentuated if the individual terms of this equation were also cited with the papers that discuss the individual terms (for example reference 9 discusses 'energy to stand' while reference 10 and 11 discusses drag).

This is an important point, and we have worked to integrate references more thoroughly into the paper, rather than only citing them at the beginning. We note that the energy utilization model (the model from the original paper) is no longer the focus of the paper and is in the Methods section. However, we have added the suggested references into the description of the model.

Methods Ln. 486-505:

1) *Produced specific energy, e_{prod}, considering the production efficiencies: Any impedance mismatches between components or viscous losses will reduce the available energy. Practically, the force-displacement profiles of biological muscle and tendons limits jumpers to obtain 30-50% of the potential muscle energy[26,27].*
2) *Initial specific energy before movement, e_0, that can be released in a single jump: Any payload requires apportionment across the entire mass[26].*
3) *Total specific kinetic energy, e_{KE}, after the full stroke has occurred: This deducts the potential energy surrendered to raise the centre of mass from crouch to stand[21]. This delivers the jump height as the change in height of the centre of mass above its position when the jumper is fully standing.*
4) *Vertical specific kinetic energy, e_{vert}, due to movements in the vertical (z) direction only[19]. This deducts the fraction of the kinetic energy due to movements in any horizontal direction (β_{xy}) and due to rotations (β_θ). This also includes potential losses due to sliding on the ground surface or frictional losses in joints.*
5) *Vertical Centre-Of-Mass (COM) specific kinetic energy, e_{COM}, after launch: This deducts the transfer losses shifting energy from individual masses to the COM motion[18,19,34]. It effectively*

removes energy of internal relative motions, accelerating the foot and the portion of the spring that was stationary prior to launch.

6) *Potential energy at the jump apex, e_{apex}: This deducts the aerodynamic drag losses occurring during the jump*[11,30]*.*

R2.3 Figure 1 also does not include insect data, for reasons that are clear in the supplemental material, but not discussed in the main text (there are, btw, non-latched jumping insects that could be included on this plot that, I think, would fill the data between salticid and frog quite nicely....)

We realized that the decision to not include the latched insect data in the main text was confusing. This plot has been removed and instead we present Extended Data Fig. 1, including all of the data together. And thank you for the suggestion of non-latched jumping insects; we have added data from

Epiphyas postvittana

Xanthorhoe fluctuate

Crambus pascuella

which range from 0.01 s to 0.02 s take-off times, filling in this gap nicely.

R2.4 Overall, I approve of the wholistic model of jumping, but am concerned about how the relevant papers are engaged... I'm willing to be convinced otherwise, but I'd like to see the authors justify these decisions.

We now engage the relevant papers in the discussion of the utilization model, and at the same time, introduce what we believe is a more compelling model of energy production.

R2.5 The robot, however, does not connect to this data as well as the authors suggest. Yes, the robot jumps spectacularly high, but a ratcheting latch mediated jumping system could, in theory, jump almost arbitrarily high, could it not; with the limits only being the mass of the motor/spring system relative to the amount of stored spring energy? It is a spectacular video, no doubt, but its connection to the biological data - particularly since the biological data shows a limit on jump height of about 1 m...connecting this to the 26m jumping robot seems a major stretch.

This comment was very helpful for us in refocusing and rewriting the paper. Upon reflection, we agree that the connection between the model/data and the jumper was tenuous. We therefore derived a jump energy production model to examine potential differences in energy production between biology and engineering. We found substantial differences: biology is limited by motor specific work, whereas engineering is limited by spring specific energy; and engineering should have a spring-motor mass ratio ~100x larger than biology. With these insights, we are able to connect biology and engineering, understanding why engineering can surpass biology by an order of magnitude.

And yes, as suggested in this comment, an engineered jumper can go very high; it is by quantifying the actual limits on this (spring specific energy and spring-motor mass ratio) that allowed us to focus our design. Of note, the extreme difference in ideal spring-motor mass ratio between biological and engineered jumpers implies that direct copying of the leg-like linkage found in biology is potentially not ideal. Instead, we designed a new type of hybrid spring mechanism, with a tension spring stretched between two buckling beams. We pushed the spring specific energy to over 2500 J/kg and the spring-motor mass ratio to almost 3, enabling a jump height of over 32 m.

We note that the previous state-of-the-art motor-driven jumpers have over the last decades incrementally increased jump height by matters of tens of centimeters to between 3 and 4 m, with dedicated engineering efforts, seeking to maximize this metric (e.g., Ref. 15, 16).

R2.6 I do have a 2 specific questions - 1 was the spring stiffness optimized to the motor properties to maximize energy storage?

This is a good question that was not clearly answered in the original manuscript. In our new design, the spring force-displacement curve closely matches that of the motor, to maximize the energy that the motor can store in the spring. This, interestingly, is not the case in biology. We add clarifying text.

> *Ln. 148-150: Further, this spring has a nearly constant force-displacement curve, which provides the best overall energy for a given force level, for example governed by a given gearmotor.*
>
> *Methods Ln. 483-487: Produced specific energy, e_{prod}, considering the production efficiencies: Any impedance mismatches between components or viscous losses will reduce the available energy. Practically, the force-displacement profiles of biological muscle and tendons limits jumpers to obtain 30-50% of the potential muscle energy[26,27]. In contrast, our constant force matches the nearly constant force output of our motor, mitigating this loss.*

R2.7 2) why does reset time affect jump height? Shouldn't the spring energy stay 'stored' during arbitrarily long resets?

After reconsidering, we have removed dependency on reset time. We agree now that it is not a metric that is particularly helpful.

R2.8 So, overall, I'm happy with the analysis, but would like the authors to address why the literature was engaged the way it was - there may be spectacularly good reasons for this that I may not recognize.

We hope our addition of the literature into the description of the utilization model improves our paper.

R2.9 As for the robot, I don't see how these analyses affect the robots jump height - is the robot at a 'maximum' for its size? The movie is stunning, but the authors need to justify the applicability of the robot a bit more...

This is another comment that helped direct our paper during rewriting. We were able to derive the jump energy production model that offers insights into differences between biological and engineered jumpers, and from these results, directly inform the design of the robot. We hope this connection (outlined in detail above in R2.5) helps clarify how the analysis affect the robot design and explains it ability to jump to 32 m.

R2.10 I'm somewhat discomforted, specifically by the use of the word 'supernatural' in the manuscript - this is not a precise word and can cause difficulties if used in a scientific manuscript.
This has been removed, as almost the entire text has been rewritten in accordance to the reviewers' comments.

Referee #3 (Remarks to the Author):

R3.1 This paper introduces a model that attempts to capture many of the important effects that determine jump height in animals and mechanical systems. These include the relative mass of the foot and body, actuator speed, work output per actuation cycle, air drag, and the potential energy that is absorbed in the course of elevating while the foot is still in contact with the ground, which is larger for a longer stroke length. The authors give evidence of the validity of their model by plotting its prediction of jump hight versus measured jump heights of animals of various size scales ranging from spiders to elephants. The approximations and physics-based modeling effort (described in detail in the SI) is well-founded and I do not have any concerns with it. The authors then consider the design of an engineered jumper that is not subject to the constraint largely present in nature that a latch-clutch (ratchet?) mechanism is impossible. Building on this relatively un-surprising innovation
(a few previous examples of spring-loading jumpers in the literature are given below), the authors nevertheless introduce a robot that achieves a substantial jump height of 26 m by optimizing a number of factors in their jump height model. The robot also has the desirable property that its design includes the ability to self-right during the process of resetting the spring loading, as well as low frontal area for low air drag in flight. I have no reason to doubt the strength of their optimization approach given the convincing robot demonstration.
Thank you for a thorough summary of the previous paper.

The paper has merit and should be published somewhere, but has three main issues:

R3.2 First, it suffers substantially from the need to condense its material into the nature format. For example, fig. 1a and b are so dense as to be nearly unintelligible. A bit more tutorial would help here. After the fourth or fifth reading I think I can make sense of it, but I had to figure out that “specific energy” refers to kinetic + potential - stored potential (per unit mass). The same holds to a lesser degree for Fig. 3.
This was helpful feedback. We have redone all of the figures with this in mind. We believe they are much easier to parse and therefore, hopefully more informative. Also, in re-writing the text have closely followed the nature guidelines for lengths of relevant sections (main text, Methods, and SI).

R3.3 Second, it it is not stated how the assumptions were made to create fig. 1c in the main text (“shown here with values relevant to biological jumps”), e.g. what quantities were used or, in many cases, how they were estimated, anywhere I could find. Some detail for numbers here and why and how they were chosen for animals is needed here; as it is I am not convinced that numbers in the model werent just chosen to fit the data set of jump heights that are available.
After considering this comment, along with the many others from the reviewers, we shifted the focus of the modeling to energy production (the former model, focuses on losses or energy utilization, has now been moved to the Methods). We find that the energy production model explains the fundamental differences between biological and engineered jumpers, and hence we have brought it to the fore. As a result, the replacement for Fig. 1c (now Extended Data Fig. 1) includes the same data (with some different animals, as suggested by Reviewer 2), but now

with the energy production model. The energy production model requires only three parameters, which are easily found in the biological literature: muscle specific work, muscle specific power, and spring specific energy. We clearly state where these quantities were found and what their values are.

> *Ln. 93-98: (i) the motor's single-stroke specific work (muscle: ~200 J/kg[26]), or the integral of specific force over stroke length (dashed green) and (ii) the product of motor specific power (muscle: ~300 W/kg[41]) and available time (dashed blue).* ***b,*** *For engineered, direct-drive systems, work multiplication removes the motor specific work limiter, and motor specific power (electromagnetic motor: ~2000 W/kg[42]) is the only limiter.* ***c,*** *For biological, power-amplified systems, the addition of a latched spring (tendon/apodeme: ~7000 J/kg[26])*

R3.4 Third, the jumper design is innovative, but it is not surprising that a high jump is possible using an engineering design effort that is focused on maximizing this metric and the use of a geared motor to slowly load the elastic mechanism.

This is a very important comment that made clear to us that we did not adequately frame the jumper with respect to the state of the art. We now clarify in the text that we are not the first group to make an engineering design effort focused on maximizing jump height with a geared motor and elastic mechanism. Indeed, many papers from leading groups around the world have attempted to push the limits of jump height and distance. For example, Ref. 15 states:

> "The design goal was for a given robot mass to increase the possible height and distance of the jump."

And Ref. 16 had the same goal, even completing optimizations for ~5% improvements:

> "Thus, an improvement of the cost function of 4.7% (figure 8) has been obtained for the jumping mechanism by optimizing the shape and weight of the main leg."

As such, we ourselves were surprised when we were able to improve on the state of the art not by another 5%, but by nearly 1000%. We still are uncertain what is the primary reason for this substantial improvement, but possibly it is the somewhat counter-intuitive realization that, unlike biology, engineered jumpers should have a spring mass larger than the motor.

> Ln. 160-164: *Interestingly, the two previously best motor-driven engineered jumpers with very different morphologies can reach 3.7 m[15] and 3.8 m[13], yet our analysis and demonstration show their mechanism specific energy (approximately 100 J/kg[15] and 115 J/kg[13]) is not near a fundamental limit. With a mechanism specific energy of 1100 J/kg, we measured our jumper reaching 32.6 +/- 0.7 m (Fig. 4c).*

R3.5 The combination of a weak biological claim, too much detail needed for the proposed paper length, and an un-surprising engineering do not meet Nature's criterion of being "of extreme importance." I suggest that a better venue might be a publication available with longer format and robotics emphasis. Examples might be Nature Communicaitons , Science Robotics, or Royal Society Interface.

Based on these three comments, as well as the comments of the other two reviewers, we have refocused and rewritten the paper, deriving a new model that now offers insights into the differences in energetics between biological and engineered jumpers. We have: (1) re-made and simplified all figures and restructured to follow Nature's guidelines; (2) re-made the biological data figure (Extended Data Fig. 1) with three simple parameters from the literature that are clearly stated; and (3) clarified that the jumper, redesigned in accordance with the model and capable of now jumping over 32 m, represents a step change with respect to the state-of-the-art motor-driven jumpers that also sought to maximize jump height. We believe the new paper is substantially improved and an important contribution to both biology and engineering, thanks to the thorough comments of the reviewers.

R3.6 References:
-Burdick, Joel, and Paolo Fiorini. "Minimalist jumping robots for celestial exploration." The International Journal of Robotics Research 22.7-8 (2003): 653-674.
-Bhushan, Palak, and Claire Tomlin. "An Insect-scale Untethered Laser-powered Jumping Microrobot." arXiv preprint arXiv:1908.03282 (2019).
Thank you for these suggestions. We included the Burdick paper. We were unable to find a peer-reviewed version of the Bhushan paper, and so instead included other micro jumping robots:

37. Gerratt, A. P. & Bergbreiter, S. Incorporating compliant elastomers for jumping locomotion in microrobots. Smart Mater. Struct. (2013) doi:10.1088/0964-1726/22/1/014010.
38. Greenspun, J. & Pister, K. S. J. First leaps of an electrostatic inchworm motor-driven jumping microrobot. in 2018 Solid-State Sensors, Actuators and Microsystems Workshop, Hilton Head 2018 (2018). doi:10.31438/trf.hh2018.45.
39. Greenspun, J. & Pister, K. S. J. Mechanisms for jumping microrobots. in International Conference on Manipulation, Automation and Robotics at Small Scales, MARSS 2017 - Proceedings (2017). doi:10.1109/MARSS.2017.8001944.
40. Bergbreiter, S. & Pister, K. S. J. Design of an autonomous jumping microrobot. in Proceedings - IEEE International Conference on Robotics and Automation (2007). doi:10.1109/ROBOT.2007.363827.

Reviewer Reports on the First Revision:

Referees' comments:

Referee #1 (Remarks to the Author):

Summary of key results:
The authors have identified work multiplication for the actuator as a key component to improve energy density in jumping robots and use this idea in a jumping robot that can jump an incredible 30+ m. Specific differences between biology and engineering actuators (e.g., single stroke vs continuous stroke) are highlighted and resulting design guidelines are also identified in terms of motor-spring mass ratios.

Originality and significance:
Overall, I like the change in direction focusing more on what the authors term “work multiplication.” The authors are exploiting a clear difference in actuation between biology and engineering. While this has been hinted at in past papers as cited by the authors, I am not aware of any work that makes this explicit. Identifying this is clearly significant given the amazing results of the jumping robot.

Data and methodology:
Overall, the figures and main text need some work as a key vehicle for presenting results and methods. Some specific comments are below framed in the context of what each figure is describing.

Figure 1. Not sure what the difference between pre-stretch (in caption) and pre-load in figure are. Are they the same? (A) is only showing a latched spring jumper, right? What is “utilized energy” in this figure? This could use some explanation (even if brief) as to why it differs from produced energy and dips at takeoff. Are these example curves for energy or do they correspond to an actual model? Is there any reason why the jumping mechanism is drawn as this pac-man style jumper? I think there is a beam attached to the spring that is at a fixed angle with the linkage segment on the ground for this to work, but it is tough to see. Spring seems to stay the same length though too, so I’m not sure what is changing. For part (c), I’m not sure that “arbitrary” is a good term for the stroke. Both have a finite stroke when attached to the spring and linkage — one is just defined by the motor alone and one is defined by the motor in combination with the spring.

Figure 2. The use of takeoff time on the x-axis is confusing here. I *think* this is used to help normalize motor driven and spring driven jumping and make a simple link to power/energy, but that is not discussed in the caption or main text. Some context could be helpful here (e.g., where do some common insects and robots along with your robot fall here?). For the biological systems, there is an interesting crossover point that seems to imply that this would be where systems might switch to muscle driven jumping. Is that the case? For (B), this seems to imply that direct-drive systems could jump super high as they extend their takeoff time. Ultimately this is linked to distance to accelerate as well (e.g., leg length) but limits to this ever increasing line are not discussed.

Also, I kept trying to tie the colors back to the previous figure, but I think they are unrelated. Also, please be wary of sketching lines separately when they should be on top of each other. The blue dashed line should coincide with the black and lightest grey lines showing motor only limits, but it looks like it is above the black and lightest grey lines.

Figure 3. I felt that I was going back and forth between Figs 2 and 3 frequently and the main text alternates references to these figures frequently as well. There may be a better way to distribute these figures to make the key points that you'd like to make. Fig. 3d shows the jumper's spring-mass ratio was > 1 and the number is stated as 3 in the main text (18 g spring and 5 g motor), but Table 3 in extended data has mass of spring (rods + rubber bands) as 10.92+1.4 g and motor as 10.28g. In terms of a jump height

Figure 4. I found the choices and methods for (A) confusing here. I wasn't able to easily find what numbers, dimensions, etc. were used for the spring modeling. For example, why these 3 choices for springs? Could you design the linkage system differently to improve energy density in the tension spring (e.g., what was the mass of the linkage and why was it chosen that way)? There should be tradeoffs regarding choices of spring constants as well to take advantage of large travel for the engineered actuator, but this is not discussed. Was there any optimization done here? You certainly have models that would allow this to be done. Similarly, how were mechanism energy densities calculated in (D)?

For the methods section, a significant portion of the materials was spent on topics not really addressed in a significant way in the main text (e.g., energy utilization, state space model). Instead, it would be worthwhile to move a good portion of this to supplementary while instead focusing on providing the methods used for the results in the main text. If you want to include more of the energy utilization model, link to it more often (e.g., design of nose cone to be low drag).

Conclusions:
Overall, this is still a fantastic engineering design of a jumping robot. The identification of work multiplication as a mechanism that engineering can use to outperform biology is important and significant. The results are unclear along with the methods to obtain those results as described above, but the authors could certainly improve this along with the writing (e.g., discrepancies found through text).

Suggested improvements:
Many of my suggestions for improvement show up above from methodology section and significance / contributions. But a couple other thoughts and discrepancies caught are included below.

24: While jumping has a clear metric of jump height or distance, it's still not clear that all jumpers have the objective to maximize height or distance. Many jumpers target and control their jumps and do not maximize. I do not maximize my jump height or distance every time that I jump and I doubt other systems do either.

You have great results, but I am still unclear what design guidelines I would use to design a jumping robot given a particular motor other than choosing the mass of the spring. I think this is part of what the paper is trying to convey, so it may help to provide a more detailed discussion of the design choices for the robot in the main text.

Perhaps the most important question: is 30 m the limit? Ultimately, it seems that if you are almost entirely composed of spring mass, you will approach the spring specific energy density limit which would then provide something like h = 7000/g for 100% utilization. I find it interesting that due to battery mass (and the need to size spring and motor to make this negligible), the best engineered jumpers may be an order (or orders) of magnitude more massive than the best biological jumpers. This is probably worth discussing.

Saying that a rotary motor has unlimited energy is a drastic simplification given that a jumping robot would ultimately need to be powered by a battery.

The main text states a takeoff velocity of 27 m/s while method s state 31-32 m/s.

References:
Paper includes relevant citations.

Clarity and context:
Overall, the paper was written reasonably well but there were several discrepancies and it was difficult to link the main text and the methods section. The methods section should really introduce the methods used to gather the results (details of models, robot, etc) but currently seems used to introduce new content.

Referee #2 (Remarks to the Author):

This paper has been completely rewritten to, instead of generating a generalized model for jumping for all systems (engineered and biology), discuss the difference between jumping with a ratcheting-like system (a 'work multiplied' system, as discussed in the paper), and a 'single stroke' system. Single stroke systems are limited in their jump height by the stroke specific work, while engineered systems are limited by their spring specific energy (i.e. how much energy can be stored in a spring by an actuator allowed to 'ratchet' up any number of times).

This rewrite appears to be in direct response to my previous comment: "Yes, the robot jumps spectacularly high, but a ratcheting latch mediated jumping system could, in theory, jump almost arbitrarily high, could it not; with the limits only being the mass of the motor/spring system relative to the amount of stored spring energy?" - after which, the writers did the calculations where they divided maximum stored spring energy by the mass of a spring to now discuss a parameter 'spring specific energy'. The vast majority of my other concerns with the manuscript referenced sections that have now been moved to the supplemental material or removed outright, so, if acceptable to the editor, I will discuss the rewrite without making reference to previous statements of mine about text that has been removed.

Firstly, when discussing 'single stroke' systems, the new manuscript uses discussion 1) discusses power limitations of muscle in a very 'back of the envelope way', and 2) does not discuss energetic inefficiencies that prevent the latched spring single stroke jumpers from utilizing 100% of the energy output of the actuator. Leading to odd statements like : "the upper limit for specific energy for biological mechanisms....is insensitive to changes in motor specific power" (Figure 3). This is an extremely counterintuitive statement, as motor specific power is the limiting factor for take-off velocity (i.e. specific energy) for smaller non latched biological jumpers, but authors just state this statement as 'true'. The way the authors set up the models it may be so, but it should at least be recognized that motor specific power at least appears to be a major constraint on jump height in smaller non latched jumpers. I may, however, be misunderstanding figure 3 and the text attached to it (I'm a bit unclear when the axis says 'change' in motor specific power, I don't know 'change from what'...). Overall, the new analysis of biological jumping appears to be less thorough than the one in the previous manuscript.

The main point, that it is ratcheting that allows engineered devices to jump higher than biological ones, is extremely well taken. From my read of the other reviewers, it is clear that at least one (probably both), is much more knowledgeable than I am on the engineered devices, which may make this paper of interest for generating a 30m jumping robot. The analysis of work multiplied devices relative to single stroke devices is, in my opinion, adequate, even if the quantification of the single stroke devices could be better done. The fundamental point, that work multiplied devices can store many times more energy in a spring than a single stroke device is not greatly affected by a better single stroke model.

If the work multiplied jumper analysis combined with the robot is of sufficient interest to the other reviewers, then I could be content with the authors simply softening the language of their single stroke jumper analysis to reflect that their analysis is more 'back of the envelope'.

Referee #3 (Remarks to the Author):

Reports an advance in the maximum jumping capability exceeding state of the art by nearly 10x, which was informed by insight into how engineered systems can “work multiply” to store much more elastic energy than is possible in biological organisms. Included is an analysis of how increasing the relative mass of the elastic element brings engineered jumpers closer and closer to a theoretical limit, across scales. The jumper design also is able to self-right, which is a challenging but essential task for jumping robots.

The main points are amply supported by the demonstration of a very high jump that was enabled by a high proportion of spring mass in the body of the jumper.

The design appears original and quite exceeds previous state of the art. The results are of interest to anybody considering locomotion of robotic vehicles, particularly because the new mechanism may be able to serve as a means of surmounting high obstacles without the need for energy inefficient flight.

No concerns about the data and methodology.

No significant statistics to speak of.

Conclusions valid and robust? Most are valid but I am not sure I understand the assertion that engineered jumpers should have a 100-fold greater spring to motor mass ratio; I see that it "plateaus" in Fig. 3d but it appears that it may be an asymptote - is the true optimum at infinite spring-to-motor mass? (ignoring that it would result impractically-long spring loading period). Perhaps better wording might be "100-fold or higher"?

Summary: I find that the authors have refined and focused their work into a much better supported, simpler, and more compelling set of conclusions than the previous manuscript, making the material interesting and relevant to a broad range of engineers and biologists. With some minor edits described herein I recommend publication.

Some comments:

* I couldn't tell why are you getting only about 1/3 the mechanism specific energy predicted by the model.

* it might be nice to hear just a little bit about why biological jumpers can't do work multiplication. I suspect it may be as simple as stating that ratchets have not been found except at the molecular level and similarly for rotatory motion.

* I disagree with the trend of using present tense in papers to describe things that were performed in the past (e.g. "we design …", "we achieve …") and believe that its use should be reserved for statements that hold about the world at all times (e.g. "our findings show that that engineered jumpers jump higher than biological ones").

* the ratcheted linear motor diagram is confusing. it may be easier, diagram-wise, to use as your example a representation so-called electrostatic inchworm actuators that do not use ratchets.

Author Rebuttals to First Revision:

Responses to referees' comments:
We thank all referees again for their thoughtful and helpful comments. We believe we were able to address all concerns raised, and believe our manuscript is once again substantially improved.

Referee #1 (Remarks to the Author):

Summary of key results:
The authors have identified work multiplication for the actuator as a key component to improve energy density in jumping robots and use this idea in a jumping robot that can jump an incredible 30+ m. Specific differences between biology and engineering actuators (e.g., single stroke vs continuous stroke) are highlighted and resulting design guidelines are also identified in terms of motor-spring mass ratios.
Thank you for this clear summary.

Originality and significance:
Overall, I like the change in direction focusing more on what the authors term "work multiplication." The authors are exploiting a clear difference in actuation between biology and engineering. While this has been hinted at in past papers as cited by the authors, I am not aware of any work that makes this explicit. Identifying this is clearly significant given the amazing results of the jumping robot.
Thank you for summarizing the contribution.

Data and methodology:
Overall, the figures and main text need some work as a key vehicle for presenting results and methods. Some specific comments are below framed in the context of what each figure is describing.

Figure 1.
Not sure what the difference between pre-stretch (in caption) and pre-load in figure are. Are they the same?
Yes, good catch. "Preload" has been changed to "pre-stretch" in the figure.

(A) is only showing a latched spring jumper, right?
Correct. We thought it would be cluttered to try to show both. We have added a note in the caption to clarify.

What is "utilized energy" in this figure? This could use some explanation (even if brief) as to why it differs from produced energy and dips at takeoff.
This is a good question. We have edited the caption to explain more clearly.

> "*Second, the energy utilisation (grey curve) is the energy of the centre of mass, considering losses, due to non-idealities such as energy transfer and air drag (see Methods: Energy Utilisation).*"

Are these example curves for energy or do they correspond to an actual model?
Thank you for the suggestion. These were example curves, but we are replacing them with actual simulated curves.

> "*After an optional pre-stretch (for jumpers with latched springs), the jump initiates, and a force applied to the ground accelerates the jumper upward, before take-off and flight (See SI for details of simulation).*"

We have added a section to the SI describing this simulation.

Is there any reason why the jumping mechanism is drawn as this pac-man style jumper? I think there is a beam attached to the spring that is at a fixed angle with the linkage segment on the ground for this to work, but it is tough to see. Spring seems to stay the same length though too, so I'm not sure what is changing.
Good question. We agree it was not a clear drawing, and have instead adopted a simple two-legged schematic as used in Alexander 1995.

For part (c), I'm not sure that "arbitrary" is a good term for the stroke. Both have a finite stroke when attached to the spring and linkage — one is just defined by the motor alone and one is defined by the motor in combination with the spring.
Thank you for pointing this out. We have redrawn the figure (1b) and edited the caption. We now show that even when the output stroke is kept constant, work multiplication allows an increased number of strokes in the engineered case. Functionally, the "input" stroke can be made very large while the output stroke remains constant through increasing gear reduction (and the output force will become very high).

Figure 2.
The use of takeoff time on the x-axis is confusing here. I *think* this is used to help normalize motor driven and spring driven jumping and make a simple link to power/energy, but that is not discussed in the caption or main text. Some context could be helpful here (e.g., where do some common insects and robots along with your robot fall here?).
Thank you for pointing this out, as it was unclear why we made this choice. You are right, it is so that we can make a simple link between power and energy. We have added the following text to the caption, and reference the Methods, State-space Model that explains in more detail.

> "*Note: the x-axis shows take-off time, to easily relate power and energy; take-off time relates monotonically to length scale for an isometrically scaled jumper (see Methods: State-space Model).*"

For the biological systems, there is an interesting crossover point that seems to imply that this would be where systems might switch to muscle driven jumping. Is that the case?
Yes, that is correct. We have added a note to point this interesting point out.

> "*The model's trends for biological jumpers align with previous models in the literature[26,27] and biological jump data (Extended Data Fig. 2), and show a crossover point at large scale beyond which power amplification is not helpful.*"

For (B), this seems to imply that direct-drive systems could jump super high as they extend their takeoff time. Ultimately this is linked to distance to accelerate as well (e.g., leg length) but limits to this ever increasing line are not discussed.
Thank you for pointing out that we did not mention this case. Indeed, theoretically, the specific energy production does increase with scale (of course there are practical limits of building a jumper ~100 m tall). We note that at very large scales, the direct-drive case is theoretically better.

> *"The results of our model in Fig. 2 show that for biological mechanisms, the upper bound of specific energy is the motor specific work limiter, yet for engineered mechanisms, the upper bound is the spring specific energy limiter (at all practical scales, <~100 m; See Extended Data Figs. 3-4).*

In the Methods, we have discussed this case in more detail.

"In contrast, engineered jumpers theoretically can produce more energy the larger they are (Extended Data Fig. 3a); when the energy to stand is considered, the kinetic energy eventually plateaus (Extended Data Fig. 3b). However, the energy production of these extremely large direct-drive jumpers only surpasses that of power-amplified jumpers with large spring-motor mass ratio (Extended Data Fig. 4a) at an unrealistically large scale of nearly 100 m."

Also, I kept trying to tie the colors back to the previous figure, but I think they are unrelated.
Thank you for pointing this out. We have edited the colors in Fig. 1 and Fig. 2 to avoid confusion, and believe the two figures are actually easier to read, since colors correspond.

Also, please be wary of sketching lines separately when they should be on top of each other. The blue dashed line should coincide with the black and lightest grey lines showing motor only limits, but it looks like it is above the black and lightest grey lines.
Thank you for pointing this out. We have corrected this.

Figure 3.
I felt that I was going back and forth between Figs 2 and 3 frequently and the main text alternates references to these figures frequently as well. There may be a better way to distribute these figures to make the key points that you'd like to make.
Thank you for bringing this up. After much consideration, we ended up combining the two figures.

Fig. 3d shows the jumper's spring-mass ratio was > 1 and the number is stated as 3 in the main text (18 g spring and 5 g motor), but Table 3 in extended data has mass of spring (rods + rubber bands) as 10.92+1.4 g and motor as 10.28g. In terms of a jump height
Thank you for pointing out this inconsistency. The table has been updated with the correct spring mass (12.4 g) and motor mass (5.2 g); the gearing is part of the "linkage" mass, and so is not included in the spring-to-motor mass ratio, but is included in the mechanism mass (4.9 g).

Figure 4.
I found the choices and methods for (A) confusing here. I wasn't able to easily find what numbers, dimensions, etc. were used for the spring modeling. For example, why these 3 choices for springs? Could you design the linkage system differently to improve energy density in the tension spring (e.g., what was the mass of the linkage and why was it chosen that way)? There should be tradeoffs regarding choices of spring constants as well to take advantage of large travel for the engineered actuator, but this is not discussed. Was there any optimization done here? You certainly have models that would allow this to be done.
Thank you for bringing up this concern. We agree it is important for the paper, and that we did not clearly answer all of these questions. To best address all of these questions, we added a co-author to build a simulation framework. The framework allows us compare spring designs in detail, and understand how changing parameters (e.g., spring constants) affects performance. We have added detailed content in the SI, and included an overview in the main text

Additionally, we add clarifying text to explain the choices of springs. Two are previous designs from the literature, and the third is our hybrid design, which we show stores more energy per mass than the other two designs, given the constraint of our motor force output.

> "*Simulation results of specific energy (area under curve) for three different spring configurations: two from the literature (tension-linkage[13] and compression-bow[10]) and one that we designed (hybrid tension-compression).*"

Similarly, how were mechanism energy densities calculated in (D)?
Thank you for pointing out that this was not stated. We have added a note in the caption, defining mechanism specific energy.

"Jump height of the presented and other jumpers (reference in bracket) shown as a function of the mechanism specific energy (where mechanism is the motor, linkage, and optional spring)."

Additionally, we have added details to Extended Data Table 2 that describes the calculation, and added the necessary specifications in the table to complete this calculation.

"Mechanism specific energy is calculated as the energy production divided by the mass of the mechanism (motor, spring, and linkage)."

For the methods section, a significant portion of the materials was spent on topics not really addressed in a significant way in the main text (e.g., energy utilization, state space model). Instead, it would be worthwhile to move a good portion of this to supplementary while instead focusing on providing the methods used for the results in the main text. If you want to include more of the energy utilization model, link to it more often (e.g., design of nose cone to be low drag).
This is a very helpful suggestion. We have edited the main text to include many more links to the Methods section, explicitly calling out the energy utilization and state-space models throughout (as well as Extended Data Fig. 3 and 4, which are the output of the state-space model).

Conclusions:
Overall, this is still a fantastic engineering design of a jumping robot. The identification of work multiplication as a mechanism that engineering can use to outperform biology is important and significant. The results are unclear along with the methods to obtain those results as described above, but the authors could certainly improve this along with the writing (e.g., discrepancies found through text).
Thank you for the summary, and we hope that we have addressed all lack of clarity and discrepancies.

Suggested improvements:
Many of my suggestions for improvement show up above from methodology section and significance / contributions. But a couple other thoughts and discrepancies caught are included below.

24: While jumping has a clear metric of jump height or distance, it's still not clear that all jumpers have the objective to maximize height or distance. Many jumpers target and control their jumps and do not maximize. I do not maximize my jump height or distance every time that I jump and I doubt other systems do either.
Thank you for bringing up this concern again. We had edited it in the previous round of revisions to change "objective" to "metric." However, we agree that this is still unclear, so we added the text: "*metric by which best performances can be compared*."

You have great results, but I am still unclear what design guidelines I would use to design a jumping robot given a particular motor other than choosing the mass of the spring. I think this is part of what the paper is trying to convey, so it may help to provide a more detailed discussion of the design choices for the robot in the main text.
This is a great suggestion. We have added considerable detail for the design choices of the robot.

"Accordingly, to push the boundaries of power-amplified engineered jumping mechanisms, we follow these two insights: increase both the spring specific energy limiter and the spring-motor mass ratio. To implement these insights, we completed the following design process. First, to set a high spring-motor mass ratio, we selected a very small rotary motor (5 g) but a very large gear reduction (1000:1), enabling the motor to compress a relatively large spring with 150 N of tension in a line wrapped around its spindle (See Methods: Jumper Design). With this peak force constraint, we

built a non-linear quasistatic simulation framework to find the spring design that would offer the highest specific energy (See Methods: Jumper Design for details). We first compared two spring designs from the literature: tension-linkage[13] and compression-bow[10] (Fig. 3a). Our simulation found that the tension-linkage spring has a slightly lower specific energy (1,350 J/kg) than the compression-bow (1,592 J/kg). Despite the very high specific energy of the material in tension used in the tension-linkage spring (7,000 J/kg, Fig. 2,3), the mass of the passive linkage that is required to make a functional spring for jumping reduces the overall performance substantially. To improve on these springs, we designed a hybrid-tension-compression spring, supporting the high-specific-energy material in tension with a compression-bow spring rather than a passive linkage, and found a specific energy of 1,922 J/kg. This spring has a nearly constant force-displacement curve, which helps to provide a large amount of energy given the force constraint. The spring has a mass of 12.4 g, resulting in a mechanism with a spring-motor mass ratio of 2.4 (versus 0.025-0.06 in biology).

Using this mechanism, we designed a 30-g jumper (Fig. 3b, Extended Data Fig. 5), taking care to keep losses in the six identified stages of energy utilisation minimal (See Methods: Energy Utilisation). For instance, we minimized the mass of the "foot" (components of the jumper that are stationary during take-off) to minimize energy transfer losses, and created a shape-changing morphology that becomes streamlined after take-off to minimize air drag."

Perhaps the most important question: is 30 m the limit? Ultimately, it seems that if you are almost entirely composed of spring mass, you will approach the spring specific energy density limit which would then provide something like h = 7000/g for 100% utilization. I find it interesting that due to battery mass (and the need to size spring and motor to make this negligible), the best engineered jumpers may be an order (or orders) of magnitude more massive than the best biological jumpers. This is probably worth discussing.
This is a very interesting question. We have modified the state-space model to be able to answer this question, adding specifics of our jumper design. We then varied two key parameters. First, we examined the effect of increasing the spring-motor mass ratio to the optimal (from 2.5 in our jumper to infinite), and found a small improvement (32.9 m to 37.2 m). Second, we examined scale, during which we maintained the battery mass percentage (since batteries have a roughly constant specific energy across scale). We found that a similar improvement could be achieved by increasing scale by approximately an order of magnitude (a 10x isometric scaling results in a 39.1 m jump).

"Our model suggests that this is near the practical limit of jump height with currently available materials at this or any scale. Within energy production, the primary potential improvement is in the spring-motor-mass ratio, assuming that the spring specific energy could be increased only marginally. However, increasing the ratio from 2.4 to infinite would only increase jump height by approximately 9% (See Methods: State-space Model, Extended Data Fig. X). Within energy utilisation, the primary improvement comes from reducing air drag by scaling, assuming other losses can be reduced only marginally. However, an isometric scaling of the presented jumper by 10x (the predicted optimum) would result in only a 19% increase in jump height."

Saying that a rotary motor has unlimited energy is a drastic simplification given that a jumping robot would ultimately need to be powered by a battery.
Thank you for pointing out this over-simplification. We have edited the text to now say that we would be limited by the energy source. Interestingly, batteries have a much higher specific energy than springs, at ~900 kJ/kg, so it is a relatively small portion of the mass.

“In contrast, for engineered jumpers with sufficient work multiplication, large amounts of energy could be accumulated (limited only be the energy source), implying that the spring-motor mass ratio should be at least a hundred-fold larger than the ideal ratio for biology; larger ratios are possible, but offer diminishing returns.”

The main text states a takeoff velocity of 27 m/s while method s state 31-32 m/s.
Thank you for pointing out this inconsistency. We have updated to be consistent with the correct take-off velocity throughout, 28-29 m/s.

References:
Paper includes relevant citations.

Clarity and context:
Overall, the paper was written reasonably well but there were several discrepancies and it was difficult to link the main text and the methods section. The methods section should really introduce the methods used to gather the results (details of models, robot, etc) but currently seems used to introduce new content.
This is a good suggestion, and we have edited the methods (and the main paper) to better link them.

Referee #2 (Remarks to the Author):

This paper has been completely rewritten to, instead of generating a generalized model for jumping for all systems (engineered and biology), discuss the difference between jumping with a ratcheting-like system (a 'work multiplied' system, as discussed in the paper), and a 'single stroke' system. Single stroke systems are limited in their jump height by the stroke specific work, while engineered systems are limited by their spring specific energy (i.e. how much energy can be stored in a spring by an actuator allowed to 'ratchet' up any number of times).
Thank you for this clear summary.

This rewrite appears to be in direct response to my previous comment: "Yes, the robot jumps spectacularly high, but a ratcheting latch mediated jumping system could, in theory, jump almost arbitrarily high, could it not; with the limits only being the mass of the motor/spring system relative to the amount of stored spring energy?" - after which, the writers did the calculations where they divided maximum stored spring energy by the mass of a spring to now discuss a parameter 'spring specific energy'. The vast majority of my other concerns with the manuscript referenced sections that have now been moved to the supplemental material or removed outright, so, if acceptable to the editor, I will discuss the rewrite without making reference to previous statements of mine about text that has been removed.
We are glad that we were able to correct or remove all of the text that was of concern in the original manuscript.

Firstly, when discussing 'single stroke' systems, the new manuscript uses discussion 1) discusses power limitations of muscle in a very 'back of the envelope way', and 2) does not discuss energetic inefficiencies that prevent the latched spring single stroke jumpers from utilizing 100% of the energy output of the actuator. Leading to odd statements like : "the upper limit for specific energy for biological mechanisms....is insensitive to changes in motor specific power" (Figure 3). This is an extremely counterintuitive statement, as motor specific power is the limiting factor for take-off velocity (i.e. specific energy) for smaller non latched biological jumpers, but authors just state this statement as 'true'. The way the authors set up the models it may be so, but it should at least be recognized that motor specific power at least appears to be a major constraint on jump height in smaller non latched jumpers. I may, however, be misunderstanding figure 3 and the text attached to it (I'm a bit unclear when the axis says 'change' in motor specific power, I don't know 'change from what'...). Overall, the new analysis of biological jumping appears to be less thorough than the one in the previous manuscript.
We appreciate you bringing this to our attention, and we realize that our previous manuscript was very unclear, leading to your understanding of the text (which is different than what we were trying to convey). We have completely rewritten the section to hopefully correct our lack of clarity.

Specifically, in the previous manuscript, we did not clarify that our analysis in Fig. 3 and the surrounding text was for the <u>best</u> biological jumpers, not all biological jumpers. This led to the confusion around small non-latched biological jumpers, which are not part of this analysis. Indeed, our models hold for all jumpers, but the results of this specific analysis hold for large-scale biological jumpers and small latched (power-amplified) biological jumpers.

However, given how confusing this is, and given the fact that we do not think this analysis provides information that is not already included in Fig. 2, we have decided to remove Fig. 3a-c and the associated text. The new text reads:

> *"The results of our model in Fig. 2 show that for biological mechanisms, the upper bound of specific energy is the motor specific work limiter, yet for engineered mechanisms, the upper bound is the spring specific energy limiter (at all practical scales, <~100 m; See Extended Data Figs. 3-4). For biological mechanisms, power amplification at small scales and sufficient time at larger scales allows the specific energy to approach but never exceed this upper bound set by the motor specific work*

limiter (practical limitations prevent it from passing even 50%[27] of this limit). For engineered mechanisms, power amplification coupled with work multiplication allows specific energy to approach the upper bound set by the spring specific work limiter. The specific energy of mechanisms near one of these limiters will be highly sensitive to changes in that limiter, and less so to changes in other limiters. This provides an insight for designing power-amplified engineered mechanisms with a high spring-to-motor mass ratio: changing the spring specific energy will directly affect the mechanism specific energy, but changes in the motor specific power will have little effect."

Additionally, we added a note in the main text about the concern that 100% of muscle energy is not stored in biological springs.

"For biological mechanisms, power amplification at small scales and sufficient time at larger scales allows the specific energy to approach but never exceed this upper bound set by the motor specific work limiter (practical limitations prevent it from passing even 50%[26,27] of this limit)."

The main point, that it is ratcheting that allows engineered devices to jump higher than biological ones, is extremely well taken. From my read of the other reviewers, it is clear that at least one (probably both), is much more knowledgeable than I am on the engineered devices, which may make this paper of interest for generating a 30m jumping robot. The analysis of work multiplied devices relative to single stroke devices is, in my opinion, adequate, even if the quantification of the single stroke devices could be better done. The fundamental point, that work multiplied devices can store many times more energy in a spring than a single stroke device is not greatly affected by a better single stroke model.

Thank you for summarizing the fundamental point of the work.

If the work multiplied jumper analysis combined with the robot is of sufficient interest to the other reviewers, then I could be content with the authors simply softening the language of their single stroke jumper analysis to reflect that their analysis is more 'back of the envelope'.

We hope we have clarified our single stroke jumper analysis, rather than softened it, as we believe it is in line with your understanding, and simply was not presented in a way that was easy to understand. We believe the removal of Fig. 3a-c, which was focused on a subset of jumpers, clarifies our work.

Referee #3 (Remarks to the Author):

Reports an advance in the maximum jumping capability exceeding state of the art by nearly 10x, which was informed by insight into how engineered systems can “work multiply” to store much more elastic energy than is possible in biological organisms. Included is an analysis of how increasing the relative mass of the elastic element brings engineered jumpers closer and closer to a theoretical limit, across scales. The jumper design also is able to self-right, which is a challenging but essential task for jumping robots.
Thank you for the concise summary of the paper.

The main points are amply supported by the demonstration of a very high jump that was enabled by a high proportion of spring mass in the body of the jumper.
Thank you.

The design appears original and quite exceeds previous state of the art. The results are of interest to anybody considering locomotion of robotic vehicles, particularly because the new mechanism may be able to serve as a means of surmounting high obstacles without the need for energy inefficient flight.
Thank you.

No concerns about the data and methodology.

No significant statistics to speak of.

Conclusions valid and robust? Most are valid but I am not sure I understand the assertion that engineered jumpers should have a 100-fold greater spring to motor mass ratio; I see that it “plateaus” in Fig. 3d but it appears that it may be an asymptote - is the true optimum at infinite spring-to-motor mass? (ignoring that it would result impractically-long spring loading period). Perhaps better wording might be "100-fold or higher"?
This is a good point, and we have edited the paper to clarify, adopting “at least a hundred-fold greater.”

Summary: I find that the authors have refined and focused their work into a much better supported, simpler, and more compelling set of conclusions than the previous manuscript, making the material interesting and relevant to a broad range of engineers and biologists. With some minor edits described herein I recommend publication.
Thank you.

Some comments:

* I couldn't tell why are you getting only about 1/3 the mechanism specific energy predicted by the model.
This is a good question. It is because 7000 J/kg is for a spring in pure tension, but there must be some linkage element in compression in a real system. This note is added to the Fig. 2 caption:

> *“In all plots, we exclude linkage mass; inclusion does not change trends, but decreases numerical values dependent on configuration and design. For example, in (**d**), a linkage is required to hold a material in tension, thus the specific energy of a real mechanism will be far below 7000 J/kg.*

* it might be nice to hear just a little bit about why biological jumpers can’t do work multiplication. I suspect it may be as simple as stating that ratchets have not been found except at the molecular level and similarly for rotatory motion.
This is a good suggestion. We have added text mentioning this:

“Work multiplication is available only to engineered jumpers; ratchets and rotary motors have not been found above the cellular scale in biology[38].

* I disagree with the trend of using present tense in papers to describe things that were performed in the past (e.g. “we design …”, “we achieve …”) and believe that its use should be reserved for statements that hold about the world at all times (e.g. “our findings show that that engineered jumpers jump higher than biological ones”).
We have edited according to your suggestion.

* the ratcheted linear motor diagram is confusing. it may be easier, diagram-wise, to use as your example a representation so-called electrostatic inchworm actuators that do not use ratchets.
We agree with you and have completely redrawn it. We believe the new drawing is a simple and clear representation.

Reviewer Reports on the Second Revision:

Referees' comments:

Referee #1 (Remarks to the Author):

Summary of key results (same as previous):
The authors have identified work multiplication for the actuator as a key component to improve energy density in jumping robots and use this idea in a jumping robot that can jump an incredible 30+ m. Specific differences between biology and engineering actuators (e.g., single stroke vs continuous stroke) are highlighted and resulting design guidelines are also identified in terms of motor-spring mass ratios.

Originality and significance (same as previous):
Overall, I like the change in direction focusing more on what the authors term “work multiplication.” The authors are exploiting a clear difference in actuation between biology and engineering. While this has been hinted at in past papers as cited by the authors, I am not aware of any work that makes this explicit. Identifying this is clearly significant given the amazing results of the jumping robot.

Data and methodology:
Overall, I’m still generally happy with the data and the methodology. I have specific comments that I have primarily included in the clarity section below.

Conclusions:
Overall, this is still a fantastic engineering design of a jumping robot. The identification of work multiplication as a mechanism that engineering can use to outperform biology is important and significant. The writing is still somewhat unclear and can be significantly clarified as described (at least in part) below.

Appropriate use of statistics and uncertainties:
This is no discussion of uncertainties in the measurements describe starting at line 614. For example, what is resolution of camera and what is frame rate? What is scale accuracy?

Somewhere along the way, the authors lost the number of jumps accomplished in the main text (leading to the uncertainty in jump height).

Suggested improvements:
It struck me while reading through this that your hybrid spring is effectively a tension spring in which the mechanism around it can also store energy (in compression). Alternately, the tension springs add a little extra specific energy to the compression spring. This may help explain the improvements seen in this hybrid design.

References:
Reference 1 looks like it is missing some data — is that section 3?

Clarity and Context:

There is still a fair amount of language in the text that bothers me, mostly in regards to terms that are unclear and claims that I read as overstated. There are still plenty of typos as well. In general, I recommend that the authors read through the paper to tighten up the language as I'm sure I didn't catch everything. It looks like a lot, but most of these just need short clauses or greater clarity in language. I haven't spent the time to pick out the perfect phrasing here either, so feel free to modify as long as clarity is maintained.

Title: I don't think that "outjumps" is a word. Not sure what Nature policies are on that.

Abstract:
In the abstract, you talk about limits early on, but don't describe limits to what? "Scientists have explored the limits of jumping animals… and engineers have sought to design jumping machines that exceed these limits." Just add jump height or jump specific energy somewhere in there to clarify.

"Biological jumpers are always limited" makes me twitchy — certainly the jump height of all known biological jumpers is limited by…

"Engineered jumpers overcome this limit" —> "Engineered jumpers can overcome this limit". For the most part, as you point out in the text of the paper, they have not overcome that limit (but you do!).

You introduce the idea of a spring and the energy capacity of that spring without any context. You have only been talking about motors to that point.

"High-energy hybrid…" —> "high specific energy hybrid"

Order of magnitude improvement in jump energy over biological … You should include either something regards to "similarly sized" or change to jump height

Main text:
Vs. and versus both used — change this to a single

Can you really take advantage of work multiplication without a latch? Doesn't the ratchet itself serve as a latch?

I also think there is a little confusion throughout on motor versus actuator. Sometimes the spring serves as the jump actuator, but is not a motor. I think this language was clarified in reference 29 from what I remember.

Speaking of reference 29, it would be nice if authors used the term described in (29) — latch mediated spring actuation (LaMSA) to describe the systems that they are analyzing for the work multiplication approach. The term "power amplified" is generally problematic because I could just run my motor more slowly on loading and achieve greater "power amplification".

Line 80: Not sure how take-off time is defined in this line. I originally thought of energy production from the motor is limited by power x storage time. If take-off time also includes time to store energy, this makes sense, but most people think of take-off time as time to take off once energy is stored. Storage time is not necessarily correlated to size as in Fig. 2 though. I assume you mean specific energy of the jumping mechanism for energy production. Either way, clarification will help prevent your readers from being confused on this point.

91: 100 m is not a specific energy (J/kg) — I think it's nice to use this as a very clear reference, but you could state "X J/kg, which correlates to a jump height of 100 m in Earth's gravity" to be clear

Line 97 and others: very unclear what "mechanism" refers to in a lot of places. Is this the jumper or part of the jumper?

101: add "on jump height" — motor power will affect time to jump so "effect" needs to be clarified

The 100x that keeps coming up starting in the paragraph from line 103 is confusing. Authors say that "biological mechanisms should have a spring-motor mass ratio that is at least a hundred-fold smaller than that of engineered mechanisms…" This statement is problematic for a variety of reasons. There are lots of reasons organisms might end up with a particular spring-motor mass ratio. Maybe they aren't trying to optimize jump height. Maybe they have other things going on. You can state that engineered systems should have a much higher ratio because they can multiply work, but going the other way is an issue. I would leave out the 100x until you justify it from the biology data later in the paragraph as well. Or you could describe more clearly the result found on lines 397 and 400 to explain the 100x.

You start talking about spring-motor mass ratio before really defining it.

112: "limited only be" —> "limited only by"

118: "two insights" —> "two insights in the design of engineered jumpers"

119: "design process" —> "design process for a jumper"

"Practical" is used several times throughout, but it is unclear what that means in each context. For example, in line 152, "currently available materials at practical scales."

Last part around line 170, are these #s for the same robot? Not clear as stated.

Methods:
Note — methods section here seems to include some of the interesting discussion as well instead of strictly methods. Not sure if this can be easily moved into the main text.

Add a note that you are also ignoring the energy limitations of an on-board energy source like a battery or other fuel (otherwise equation on line 373 makes no sense)

Why is linkage included in energy production vs energy utilization (as payload)?

Line 421 “rotary motors” —> “electromagnetic rotary motors”

427-428: More energy only available at take-off if driven by motor during this time (which many jumpers do not do)

429: Not sure what “reasonable” means here. “Monodically increasing with scale” —> “monotonically increases with scale”

431-432: “time-off time” —> “take-off time”

432: “scales linearly with scale” —> “scales linearly” and where am I supposed to see below?

435: A more generous view is that this previous work attempted to describe projectile systems beyond self contained jumpers (e.g., mantis shrimp, spore dispersal).

447: “The energy utilization model” makes it sound like this has already been described in detail. Instead, you are really introducing this for the first time. “An energy utilization model” works better here.

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506: This is a very weird sentence — I think you are just trying to say that the leg length is L. As written, it sounds like the mass increases.

517: equation has force = force - a mass. I think you are missing a g here.

519: specific power instead of power

521: grammar

543: where does 1/3 come from — I think 1/2 is common knowledge for a linear spring, but 1/3 is not

576-ish: Authors keep saying “carbon” where I believe they intend “carbon fiber”

581: Spectra line means a line on a spectrum plot to most people :)

583: given earlier discussion, would help to call this the latch

588: “a small lithium polymer”

590: sable —> stable

627: Was force-displacement data for spring actually measured? Where is this data?

630: Model predicts a mechanism specific energy closely aligned with that measured in the spring directly — but what are these numbers? How close is closely aligned?

Figures:

Fig 1a — takeoff time could be defined here to use in text.
For Fig 1b, isn't the key that you are getting more displacement due to work multiplication? It is unclear why you focus on greater force that would just come from gearing. Instead, it seems you can just keep on clicking to get n x d.

Fig 2 caption — not sure what ", and leaving motor specific power" means. Typo?
I missed why you are including dots at a takeoff time of 0.03 s — doesn't look like your jumper tick mark is here and didn't see it in the caption

Referee #2 (Remarks to the Author):

I have one, major concern left with this manuscript, that ties to a comment made by reviewer 4.

Reviewer 4 states:
* I couldn't tell why are you getting only about 1/3 the mechanism specific energy predicted by the model.*

This reduction of specific energy appears, to me, to be a direct consequence of the interaction between force/length parameters and spring energy storage, illustrated in references 27, 33 (34?, which looks identical to reference 33?), and specifically discussed for muscle in Rosario et al., (2016). This represents a limit of how much energy can be stored by a spring relative to energy produced by an actuator. This is the only way I can make sense of Figure 1.

I am left very puzzled as to 1) why the spring is able to store near 100% of the energy production capacity of the actuator, and 2) why a model that has no apparent energy dissipation only returns less than half of the energy storage. I find it much more probable that the actuator was only able to store less than half of its possible energy in the spring, and that the less than half is returned. The authors say that this is because of 'linkage mass', but mass is energetically conservative, and consequently I'm very puzzled by this response.

when the authors discuss the limited energy storage capacity in the text, the revised manuscript simply refers to 'practical limitations' (line 94) and cites 26 and 27.

I may be completely misunderstanding the text as written, can the authors' please explain? As I read it, the energy loss seen in figure 1 is clearly a consequence of the 'practical limitations' in references 26 and 27 (which would apply to both engineered and biological systems).

The term 'practical limitations' to refer to consequence of acuator/spring geometry makes me very uncomfortable with its lack of precision.

I have one small point, line 87; please mention that these crossover points are discussed in references 27 and 33 (34?).

The language now about biological jumpers looks appropriate to me.

Author Rebuttals to Second Revision:

Responses to referees' comments:
We thank both referees again for their thoughtful and helpful comments. We believe we were able to address all concerns raised without significant changes, yet believe our manuscript is once again substantially improved.

Referee #1 (Remarks to the Author):

Summary of key results (same as previous):
The authors have identified work multiplication for the actuator as a key component to improve energy density in jumping robots and use this idea in a jumping robot that can jump an incredible 30+ m. Specific differences between biology and engineering actuators (e.g., single stroke vs continuous stroke) are highlighted and resulting design guidelines are also identified in terms of motor-spring mass ratios.
Thank you again for this clear summary.

Originality and significance (same as previous):
Overall, I like the change in direction focusing more on what the authors term “work multiplication.” The authors are exploiting a clear difference in actuation between biology and engineering. While this has been hinted at in past papers as cited by the authors, I am not aware of any work that makes this explicit. Identifying this is clearly significant given the amazing results of the jumping robot.
Thank you for summarizing the contribution.

Data and methodology:
Overall, I’m still generally happy with the data and the methodology. I have specific comments that I have primarily included in the clarity section below.
Hopefully, we have addressed those specific comments, below.

Conclusions:
Overall, this is still a fantastic engineering design of a jumping robot. The identification of work multiplication as a mechanism that engineering can use to outperform biology is important and significant. The writing is still somewhat unclear and can be significantly clarified as described (at least in part) below.
Thank you for the overall assessment. With regard to lack of clarity, we appreciate all of your thoughtful feedback below, and believe in addressing these comments, the manuscript is much clearer.

Appropriate use of statistics and uncertainties:
This is no discussion of uncertainties in the measurements describe starting at line 614. For example, what is resolution of camera and what is frame rate? What is scale accuracy?
Thank you, we have added details of camera resolution and framerate, as well of uncertainty based on the size of the pixel in the plane of the jumper, converting this to uncertainty in take-off velocity. This section has been moved to SI due to space considerations.

Somewhere along the way, the authors lost the number of jumps accomplished in the main text (leading to the uncertainty in jump height).
Thank you for pointing this out; we have added the number of jumps in the main text.

Suggested improvements:

It struck me while reading through this that your hybrid spring is effectively a tension spring in which the mechanism around it can also store energy (in compression). Alternately, the tension springs add a little extra specific energy to the compression spring. This may help explain the improvements seen in this hybrid design.
This is a nice way of summarizing the effect. We have included this in the text that discusses the spring-linkage design.

> *The improvement can be thought of in two ways: compared to the tension linkage, we enable the linkage to store energy so it is no longer passive; compared to the compression bow, we add a high-specific-energy material.*

References:
Reference 1 looks like it is missing some data — is that section 3?
Thank you for checking on this. We found a Nature paper that references this same text, and it has this format:
9. Aristotle *Problemata* **3**, 705 a, 12–19.

Clarity and Context:

There is still a fair amount of language in the text that bothers me, mostly in regards to terms that are unclear and claims that I read as overstated. There are still plenty of typos as well. In general, I recommend that the authors read through the paper to tighten up the language as I'm sure I didn't catch everything. It looks like a lot, but most of these just need short clauses or greater clarity in language. I haven't spent the time to pick out the perfect phrasing here either, so feel free to modify as long as clarity is maintained.
We really appreciate the significant time and effort you put into these suggestions. We have addressed every one, and also proofread the paper to catch and improve other issues.

Title: I don't think that "outjumps" is a word. Not sure what Nature policies are on that.
Thank you for checking on this. Although it is in the Merriam-Webster dictionary, we agree that if it is not a commonly known word, it is not ideal for a title and have removed it.

Abstract:
In the abstract, you talk about limits early on, but don't describe limits to what? "Scientists have explored the limits of jumping animals… and engineers have sought to design jumping machines that exceed these limits." Just add jump height or jump specific energy somewhere in there to clarify.
Great point. Corrected.

"Biological jumpers are always limited" makes me twitchy — certainly the jump height of all known biological jumpers is limited by…
Yes; corrected.

"Engineered jumpers overcome this limit" —> "Engineered jumpers can overcome this limit". For the most part, as you point out in the text of the paper, they have not overcome that limit (but you do!).
Fair point! Corrected.

You introduce the idea of a spring and the energy capacity of that spring without any context. You have only been talking about motors to that point.
Good point; we have slightly shortened the abstract to meet guidelines and have actually removed this.

“High-energy hybrid…” —> “high specific energy hybrid”
We agree with this edit, but have removed the “hybrid” terminology from the abstract, and in doing fixed the concern.

Order of magnitude improvement in jump energy over biological … You should include either something regards to “similarly sized” or change to jump height
We have corrected this by changing to jump height.

Main text:
Vs. and versus both used — change this to a single
Good catch. We have changed this text slightly to avoid the use of either version of versus.

Can you really take advantage of work multiplication without a latch? Doesn’t the ratchet itself serve as a latch?
Yes. Consider a rotary motor: it is performing work multiplication without a latch simply by rotating multiple times. And linear motors that ratchet are not necessarily also latched (a latch opens to release energy). The ratchet on a linear motor never opens to release energy, rather continues to help store energy. We have added a clarifying sentence, describing how work multiplication can be done in a direct-drive case without a latch:

> *For a direct-drive transmission, work multiplication occurs during the acceleration phase, and for a spring-actuated transmission, it primarily occurs during the pre-stretch phase.*

I also think there is a little confusion throughout on motor versus actuator. Sometimes the spring serves as the jump actuator, but is not a motor. I think this language was clarified in reference 29 from what I remember.
Thank you for pointing this out. To avoid confusion, we have removed “actuator” from the manuscript, and explicitly state motor or spring when referring to each of these.

Speaking of reference 29, it would be nice if authors used the term described in (29) — latch mediated spring actuation (LaMSA) to describe the systems that they are analyzing for the work multiplication approach. The term “power amplified” is generally problematic because I could just run my motor more slowly on loading and achieve greater “power amplification”.
We are happy to use “spring-actuated” instead of “power-amplified.” For a reader not in this field, “spring-actuated” is likely more intuitive. We have edited throughout.

Line 80: Not sure how take-off time is defined in this line. I originally thought of energy production from the motor is limited by power x storage time. If take-off time also includes time to store energy, this makes sense, but most people think of take-off time as time to take off once energy is stored. Storage time is not necessarily correlated to size as in Fig. 2 though. I assume you mean specific energy of the jumping mechanism for energy production. Either way, clarification will help prevent your readers from being confused on this point.
Thank you for pointing this out. We have added clarification of take-off time (now acceleration time), which is indeed the time to take off (or accelerate) once energy is stored, as you suggest is standard.

…acceleration phase during which a force is applied to the ground to accelerate the jumper upward…We assume sufficient time between jumps to fully pre-stretch the spring regardless of the motor's power as well as sufficient spring power to discharge the energy during the acceleration time.

91: 100 m is not a specific energy (J/kg) — I think it's nice to use this as a very clear reference, but you could state "X J/kg, which correlates to a jump height of 100 m in Earth's gravity" to be clear

This parenthetical note was unclear. We wrote, "the upper bound is the spring specific energy limiter (at all practical scales, <~100 m)." What we meant to say was that the 100 m is a scale of the jumper, not a jump height. We have corrected this:

First, a spring-actuated rather than direct-drive transmission should be used for biological jumpers smaller than approximately 1 m length scale (0.6 s acceleration time), but for engineered jumpers, this crossover scale is nearly two orders of magnitude larger, at approximately a 100 m length scale (3 s acceleration time). (For crossover times, see Fig. 2; for conversion to scale, see Methods: State-space Model and Extended Data Fig. 3-4.)

Line 97 and others: very unclear what "mechanism" refers to in a lot of places. Is this the jumper or part of the jumper?

We agree that the definition of mechanism was not made clear. Upon reflection, we realized that it was a term that was not necessary to introduce, and as such we have removed it. The term mechanism referred to the motor, linkage, and optional spring, which is the entire jumper except the payload. We now simply discuss the "jumper," and note at the beginning that we assume the payload mass to be negligible in this analysis, since we are looking for upper limits.

101: add "on jump height" — motor power will affect time to jump so "effect" needs to be clarified

Thank you, corrected.

The 100x that keeps coming up starting in the paragraph from line 103 is confusing. Authors say that "biological mechanisms should have a spring-motor mass ratio that is at least a hundred-fold smaller than that of engineered mechanisms…" This statement is problematic for a variety of reasons. There are lots of reasons organisms might end up with a particular spring-motor mass ratio. Maybe they aren't trying to optimize jump height. Maybe they have other things going on. You can state that engineered systems should have a much higher ratio because they can multiply work, but going the other way is an issue. I would leave out the 100x until you justify it from the biology data later in the paragraph as well. Or you could describe more clearly the result found on lines 397 and 400 to explain the 100x.

This is a good point. We have changed the text to only state that engineering should have a much larger ratio, rather than the other way around. We have also removed the 100x statement, since 100 is somewhat arbitrary, given the shape of the curve in Fig. 2e.

You start talking about spring-motor mass ratio before really defining it.

Thank you for pointing this out. We now define it in parentheses.

Third, the jumper should use a spring-motor mass ratio (ratio of spring mass to motor mass) that is orders of magnitude larger than that of biological jumpers (Fig. 2e).

112: “limited only be” —> “limited only by”
Corrected.

118: “two insights” —> “two insights in the design of engineered jumpers”
This text has been edited.

119: “design process” —> “design process for a jumper”
This text has been edited.

“Practical” is used several times throughout, but it is unclear what that means in each context. For example, in line 152, “currently available materials at practical scales.”
We have removed “practical” and instead precisely define the scale which we consider (smaller than 1 m).

> *These results lead to three design insights for maximizing the specific energy of a jumper at the length scales of current engineered devices (< 1 m).*

Last part around line 170, are these #s for the same robot? Not clear as stated.
Corrected.

Methods:
Note — methods section here seems to include some of the interesting discussion as well instead of strictly methods. Not sure if this can be easily moved into the main text.
Thank you for pointing this out. We have moved over some of the discussion, as space would allow. Specifically, we now discuss what we define as payload and why it is considered in the utilization section; when work multiplication occurs for direct-drive versus spring-actuated jumpers; and how linkage mass is considered and the implications of linkage mass on specific energy for different types of jumpers.

Add a note that you are also ignoring the energy limitations of an on-board energy source like a battery or other fuel (otherwise equation on line 373 makes no sense)
This is a good point. We have added a note.

> *Similarly, a rotary motor has an unlimited stroke and hence an unlimited energy (limited ultimately only by the energy supply; because battery specific energy is orders of magnitude larger than those considered in this analysis, approximately 500 kJ/kg, we assume it is nearly infinite).*

Why is linkage included in energy production vs energy utilization (as payload)?
The linkage is an integral part of energy production (a jumper cannot produce a jump with a motor only), whereas a payload is optional and only decreases the specific jump energy and jump height. We have added clarifying text.

> *Note we include linkage mass in the energy production rather than utilisation, as neither motors nor springs can operate in isolation. Indeed, to fairly evaluate the energy production, we must consider how much linkage mass a design requires to function.*

Line 421 “rotary motors” —> “electromagnetic rotary motors”
Corrected.

427-428: More energy only available at take-off if driven by motor during this time (which many jumpers do not do)

429: Not sure what “reasonable” means here. “Monodically increasing with scale” —> “monotonically increases with scale”
We have re-written to clarify our scaling, defining it more precisely as isometric. We also corrected the typo.

431-432: “time-off time” —> “take-off time”
Corrected.

432: “scales linearly with scale” —> “scales linearly” and where am I supposed to see below?
Corrected. And we now state:

(See State-space Model below.)

435: A more generous view is that this previous work attempted to describe projectile systems beyond self contained jumpers (e.g., mantis shrimp, spore dispersal).
This is a good thought. We have clarified that the previous work was attempting to create a very broad model, beyond just jumpers.

447: “The energy utilization model” makes it sound like this has already been described in detail. Instead, you are really introducing this for the first time. “An energy utilization model” works better here.
Edited as suggested.

456: Variables are not defined. As an alternative, this equation could also be moved to after the descriptions.
Thank you for noting this. We have moved the equation after the descriptions, as suggested, and defined all other variables that were not defined in the descriptions.

506: This is a very weird sentence — I think you are just trying to say that the leg length is L. As written, it sounds like the mass increases.
We have rewritten the sentence:

The jumper has a length scale, L, which we define as the leg stroke, or difference between the body height when the jumper is fully crouched ($z = 0$) and when standing ($z = L$); the jump height is measured above $z = L$.

517: equation has force = force - a mass. I think you are missing a g here.
We have added the missing g.

519: specific power instead of power
We have added “specific.”

521: grammar
Edited to correct grammar.

543: where does 1/3 come from — I think 1/2 is common knowledge for a linear spring, but 1/3 is not

This is a good point. We have added a citation for a derivation of this for a massive spring.

576-ish: Authors keep saying “carbon” where I believe they intend “carbon fiber”
Corrected.

581: Spectra line means a line on a spectrum plot to most people :)
Good point. We have added the material name (ultra-high-molecular-weight polyethylene).

583: given earlier discussion, would help to call this the latch
Added the term latch.

588: “a small lithium polymer”
Corrected.

590: sable —> stable
Corrected.

627: Was force-displacement data for spring actually measured? Where is this data?
The data is shown in Extended Data Fig. 5b.

630: Model predicts a mechanism specific energy closely aligned with that measured in the spring directly — but what are these numbers? How close is closely aligned?
As noted above, we have added details of camera resolution and framerate, as well of uncertainty based on the size of the pixel in the plane of the jumper, converting this to uncertainty in take-off velocity. This section has been moved to SI due to space considerations.

Figures:

Fig 1a — takeoff time could be defined here to use in text.
We agree and have added a definition (note that we have re-named take-off time to now be acceleration time). We have also clearly marked it on Fig. 1a.

> *an acceleration phase during which a force is applied to the ground to accelerate the jumper upward*

For Fig 1b, isn’t the key that you are getting more displacement due to work multiplication? It is unclear why you focus on greater force that would just come from gearing. Instead, it seems you can just keep on clicking to get n x d.
Thank you for this feedback. We were trying to figure out the best way to convey this information, but based on this suggestion, we now simply show the increased stroke, as you suggest in Fig. 1b. We have also added a flowchart in Extended Data Fig. 1b to help convey that in a real jumper, where the leg stroke might be limited, one can convert the additional motor stroke into a large leg force using a gear reduction.

Fig 2 caption — not sure what “, and leaving motor specific power” means. Typo?
Corrected.

I missed why you are including dots at a takeoff time of 0.03 s — doesn’t look like your jumper tick mark is here and didn’t see it in the caption

Referee #2 (Remarks to the Author):

I have one, major concern left with this manuscript, that ties to a comment made by reviewer 4.

Reviewer 4 states:
* I couldn't tell why are you getting only about 1/3 the mechanism specific energy predicted by the model.*

This reduction of specific energy appears, to me, to be a direct consequence of the interaction between force/length parameters and spring energy storage, illustrated in references 27, 33 (34?, which looks identical to reference 33?), and specifically discussed for muscle in Rosario et al., (2016). This represents a limit of how much energy can be stored by a spring relative to energy produced by an actuator. This is the only way I can make sense of Figure 1.

I am left very puzzled as to 1) why the spring is able to store near 100% of the energy production capacity of the actuator, and 2) why a model that has no apparent energy dissipation only returns less than half of the energy storage. I find it much more probable that the actuator was only able to store less than half of its possible energy in the spring, and that the less than half is returned. The authors say that this is because of 'linkage mass', but mass is energetically conservative, and consequently I'm very puzzled by this response.

when the authors discuss the limited energy storage capacity in the text, the revised manuscript simply refers to 'practical limitations' (line 94) and cites 26 and 27.

I may be completely misunderstanding the text as written, can the authors' please explain? As I read it, the energy loss seen in figure 1 is clearly a consequence of the 'practical limitations' in references 26 and 27 (which would apply to both engineered and biological systems).
We thank you for the comments regarding the difference between the model specific energy and the specific energy reported for the jumper. Your thoughts have helped us understand that we were lacking clarity in our discussion.

To explain, the reduction in specific energy is exactly as you mention above, due to linkage mass. Because we are examining specific energy, we care about the energy per unit mass. Therefore, while a single piece of rubber in tension can have a very high specific energy (~7000 J/kg), once the passive linkage mass is included, the *total* energy remains the same, but the *specific* energy decreases to around 2000 J/kg. For example, consider 1 kg of rubber in tension, storing 7000 J of energy. Now, add the required linkage mass to transfer this tension force to the ground while accelerating the jumper upward, say 2.5 kg of carbon fiber. The overall specific energy of the spring-linkage required for jumping is then 7000 J / (1 kg + 2.5 kg) = 2000 J/kg. We have added new text in the introduction to hopefully clarify:

> *We examine two aspects of a jump: specific energy production limits (the maximal energy that could be created for a single jump per unit mass of a jumper) and specific energy utilisation (the efficiency of converting this specific energy into jump height). We concentrate the following discussion on specific energy production limits, as in previous biological studies[26], since we are interested in the upper bounds of jumping, and specific*

energy directly corresponds to maximum (lossless) jump height in a given gravitational field ($e = gh$).

Additionally, we have added linkage mass to Fig. 2 to help visualize the way in which it decreases the specific energy. Hopefully, this will further clarify the point for readers.

To your question about storing nearly 100% of the energy produced by the motor, this is indeed possible for engineered devices, since the force-displacement relationship of both the motor and spring can be constant. This is not true in biology, where both the spring and the motor (muscle) show a length dependence for their output force, meaning somewhere between 30%-50% of the energy of the muscle can be stored (as you note, from references 26 and 27). We note how our spring has the characteristic:

Our spring-linkage also has a nearly constant force-displacement curve, which helps it store a large amount of energy given the force constraint.

The term 'practical limitations' to refer to consequence of acuator/spring geometry makes me very uncomfortable with its lack of precision.

Thank you for bringing this up. We have removed this terminology, and now describe precisely to what we are referring.

Biological spring-actuated jumpers at a small scale have sufficient power, but again specific energy is capped by the motor work limiter; above the crossover scale, springs are unnecessary and actually decrease specific energy due to added mass and muscle-spring force-displacement characteristics[26,27,32].

I have one small point, line 87; please mention that these crossover points are discussed in references 27 and 33 (34?).

We have added this reference when discussing crossover, and corrected the duplicated reference.

The language now about biological jumpers looks appropriate to me.

Thank you.